Effects of Superheated Steam Processing on the Drying Kinetics and Textural Properties of Instant Asian Noodles

by

CARL PRONYK

A Thesis
Submitted to the Faculty of Graduate Studies of
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In Partial Fulfilment of the Requirements
For the degree of

DOCTOR OF PHILOSOPHY

Department of Biosystems Engineering

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

Superheated steam drying has been known for over 100 years, but acceptance in industry has been slow. Before industry accepts a new technology like processing in superheated steam it must be proven to provide benefits that exceed additional costs and risks. Superheated steam may provide these benefits in the area of processing where drying of a product is not the primary concern. Superheated steam has the potential to create a healthy instant noodle without frying them in oil. The objective for this work was to develop a novel technique for creating instant noodles by determining the drying kinetics and effects of superheated steam conditions on key physical and textural properties of noodles undergoing simultaneous drying and cooking using superheated steam.

Equilibrium moisture content isobars and a mathematical model of moisture ratio with regression determined coefficients based on steam temperature and velocity were determined from mass changes during superheated steam processing. The mathematical model of moisture ratio was differentiated to determine the drying rates of noodles during processing. There was a constant rate drying period for all temperatures at a steam velocity of 1.5 m/s, but the constant rate drying period at a steam velocity of 0.5 m/s was masked by condensation on the sample tray. The constant rate drying period determined by measurement of internal noodle temperature is much longer and well defined for all processing conditions than from the drying curves. The constant drying rate period, was nearly 200 s at 110°C but decreased to 50 s at 150°C.

Time effects on textural properties of raw and superheated steam processed noodles were not significant ($p > 0.05$) between 40 and 200 min after sheeting. Pre-treatment with saturated steam increased hardness and chewiness. Textural properties of adhesiveness, springiness, cohesiveness, chewiness, resilience, and hardness determined from a TPA were generally unaffected by steam velocity. All textural properties except springiness increased with an increase in processing time. An increase in superheated steam temperature decreased adhesiveness, springiness, cohesiveness, and resilience but slightly increased hardness and chewiness.

Noodles processed at a steam velocity of 1.5 m/s and at 125°C for 200 s, 130°C for 167 s, 135°C for 150 s, 140°C for 133 s, 150°C for 100 s, and a steam velocity of 1.0 m/s and 150°C for 133 s had acceptable colour values (L^* values greater than 63, a^* values less than 0, and b^* values above 20) and moisture at or below the safe storage limit. Results indicated these noodles had textural properties and breaking strengths that were comparable to commercial instant noodles. These conditions are the optimum to produce a noodle that has physical and textural properties that would be acceptable to consumers.

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LIST OF SYMBOLS

BS	Breaking stress (g/mm^2)
D_m	Overall moisture diffusion coefficient (m^2/s)
ERH	Equilibrium relative humidity (decimal)
f_{max}	Maximum force (g)
k	Drying coefficient (s^{-1})
L	Span (mm)
$\overline{M}$	Average moisture content (kg/kg, db)
M_e	Equilibrium moisture content (kg/kg, db)
M_o	Initial moisture content (kg/kg, db)
MCS	Maximum cutting stress (g/mm^2)
MR	Moisture ratio (decimal)
P_r	Relative pressure - ratio of working pressure of the steam to the pressure of saturated steam at the working temperature (decimal)
P_{sat}	Saturated vapour pressure (kPa)
P_v	Vapour pressure (kPa)
T	Temperature (°C)
T_s	Steam temperature (°C)
T_n	Noodle thickness (mm)
V_s	Steam velocity (m/s)
W	Noodle width (mm)
w_n	Width of three noodle strands placed beside each other (mm)
w_b	Width of cutting edge of the blade (mm)
θ	Time (s)

1 INTRODUCTION

The primary objective of food drying is preservation. Lowering moisture content in food helps prevent, or reduce microbial and enzymatic reactions. However, drying may have an adverse effect on chemical, physical, and nutritional value of food products (Chou and Chua 2001). Research goals for refining drying technologies are to improve on economics of operation (reduce energy consumption, increase capacity, reduce size of equipment, increase ease of control), environmental considerations (minimise energy consumption, reduce emissions, increase safety), and improve product quality (uniform drying, minimise chemical, physical, and nutritional degradation) (Chou and Chua 2001, Kudra and Mujumdar 2002). Some of these goals must be proven to provide benefits that exceed additional costs and risks before industry is willing to adopt a new technology.

Superheated steam drying has been known for over 100 years, but has only made small gains in acceptance within certain industrial applications (Pronyk et al. 2005). The benefits of superheated steam over hot air are many. It has been shown that energy consumption is often lower, smaller equipment may be used, reduced risks for fires and explosions, and harmful emissions may be eliminated (Lane and Stern 1956, Shibata and Mujumdar 1994, van Deventer and Heijmans 2001). Acceptance has occurred with lumber and coal drying where superheated steam has proven quality benefits over the use of hot air (Bainbridge and Satchwell 1947, Chen et al. 2000, Ishikawa et al. 2004, Kollmann 1961, Kudra and Mujumdar 2002, Lavine et al. 1930) as well as in the sugarbeet industry where energy efficiencies compared to hot air are very high (Urbaniec and Malczewski 1997). The next step in utilization of superheated steam may be in the field of processing, where drying of a product is not the primary objective. As a processing medium, superheated steam may change the properties of a product in ways that would not be possible with the use of hot air or other media.

A potential method for creating instant noodles is by processing them with superheated steam at temperatures between 100 and 200°C. At high temperature processing using superheated steam, Asian noodles (non-extruded, sheeted and cut noodles) become partially cooked, creating an instant noodle and eliminating the necessity of additional cooking in oil (Markowski et al. 2003). Instant noodles were first created in 1958 and have remained popular ever since (Miskelly 1993). Instant noodles have found a large market in North America with Canadian sales of M$71/year (Bailey 2002). Instant noodles are created by frying raw Asian noodles in oil. This reduces the moisture content which helps to lengthen the storage life, creates a porous internal structure that aids in quick cooking, but adds a large amount of fat to the final product. Currently, there are health concerns in North American society over the fat content in foods and the presence of trans-fatty acids from partially hydrogenated and hydrogenated oils used in the frying process. Trans-fatty acids have been associated with an increased risk of coronary heart disease in epidemiologic studies (Willett and Ascherio 1994). By using superheated steam to process the noodles, fat can be completely eliminated.

Markowski et al. (2003) found some improvements to noodle texture, but an acceptable consumer product was not achieved. However, they did not compare their processed noodles to commercially available noodles or control samples to see if these results were similar to properties of other instant noodle products. The processing procedure was limited in these experiments to one steam velocity (0.20 m/s) and four temperature levels (110, 120, 130, and 140°C). The potential to create commercially acceptable instant noodles with superheated steam is plausible as studies of impingement drying of potato chips using superheated steam showed that the textural characteristics of superheated steam processed samples were more similar to the commercial oil fried chips than those dried with hot air (Caixeta et al. 2002).

Determination of the fundamental drying and textural characteristics of superheated steam processing of instant Asian noodles is a difficult undertaking. A systematic and thorough study would require large numbers of small samples because of the size of the superheated steam system available. In comparison the amount of material to mix and sheet the dough necessary to create noodles for processing is large. All of this is exasperated by the limited amount of flour available to complete all of the experiments. Some of these problems can be mitigated by utilizing small-scale laboratory equipment to create a smaller noodle sheet (Kovacs et al. 2003). Creating smaller samples for processing is possible, but in some cases where many experiments are run, the time to mix and sheet new samples is not practical. A convenient way to obtain many small samples for testing new processing methods would be to create a single noodle sheet and cut samples from it as needed. The drawback to this approach is the possibility of changes in textural properties of the noodle sheet with resting time. Literature on the subject of changes in textural properties of Asian noodle dough with resting time is nonexistent but would be of use to other researchers who require many samples of the same noodle recipe for testing new processing methods or evaluating current ones.

The main objective is to develop a novel technique for creating instant noodles by simultaneous drying and cooking of noodles using superheated steam. The specific objectives are to:

(1) Measure the drying kinetics of Asian noodles processed in superheated steam at steam velocities of 0.5, 1.0, and 1.5 m/s and at steam temperatures between 110 and 150°C at 5°C intervals.

(2) Develop a mathematical model of drying of noodles undergoing superheated steam processing.

(3) Determine the effects of resting time and pre-treatment with saturated steam on the textural properties of Asian noodles.

(4) Ascertain the effects of superheated steam processing conditions on physical and textural properties of Asian noodles. Results will be used to expand knowledge by explaining the phenomena taking place during processing under different regimes using the novel system of superheated steam processing.

(5) Determine the optimum conditions for processing noodles in superheated steam with respect to physical and textural properties compared to air dried and fried control samples and commercial products.

2 LITERATURE REVIEW

2.1 Superheated steam drying

2.1.1 History

Drying is often a necessary operation to preserve products for consumption at times and places far removed from production. Humankind has been drying products for over 20 000 years for the purpose of preservation (Hayashi 1989). Reducing the water content of a product helps prevent or decrease microbial and enzymatic reactions in addition to reducing mass, thus improving the economics of storage and transportation. Early drying methods utilized the natural energies of the sun and wind to effect a change in moisture content. These methods were good but people were at the mercy of the weather, and had little control over the drying process, which was often slow and uneven. The need for anything more than the most primitive drying methods was unnecessary in the pre-industrial world. It was not until the nineteenth century that the informal drying methods of the previous era became inadequate for the increasing scale and rates of production experienced during the industrial revolution (Keey 1980). Indeed, drying technology rapidly improved during the century so that prototypes of many modern dryers were patented, including: a radiant heat dryer (1878), a vacuum dryer (1891), a pneumatic-conveying dryer (1896), and a spray dryer (1901) (Keey 1980).

As drying technology advanced, so did the field of drying theory. Perhaps the earliest treatise on drying theory was *Drying by Means of Air and Steam* written in German by Hausbrand in 1898 and later translated into English in 1901 (Hausbrand 1912). Hausbrand (1912) mentioned that the theoretical principles for calculating the dimensions of drying apparatus could be found in the textbooks on heat transfer of the day. However, they were not really suitable for the purpose due to the continuous and rapid changes in temperature and moisture so that conditions for any one apparatus may be so different that one calculation should not be sufficient. Hausbrand goes on to consider the possibility of drying "without air by steam alone". He states that to his knowledge no mention has been previously made about drying by means of steam and that it is his hope that "the advantages of this method should be known; it may then attain wide application". From these early humble beginnings, the practice of superheated steam drying has slowly gained industrial acceptance.

Even in its infancy there were examples of industrial use of superheated steam drying, especially for lumber and coal. Kauman (1956) reports that there were superheated steam kilns for the drying of lumber operating on the West Coast of the United States as early as 1908. In addition a man named Tiemann developed a "high velocity, low superheat" kiln during the First World War. However, these kilns fell out of favour because of energy inefficiencies and corrosion problems (Kauman 1956). Not until after the Second World War was any more work done with industrial superheated steam drying of lumber. This work was taken up in Germany, where kilns that ran with superheated steam or air and superheated steam mixtures gained industrial acceptance and later spread outside of the country (Kollmann 1961). At least two companies were supplying superheated steam kilns to the market at that time.

The other area where superheated steam gained some industrial acceptance was to dry brown coal (a low-grade high-moisture content (55-65%) coal). In Austria the Fleissner process was developed in the late 1920s to provide a dry coal from a brown coal (Potter and Beeby 1994). Some work was also accomplished in the USA for the drying of lignite using the Fleissner process (Cooley and Lavine 1933, Lavine et al. 1930). In the Fleissner process, a large portion of the liquid leaves the product in a physico-chemical process within a vessel filled with saturated steam. The pressure is then reduced and a portion of the remaining moisture flashes to steam and leaves the product. The Fleissner process is not always considered true superheated steam drying because the process may occur in the absence of a saturated steam environment, in addition to most moisture being removed as a liquid (Potter and Beeby 1994). Still, there is some superheated steam drying occurring in the system. A plant using this process commercially operated in Austria until the middle of the 1970s (Potter and Beeby 1994).

In addition to lumber and coal drying there are at least two more early examples of the commercial use of superheated steam drying. In 1920 a commercial operation was drying foundry sand with superheated steam in a specially converted drying oven (Kaner 1920). In the other case an industrial operation for producing resin using superheated steam, or any other superheated solvent was commissioned in 1960 (Basel and Grey 1962). For the next 20 years there were no new commercial developments of superheated steam drying or processing.

Drying theory and application of superheated steam grew during the first part of the 20th century. From the basic principles, equations, and tables for quantities of steam necessary to evaporate moisture from a product given by Hausbrand (1912), researchers have continued to expand the knowledge. Early work tended to focus on the merits of superheated steam drying versus hot air drying and on the fundamentals of evaporation into superheated vapours (Chu et al. 1953, Chu et al. 1959, Lane and Stern 1956, Wenzel and White 1951). Some work was also conducted into the design and operation of superheated steam drying systems (Basel and Grey 1962, Kollmann 1961). Except for lumber and coal, there was a lack of research conducted on the drying of specific products in superheated steam until the 1960s. A notable exception is mentioned briefly by Potter and Beeby (1994) about work done by Kaner (1920) who dried cabbage and hay. It was the research of Yoshida and Hyodo in Osaka, Japan that began the trend of looking at a specific product and the changes that occur when it is dried in superheated steam. They looked at the quality of synthetic fibres spun in a superheated steam dryer (Yoshida and Hyodo 1963). The fibre was stronger and finer when dried in superheated steam and smaller, simpler equipment could be used. Yosida and Hyodo (1966) also looked at the drying of potato slices. Results showed that there was less oxidation, greater porosity, and a higher drying rate in superheated steam than in dry air.

There was very little research done through most of the 1970s. This all changed towards the latter part of the decade when there were large advances in the field and a proliferation of industrial applications of superheated steam drying. The increased interest in the field of superheated steam drying was probably brought about by the energy crisis of the 1970s because of the well known energy efficiencies that may be achieved with superheated steam (Wimmerstedt 1995). In the last 25 years many companies have come forward to offer industrial superheated steam dryers and a fertile worldwide research community has formed.

2.1.2 Industrial applications

Around the world there are hundreds of superheated steam drying systems in use by industry. Most suppliers of superheated steam drying systems are located in Europe (Table 2.1) and the greatest acceptance for the technology seems to be in Europe, although units are in existence in many other countries. The list of suppliers is not complete, but represents most of the major suppliers of superheated steam drying systems.

Table 2.1 Major suppliers of superheated drying and processing systems.

Company	Country	Name	Design	Number of Units	Products Dried
GEA Barr-Rosin	Sweden	GEA Exergy Barr-Rosin Dryer	pneumatic	approximately 24	paper pulp, grain, cellulose derivates, corn by-products, mineral wool, distillers and brewers grain, wood chips, peat, sugar beet pulp, sawdust, potato waste, bark, fish meal, biomass, tobacco, sewage sludge, fibre sludge, manure, citrus peel/pulp, grass, grape skins, lucerne, coffee grounds, straw, spices, bagasse, olive residues
BMA AG	Germany	BMA (formerly NIRO)	fluidised bed	more than 14	sugar beet pulp
EnerDry ApS	Denmark	EnerDry ApS	fluidised bed	1 supplied/6 rebuilt BMA/NIRO/3 supported	sugar beet pulp, wood chips, fibrous material
Maschinenfabrik Gustav Eirich GmbH	Germany	Eirich mixing SHS dryer	batch	12	sludges, pigments, washpowder
W. Kunz dryTec AG	Switzerland	Swiss Combi ecoDry	rotary drum	more than 60	sawdust, wood chips, sludge
Moenus Artos Textilmaschinen GmbH	Germany	Moenus (formerly Babcock)	impingement	2	dyed textiles, textiles
Ceramic Drying Systems Ltd.	UK	CDS airless dryer	continuous / batch	unknown	ceramics, bricks, sanitary ware, tableware, insulators, meat and bone meal
Keith Engineering	New Zealand	Superheated steam drum dryer	rotary drum	1	animal byproducts, blood, wood chips, sewage sludge
WTT (Wood Treatment Technology), Formerly Iwotech	Denmark	SSV dryer & Energy vacuum dryer	batch/vacuum	more than 250	timber
Brunner Hildebrand Lumber Dry Kiln Co.	USA	High capacity vacuum dry kiln	batch/vacuum	unknown	timber
HB SWS Ltd.	The Netherlands	Superheated steam drying kiln	batch	unknown	timber
Sharp Corporation	Japan	"Healsio" water oven	oven	consumer appliance	roasts food using water in the form of superheated steam

The greatest number of superheated steam dryers are used by the lumber industry. The biggest suppliers are the Brunner/Hildebrand Lumber Dry Kiln Co., HB SWS Ltd., and WTT (Wood Treatment Technology)(formerly IWT Iwotech Ltd). WTT alone accounts for over 250 units in operation worldwide (communications to the other suppliers were not returned so number of units in operation is unknown). All these systems operate as a batch system with the Brunner/Hildebrand and WTT systems operating under vacuum.

Two of the oldest suppliers of superheated steam systems outside of lumber drying are GEA/Barr-Rosin Company and BMA AG. The GEA Barr-Rosin Exergy dryer was developed at Chalmers University in Sweden and a report was published about the initial experience with the dryer (Svensson 1980). In 1989 Stork Friesland bv from The Netherlands took over the rights until the nineties when it was taken over by NIRO, now part of the GEA/Barr-Rosin Company (van Deventer 2004). Since the first unit was commissioned at the Rockhammer Mill in 1979, approximately 24 units have been built for drying pulpy materials in many different countries (Svensson 1980, van Deventer 2004). The BMA/NIRO fluidized bed superheated steam dryer was initiated at the pilot scale in 1982 and the first industrial scale model was commissioned in 1985 at the Stege Sugar Factory in Denmark (Kudra and Mujumdar 2002, van Deventer 2004). Since 1990, 14 dryers have been built in Europe and North America to dry sugar beet pulp (van Deventer 2004). Arne Sloth Jensen who was with Danisco in Denmark when the technology was developed and later moved to Niro A/S when the technology was transferred left that company in 1997 to found his own company EnerDry Aps. EnerDry has supplied one new unit to Minn-Dak Farmers in North Dakota, USA, has rebuilt 6 BMA/NIRO units, and currently supports three others based on the improvements made to the previous design.

Two companies that supply dryers that operate with superheated steam have appeared in the last 15 years. Swiss Combi Ecodry dryers marketed by W. Kunz dryTec AG use superheated steam to dry sludge, sawdust, wood chips, and other products in a rotary drum dryer with re-circulating superheated steam. This dryer was initially developed from research at the Fraunhofer Institute of Wood Research (WKI) in Braunschweig Germany (van Deventer 2004). They can build a new unit or convert a pre-existing unit to their technology and since 1989 they have installed upwards of 60 drying units in Europe and North America (van Deventer 2004). The other company, Maschinenfabrik Gustav Eirich GmnH & Co KG produce the Evactherm® Eirich mixing superheated steam dryer. The Evactherm® dryer is a batch system that operates with a vacuum and provides continuous mixing in a rotating pan. The dryer allows for other operations while mixing and drying occur including reacting, drying, heating, cooling, stripping, plasticizing, and granulating. The unit is useful for processing sludge, brake linings, pigments, wash powder additives, and ferrites. Currently there are 12 of these units in operation (van Deventer 2004).

Moenus Artos Textilmaschinen GmbH from Germany supplies one of the more interesting dryers on the market. They produce a textile dryer that uses impingement jets of superheated steam. The process is continuous and sealing is accomplished by stratification of air and superheated steam within the dryer. Superheated steam has a lower specific mass than air, meaning it can be contained within a cavity that is closed at the top but open at the bottom. The textile web may enter and leave the bottom of the cavity without a loss of steam. Presently there are two units in operation (one of which is in Brazil) and the company continues to learn from the units in operation (van Deventer 2004).

An airless dryer has been developed and patented by Thomas Stubbing from the UK and was brought to market with co-operation between his company Heat-Win Ltd. and Ceramic Drying Systems (CDS) Ltd. In an airless dryer superheated steam is not supplied, but is created by circulating the air within the system through a heating device with steam being created by moisture contained within the product. Continuous and batch systems have been developed and patented with the batch system being marketed to the ceramic industry.

A new dryer for the rendering industry was developed at the research facility AgResearch (Formerly the Meat Industry Research Institute of New Zealand) in the mid to late 90s. The technology was commercialised by Keith Engineering New Zealand, a subsidiary of Pinches Industries of Melbourne, Australia in 2001. The system is an airless rotary drum dryer for animal by-products, blood, wood chips, and sewage sludge. The advantages for the rendering industry are numerous, including dramatic reductions in air pollution, improved product quality, and a lower risk of fires. One system has been commissioned in 2002 at Lowe Corporation's bovine processing plant in Hawera, New Zealand. In 2004 The Dupps Company was granted an exclusive license in North America to sell the Keith Airless Dryer and have set up a pilot plant where potential users can send material to be tested in a scaled down version.

With the benefits of drying well known, the processing benefits of superheated steam are now also being recognised by companies. Sharp Corporation in Japan has announced the introduction to the Japanese market of the "Healsio" Superheated Steam Oven. The oven sprays superheated steam from three directions at a temperature of 300°C onto food to cook and roast at the same time. The ovens are being heralded as a healthy cooking method and are being marketed as the "new must-have appliance for this century of health".

In addition to the established suppliers of superheated steam systems, several companies have prototypes and pilot systems that they are developing. These include (van Deventer 2004):

- Stramproy Projects & Systems (The Netherlands) is working on a rotary dryer for wood chips, biomass, and sludge with the co-operation of Ceramic Drying Systems Ltd.
- Techni Process Fr. (France) is working on a superheated steam spray dryer with a 50 kg/h evaporation rate at 700°C. This dryer is based on research conducted by ENSIA in France.
- Landuwasco (The Netherlands), a company that specialises in laundry equipment, is working to develop an airless superheated steam laundry dryer.

- Hosokawa Micron bv (The Netherlands) has dried many products with superheated steam at the pilot scale in their pneumatic flash dryer that normally operates with air or nitrogen. They expect industrial applications to appear soon.

Currently many institutes and universities around the world are conducting research into superheated steam and its applications. Japan has always had a rich history in superheated steam research (Shibata and Mujumdar 1994). Institutes conducting research include: Ecole Nationale Supérieure des Industries Agricoles et Alimentaires (ENSIA) in France; Netherlands Organization for Applied Scientific Research (TNO) in the Netherlands; Fraunhofer Institute for Wood Research (WKI) in Germany; VTT Technical Research Centre of Finland in Finland; and Forintek Canada Corp. in Canada. The list of universities (Table 2.2) currently conducting research, or with superheated steam expertise is not complete but is only meant a tool to show the extent of research and provide possible contacts to other researchers in the field.

Table 2.2. Universities currently conducting research or with expertise in superheated steam drying and processing

Principal Researcher(s)	University	Location
S. Cenkowski	University of Manitoba	Winnipeg, Canada
S. Devahastin, S. Soponronnarit, S. Prachayawarakorn	University of Technology Thonburi	Bangkok, Thailand
J. Fitzpatrick	University College Cork	Cork, Ireland
S. Heinrich	University of Magdeburg	Magdeburg, Germany
R. Moreira	Texas A&M University	Texas, USA
A. Mujumdar	National University of Singapore	Singapore
Z. Pakowski	Technical University of Lodz	Lodz, Poland
S. Pang	University of Canterbury	Christchurch, New Zealand
R. Renström, J. Berghel	Karlstad University	Karlstad, Sweden
M.J. Urbicain	PLAPIQUI (UNS-Conicet)	Bahía Blanca, Argentina
various researchers	Osaka City University	Osaka, Japan
R. Wimmerstedt	Lund University	Lund, Sweden

2.1.3 Characteristics of superheated steam drying

Superheated steam can be used to dry materials because it is steam that has been given additional sensible heat to raise its temperature above the corresponding saturation temperature at a given pressure. Unlike saturated steam, a drop in temperature will not result in condensation of the superheated steam as long as the temperature is still greater than the saturation temperature at the processing pressure. The moisture evaporated from the product becomes part of the drying medium and does not need to be exhausted thus allowing for recycling of the drying medium, provided additional sensible heat is added. If pressure builds in the system because of the additional superheated steam created from the evaporated moisture, it can be relieved by exhausting a portion of the steam. When the drying process is looked at there are some distinct differences between superheated steam and air as the drying medium.

The superheated steam drying process can be broken into three distinct periods. The first period begins when superheated steam comes into direct contact with the product being dried. The superheated steam raises the product's temperature to the boiling temperature at the processing pressure by giving the product a portion of its sensible heat. During this period, if there is not sufficient sensible heat in the superheated steam, some condensation may occur on the product, or in the drying chamber. The second period is known as the constant rate period where the internal resistance to moisture diffusion is less than the external resistance to water vapour removal from the products surface. In hot air drying the rate depends on the convective transfer of heat from the air to the product and diffusion of water from the product to the air through a boundary layer of moisture surrounding the product. However in drying with superheated steam the water does not have this diffusive resistance to movement through the boundary layer and water moves by bulk flow only. As well, the heat transfer coefficient is greater for superheated steam and evaporation of water into superheated steam is greater than into dry air except when the temperature of superheated steam approaches the saturation temperature (Chu et al. 1953). At the same medium temperature the temperature of the product is higher in superheated steam than hot air. The product's temperature will rise to the temperature of saturation at a given pressure for superheated steam while in hot air the temperature will only rise to the corresponding wet bulb temperature. The constant rate period is also longer than for air-drying under similar conditions.

The drying rate for superheated steam will be greater than for hot air if the temperature is above the inversion temperature. At the inversion temperature, the evaporation rates into pure superheated steam and completely dry air are equal (Fig. 2.1). Conversely, above the inversion temperature the rate of evaporation will be greater into superheated steam than dry air. Values between 160 and 260°C for the inversion temperature were summarised from several sources by Schwartze and Bröcker (2002) and represent both experimental and theoretical values. If the superheated steam temperature is below the inversion temperature the process could still be economical if the drying rate is greater in the falling rate period.

After the outer surface begins to dry, the third period, called the falling rate period begins. In the falling rate period the drying rate decreases and the product's temperature will rise to that of the superheated steam. In this period the internal resistance to moisture transport is greater than the external resistance. The drying rate is usually greater for superheated steam than for air-drying because the product temperature is greater allowing for greater moisture diffusion in the product. As well, case-hardening (or "skinning") may not occur and the product dried in superheated steam is more porous (Kudra and Mujumdar 2002).

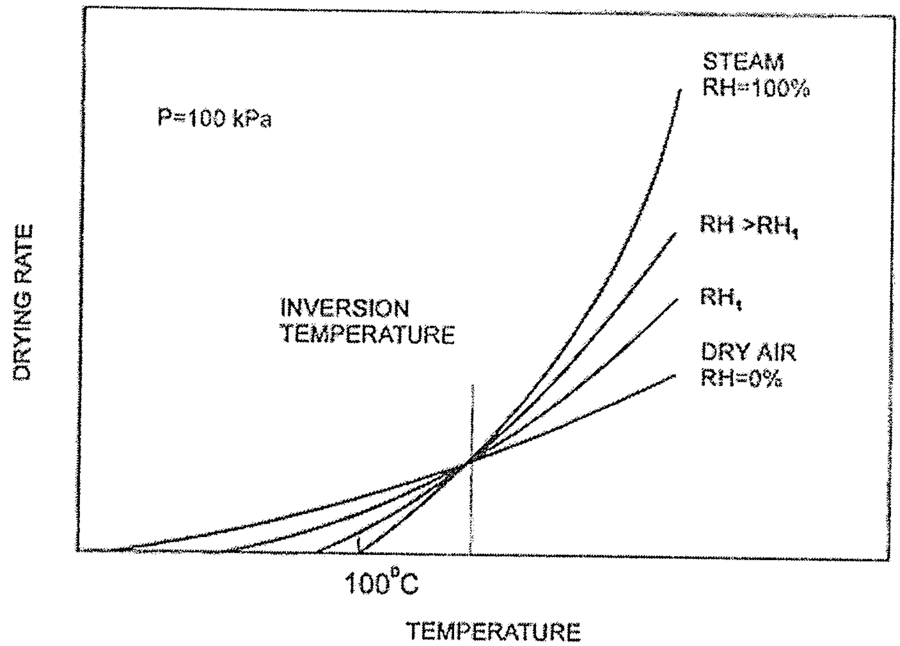


Fig. 2.1. Drying rate vs. temperature for air and steam (Kudra and Mujumdar 2002).

It has been claimed that one of the limitations for using superheated steam for drying is that products cannot be temperature sensitive because of the high temperatures experienced with superheated steam processing (Lane and Stern 1956, Meunier and Munz 1986, Taechapairoj et al. 2003). However, temperature sensitivity may be remedied by using sub-atmospheric pressure superheated steam, which produces superheated steam at temperatures below 100°C (Elustondo et al. 2001, Elustondo et al. 2002, Martinello et al. 2003). However, providing a vacuum to the system creates a greater level of complexity to the superheated steam drying equipment.

2.1.4 Simple superheated steam dryer

Although superheated steam drying is only now gaining acceptance, the concept has been known for nearly 100 years. Hausbrand (1912) presented the concept of convective drying with superheated steam and detailed a dryer in its simplest form (Fig. 2.2). In his system the product is placed in an insulated, closed system that is sealed to prevent air from entering. The interior air is circulated by the fan, which passes it through a heater where it gains thermal energy, and sends it to the drying room where a portion of the moisture in the product is converted into vapour. The air thus completes the cycle and starts again, each time picking up more moisture. As the pressure in the system builds, a valve releases excess vapour and air. Eventually, as the process continues the air will have been completely released so that only steam remains. The heater keeps the steam superheated and drying is conducted by superheated steam only. This is actually a subset of superheated steam drying because steam is not supplied to the system but is created from the product being dried. This has sometimes been called "airless drying".

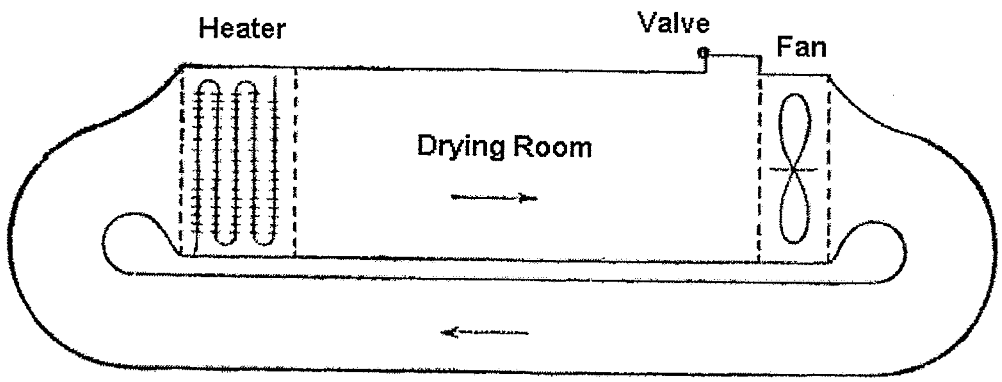


Fig. 2.2. Simple superheated steam dryer (modified from Hausbrand 1912).

2.1.5 Benefits of using superheated steam

The use of superheated steam as a drying medium has many potential benefits to the consumer and industry and has been detailed by many authors (Lane and Stern 1956, Shibata and Mujumdar 1994, Tang and Cenkowski 2000, van Deventer and Heijmans 2001):

- Use of superheated steam can lead to energy savings as high as 50 to 80% over use of hot air or flue gases. These savings can be achieved due to higher heat transfer coefficients and the increased drying rates in the constant and falling periods if the steam temperature is above the inversion temperature. The constant rate drying period is also longer in superheated steam drying thus providing high drying rates for longer periods of time. These higher drying rates will increase the efficiency of the processing operation potentially leading to a reduction in equipment size or an increase in output. High thermal efficiency is usually achieved only if the exhaust steam is collected and used elsewhere in the processing operation.

- Use of superheated steam as the drying medium instead of hot air means that there is an oxygen free environment during drying. That means there is no oxidative or combustion reactions during drying (no fire or explosion hazards). The oxygen free environment also produces improved product quality (no scorching).
- Most superheated steam dryers are designed as a closed system where the exhaust may be collected and condensed. In this way toxic or expensive compounds are removed and collected before they reach the environment thus reducing air pollution. In the same way, dust from the process can be collected.
- Processing in superheated steam allows concurrent blanching, pasteurisation, sterilization, and deodorisation of food products during drying.

Even with these proven benefits utilisation of superheated steam as a drying medium is not wide spread due to a lack of understanding about superheated steam and its effect on products during drying.

2.1.6 Processing of food products in superheated steam

Processing in superheated steam may impart physical changes upon the product in addition to any drying that may take place. These changes may be unique to superheated steam and may not be achieved any other way. Paper dried in superheated steam has an increased burst index, elastic modulus, and up to 30% greater tensile strength (Kiiskinen and Edelmann 2002). Synthetic fibres spun in superheated steam produced a stronger and finer fibre (Yoshida and Hyodo 1963). Products may have odours removed, as with distillers spent grain where acetic acid can be stripped away by the superheated steam, thus giving the spent grain an aroma like baked goods instead of a sour smell (Tang and Cenkowski 2001). When food products are processed in superheated steam they may become more porous due to increased heat transfer rates causing the moisture in a product to flash into steam creating many pores (Kudra and Mujumdar 2002, Yoshida and Hyodo 1966). This may have an application in the snack food industry where frying in oil produces the same results.

Markowski et al. (2003) processed Asian noodles in superheated steam to create a traditional dried noodle. They found that at high temperatures the noodles become partially cooked, creating an instant noodle instead of a purely dried product. Results showed that breaking strength is adversely affected by an increase in processing temperature and noodles became brown at temperatures above 130°C. A study of the starch by differential scanning calorimetry also showed that starch is being modified which affects its ability to swell when cooked. When noodles were processed at 110°C and 120°C in superheated steam textural parameters of recovery and adhesiveness were improved. However, these improvements are overwhelmed by deleterious effects on the key textural parameters of maximum cutting stress, resistance to compression, and surface firmness. These results meant that a noodle with a soft, mushy texture is produced that would not be accepted by consumers even though the drying characteristics are favourable. However, they did not compare their processed noodles to commercially available instant noodles or control samples to see if these results were similar to properties of other instant noodle products. The scope of the project was limited to the study of dried noodles and not to instant noodles which would be expected to exhibit different textural properties. The potential to create commercially acceptable instant noodles with superheated steam is plausible as studies of impingement drying of potato chips using superheated steam showed that the textural characteristics of superheated steam processed samples were more similar to the commercial oil fried chips than those dried with hot air (Caixeta et al. 2002).

Li et al. (1999) processed tortilla chips in impinging jets of superheated steam and hot air at temperatures of 115, 130, and 145°C and with convective heat transfer coefficients of 100, 130 and 160 W/(m^2 °C). The effect of superheated steam processing on product quality was evaluated based on parameters such as shrinkage, crispness, starch gelatinization, and microstructure. Higher steam temperatures caused less shrinkage and a higher modulus of deformation (crispness). However, at higher steam temperatures there was less starch gelatinization and the pasting properties showed that the tortilla chips had an increased ability to absorb water. Analysis of the microstructure of the superheated steam processed tortilla chips revealed that higher steam temperatures resulted in more pores and a coarser appearance. When compared to hot air, superheated steam processing resulted in higher drying rates and more starch gelatinization at equivalent temperatures and convective heat transfer coefficients.

Caixeta et al. (2002) processed potato chips in impinging jets of superheated steam and hot air at temperatures of 115, 130, and 145°C and with convective heat transfer coefficients of 100 and 160 W/(m^2 °C). The purpose of the study was to test the feasibility of producing low-fat potato chips with the desired texture and flavour characteristics. In general potato chips dried at the higher temperatures and convective heat transfer coefficients in superheated steam showed less shrinkage, lower bulk density, higher porosity, and darker color. When compared to the air-dried samples superheated steam processed potato chips had more shrinkage, higher bulk density, lower porosity, and lighter color at the same conditions. Superheated steam processed potato chips also retained more vitamin C and were closer in texture to the commercial potato chips than the air dried samples.

Zousoon is a pan fried pork product of intermediate moisture (2-12%) found in Taiwan and China. A study conducted by Huang et al. (2004) looked into using superheated steam as a way to process pork bundles in an oxygen free environment to inhibit lipid oxidation. Samples were pan-fried or processed in superheated steam at 150°C then packaged in cans and stored for one year. Trained panellists evaluated the stored sample after one year for "off" odours and found that the pan-fried samples generated a strong odour whereas the superheated steam processed samples developed only a slight odour. Lipid analysis showed that superheated steam was found to be effective in suppressing lipid oxidation and had greater stability compared to pan-fried zousoon.

2.2 Instant Asian noodle processing

2.2.1 Wheat varieties for noodle flour

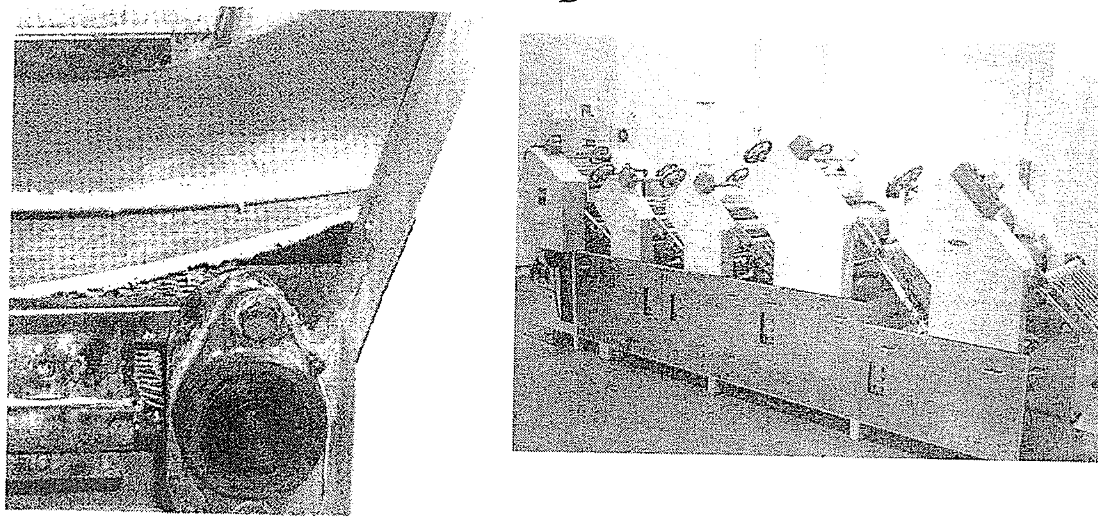
Canada has traditionally focussed on producing hard red wheat for the bread market. Canada Western Red Spring (CWRS) wheat is ideally suited for bread making with AC Barrie accounting for 40.6% and 17.8% of CWRS wheat grown in Manitoba and Western Canada respectively (CWB 2007). While protein content of flour produced from this wheat is suitable for noodle manufacture, the red colour of the seed coat results in specks within the dough and a decrease in noodle brightness when the higher extraction rates desired by millers are used (Kruger et al. 1994a; Oh et al. 1985b). Use of white wheat decreases the specks within noodle dough due to the lighter coloured bran. While soft white wheat is suitable for Japanese white salted noodles, it cannot be used for the dual purpose of bread making and alkaline noodles, which is often the goal of Asian markets. Canada Prairie Spring White (CPS White) wheat, which AC Vista is the predominant variety (CWB 2007), was developed for the Asian noodle market but lacks the protein content for bread making and alkaline noodles. A new class of wheat is emerging from Canadian farms and is known as Canada Western Hard White (CWHW) wheat. It has the desirable light bran coat allowing for higher flour extraction rates as well as the high protein contents necessary for alkaline noodles and bread making. This class of wheat will compete with Australian and American wheat, which is preferred by Asian millers for the noodle market (Veeman et al. 2002). Already the indication is that Asian millers are looking favourably on CWHW wheat for its noodle and bread making properties and would consider using it over Australian and American wheat (McMillan 2002). As of March 2004, 130,000 t of CWHW had been sold to several countries including Thailand, Singapore, the Philippines, Malaysia, and Vietnam (Anonymous 2004). Snowbird is the dominate of the two varieties grown in Canada with over 95% of the CWHW plant (CWB 2007). Still, CWHW only accounts for 4% of the planted hectares compared to 70% for CWRS (CWB 2007). Snowbird is attractive for noodles because it is a partially waxy wheat (lower levels of amylose) that improves elasticity and cohesiveness. In addition, Snowbird contains lower levels of the enzyme polyphenol oxidase (PPO). Polyphenol oxidase is a contributing factor in noodle discoloration and brightness (L*) of noodle dough sheets produced from straight grade flour (Anonymous 2004). Brightness of noodle dough sheets produced from Snowbird was greater than those produced from CWRS (74.1 versus 70.2 respectively)(Anonymous 2004).

2.2.2 Noodle composition

There are two main varieties of Asian noodles; white salted, also known as Udon or Japanese noodles, and alkaline, also known as Ramen or Chinese noodles. There are many subsets of noodles within these two varieties depending on country and region. Most white salted noodles are made with soft wheat flour of 0.36-0.40% ash and 8-10% protein content although Chinese varieties require higher protein contents. Canadian hard wheat is not suitable for Udon noodles as it lacks the high amylopectin starch content required to impart the specific textural attributes, but small amounts may be blended to ensure the proper strength characteristics (Nagao 1996). Noodles are manufactured from flour, water, and dissolved salts in the ratio of 100:28-45:2-3 (Nagao 1996). Alkaline noodles (yellow noodles) differ from white salted noodles in composition and are manufactured with flour from hard wheat of 0.33-0.38% ash and 10.5-12% protein content, water, and alkaline salts (Kansui) (sodium, or sodium and potassium carbonate) at a ratio of 100:32-35:1-3.0 (Hatcher 2001, Miskelly 1996, Nagao 1996). Common salt (1-3%), food colouring, eggs, preservatives, or additional ingredients may also be added (Miskelly 1996). Noodles may also contain sources of starch other than wheat including: rice flour, starch from beans, potatoes, corn, or buckwheat (Kruger et al. 1996). If an instant or steamed noodle is made, wheat flour with ash contents of up to 0.45% may be used (Nagao 1996). Throughout South East Asia, in countries such as Korea, Malaysia, Thailand, and Singapore, higher flour extraction rates are used for economic reasons and it is not uncommon for 14.5% protein wheat to be regularly used as it is ideally suited for the dual purposes of bread making and noodle manufacturing (Hatcher 2001).

2.2.3 Raw noodle preparation

Commercial production of Asian noodles begins by mixing ingredients in a horizontal or vertical mixer for 10-15 min. The purpose is to mix the ingredients uniformly and the result is small crumbly dough particles with little gluten development. Gluten development occurs in the sheeting process. Moisture absorption is important at this stage as insufficient absorption causes streaky dough with flaking on the surface of the dough sheet (makes weak noodle strands). Too much moisture will cause excessive gluten development. A vacuum mixer can also be used but extra water is required which leads to improved gluten development in mixing and sheeting and gives continuous internal structure that improves biting texture.



A B

Fig. 2.3. Lamination process (A) and multiple sheeting rolls (B) (Nagao 1996).

After mixing, the dough can be rested for up to 40 min to improve starch gelatinization and aid in even distribution of water throughout the dough, which promotes gluten development and produces a smoother and less sticky dough sheet (Hatcher 2001, Hou and Kruk 1998). The dough is then split into two parts with each portion being passed through a pair of sheeting rolls to create a noodle sheet. These two sheets are then laminated together by passage through a larger diameter sheeting roll to form a single sheet (Fig. 2.3a) and the dough is rested again for 30 to 60 min (resting helps moisture distribute more evenly, enhances disulphide bond formation, bonds between gluten and lipids form, and relaxes gluten for easy reduction in subsequent sheeting operation). Resting is also important because the amount of moisture absorption will affect the degree of starch gelatinization during steaming. A well rested dough has increased starch gelatinization, whereas a lack of even moisture distribution may prevent starch from being gelatinized. Also, un-relaxed gluten may suppress starch swelling. After resting, the noodle sheet is further reduced in thickness by passing it through a series of rolls with decreasing gaps (Fig. 2.3b). The noodle sheet undergoes a reduction in thickness of 15-33% at each roll (this allows gluten to maintain intact structure) (Hatcher 2001). When optimum sheet thickness has been reached, the sheet is passed through cutting rolls to produce the noodle strands (Fig. 2.4). The noodles are now ready for dehydration or instantization.

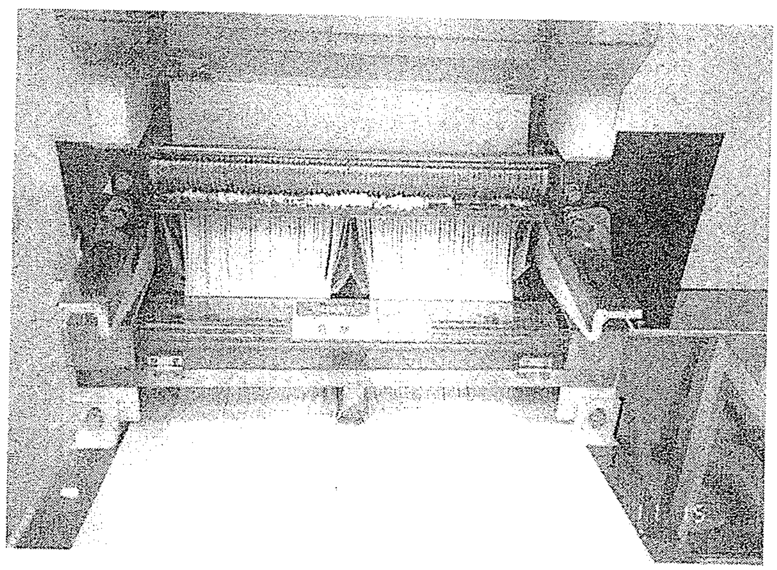


Fig. 2.4. Finished noodle sheet passing through the cutting rolls (Nagao 1996).

2.2.4 Dried noodle production

Noodles may be dried in hot air with controlled relative humidity to extend shelf life until they are consumed. Air drying involves multiple stages because rapid drying could lead to the formation of cracks on or near the surface of the product from internal mechanical stresses that result from non-uniform internal moisture distribution across the product (Markowski et al. 2003). The first stage of drying involves reduction of moisture from 40-45% to 25-27% in low temperature (15-20°C) air for 30-90 min (Hou 2001, Nagao 1996). In the second stage of drying, moisture is diffused to the surface and evaporated from the noodles. Rapid evaporation is undesirable so temperatures are moderate (40°C), relative humidity is maintained at 70-75%, and drying occurs over a period of 3-5 h (Nagao 1996). Drying is completed in the third stage while the noodles are cooled.

2.2.5 Instant noodle production

After mixing, sheeting, and cutting, instant noodles are steamed then dehydrated. Steaming partially gelatinizes the starch and is accomplished by placing the noodles in a steaming tunnel or chamber at 150-250 kPa for 60 s (Miskelly 1996) or at 100 kPa for 100-240 s (Kim 1996). After steaming, the noodles are fried in oil or dried in hot air to give additional gelatinization to the starch and lower the moisture content for long term storage.

Frying noodles removes excess water, but also incorporates undesirable oil into the product. There are health concerns in North American society over the fat content in foods and the presence of trans-fatty acids from partially hydrogenated and hydrogenated oils used in the frying process. Trans-fatty acids have been associated with an increased risk of coronary heart disease in epidemiologic studies (Willett and Ascherio 1994). During frying at 140-150°C for 1-2 min, water vaporises quickly from the exterior surface of the noodles, which drives the water migration from the interior to the exterior. This creates a porous, spongy structure that provides channels for water to enter the noodle upon rehydration (Hou 2001) (Fig. 2.5). A basic requirement for instant noodles is that the time required to rehydrate the noodles for consumption should occur within 3-4 min in hot water (Hou 2001). Fried instant noodles have an average fat content of 20% and a moisture content of 8% (Kim 1996). The high lipid content of fried instant noodles limits the storage life to 5-6 months due to oxidation of the lipids producing rancidity in the noodles (Kim 1996). To lower the fat content and eliminate the presence of trans-fatty acids in instant noodles they may be dried with heated air instead of frying in oil.

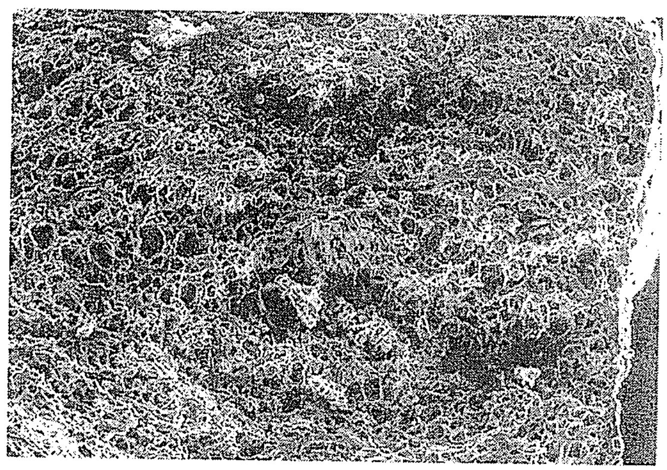


Fig. 2.5. Porous structure of a fried instant noodle (Hou 2001).

Instant noodles may be created by drying with heated air at 70-80°C for 35-45 min (Hou 2001) instead of frying in oil to gelatinize the starch. The degree of starch gelatinisation for non-fried instant noodles (80-85%) is less than the fried product (85-90%) resulting in a longer rehydration time, poor textural quality, and adverse affects on noodle brightness (Hatcher 2001, Hou 2001). During drying with hot air, water migrates slowly out of the product due to the lengthy drying times. The porous structure found in the fried product is therefore not present in the non-fried instant noodles, which increases the rehydration times for cooking (Hou 2001) (Fig. 2.6).

Fig. 2.6. Non-porous structure of an air-dried instant noodle (Hou 2001).

2.3 Quality evaluation

2.3.1 Sensory panels

Noodle quality is generally determined in customer countries using sensory evaluation by human panelists. Sensory evaluation is often laborious and expensive (Hou 2001). These evaluations can be difficult to conduct and emulate in the laboratory because of their subjective nature and differing textural preferences between regions (Hatcher 2001). Also, over time people take on the preferences of the regions they are living in if they differ from those of their home region (Wills and Wootton 1997).

Therefore, putting together a representative panel for the desired region, especially if that region is overseas, is very difficult.

When sensory testing is performed using human panelists there does not seem to be a standard approach among researchers as to the types of tests conducted. Nagao (1996) details the method of noodle quality evaluation in the Japanese wheat industry formulated with the cooperation of the National Food Research Institute and the flour milling industry. They have set up a methodology specifying standard materials, apparatus, processing, cooking, and an evaluation scoring system for Udon and alkaline noodles. Panelists judge the noodles based on colour, taste, surface appearance, speckiness, and texture (balance of softness and hardness, elasticity, and smoothness). Oh et al. (1983) evaluated noodles based only on firmness (judged as force necessary to bite through a noodle strand between the molar teeth) and chewiness (defined as length of time required to masticate 10 g of cooked noodle at the rate of one chew per second to a consistency small enough to swallow). Results showed that instrumental measurement of the maximum cutting stress and resistance to compression are reliable measures of firmness and chewiness as measured by sensory panels (Oh et al. 1983). Tang et al. (1999) also used the sensory evaluation of firmness and chewiness from Oh et al. (1983), but also included evaluation of colour (intensity), translucency (extent to which light glows through the noodle), shininess (extent to which light reflects on the noodle surface), surface smoothness (size of pinholes on noodle surface), stickiness (extent to which two pieces of noodle stick together when separated), and elasticity (extent to which one noodle returns to original length when stretched). Other researchers use their own criteria for evaluation, as with Wills and Wootton (1997) where panelists evaluated noodles based on their impressions of overall liking, texture, appearance, and taste. Others base their criteria on the standards for a particular region for which they are trying to produce noodles (Janto et al. 1998). In addition to sensory evaluation being non-standardized, many of these criteria are quite subjective.

2.3.2 Instrumental texture evaluation

Instrumental quality tests have been developed to standardize quality testing of Asian noodles and provide an objective and reproducible evaluation of texture. Tests are usually carried out with either the Instron Universal Testing Machine, or the TA-TX2 Texture Analyser (Kruger 1996). Asian noodles should be firm yet elastic and not fall apart easily. Some Asian noodle researchers are measuring this as the textural characteristics of maximum cutting stress, resistance to compression, recovery, and surface firmness (Kruger et al. 1994a, Oh et al. 1983, Oh et al. 1985a). Other researchers conduct a texture profile analysis (TPA) (Baik et al. 1994, Epstein et al. 2002, Graybosch et al. 2004, Markowski et al. 2003, Mohamed et al. 2005, Tang et al. 1999). The TPA was developed in the early 1960s from a study of the mechanical parameters significant to the definition of texture (Szczesniak et al. 1963). This work was used to design an instrument to measure these parameters and give an objective and reproducible measure of texture (Friedman et al. 1963). Use of the TPA was meant to act as a reference to sensory tests, so, the textural properties can be expressed in terms of sensory perception as well as in terms of material properties (Szczesniak 1998)(Table 2.3). The TPA was developed at a time before computers so the output was from a chart recorder that measured mass force over time. The TPA textural properties of hardness, adhesiveness, springiness, cohesiveness, chewiness, and resilience were thus derived directly from the mass force versus time chart. With the advent of computers it is possible to accurately calculate the TPA properties using proper force-deformation data reported in proper engineering units but custom is still to measure these properties directly from the resulting force-time curve produced from two compression and retraction cycles of the textural analyser probe (Fig. 2.7). Results are thus still reported in units of mass force and time. Gumminess can be measured from the force-time curve as the product of hardness and cohesiveness and is defined as the energy necessary to disintegrate a semisolid food product to a state of readiness for swallowing. Chewiness and gumminess are mutually exclusive because a product cannot be both a solid and semi-solid at the same time and should not be reported at the same time (Szczesniak 1995). There is confusion in the literature over this fact with several researchers reporting values for both chewiness and gumminess (Baik et al. 1994, Epstein et al. 2002, Markowski et al. 2003, Mohamed et al. 2005). Values of the textural properties have arbitrary units based on analysis of the TPA curve using the force-time data from the textural analyser. These values could be converted into proper engineering units with the use of the deformation data, but this is not usually done as the textural analyser results are sufficient for comparison purposes and are accepted in literature.

Table 2.3. Material and sensory definitions of textural properties produced by the TA- XT2i texture analyser. Adapted from Szczesniak (1998) and Bourne (1978).

Textural Property	Parameter	Dimensions	Material Definition	Sensory Definition	TPA Calculation
Hardness	force	mLt^{-2}	Force necessary to achieve a set deformation	Force necessary to compress a substance between molar teeth	Fmax (g)
Adhesiveness	work	mL^2t^{-2}	Work necessary to overcome attractive forces between the material and the probe surface	Force necessary to remove the material from the teeth during the normal eating process	Area 3 (g•s)
Springiness	ratio	dimensionless	Elasticity, measured as the recovery of a material's height between the first and second compressions	Degree with which the material returns to its original height following partial compression with molar teeth	Length 2/Length 1 (ratio)
Cohesiveness	ratio	dimensionless	Strength of internal bonds or the ability of the material to stick to itself	Amount of sample deformation before rupture when biting with molars	Area 2/Area 1 (ratio)
Chewiness	work	mL^2t^{-2}	Energy required to disintegrate a solid to a state ready for swallowing	Number of chews at a constant rate necessary to disintegrate a solid to a state ready for swallowing	(Fmax)(Area 2/Area1)(Length 2/Length 1) (g)
Resilience	ratio	dimensionless	Recovery of energy as the first compression is relieved		Area 5/Area 4 (ratio)

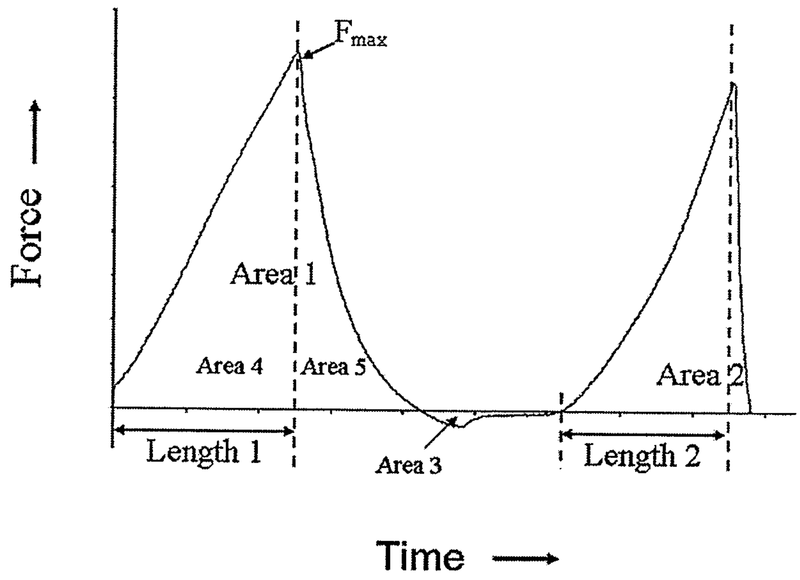


Fig. 2.7. Typical TPA curve for alkaline noodles using the TA-XT2i showing measurements used to calculate textural properties.

Even when the same standard equipment is used there is still variation in procedure between researchers. Each methodology varies slightly:

- Baik et al. (1994) used a 5 mm wide flat blade, five noodles, crosshead speed = 0.8 mm/s, maximum deformation = 70%.
- Epstein et al. (2002) used a 5 mm wide flat blade, four noodles, crosshead speed = 1 mm/s, maximum deformation = 70%.
- Graybosch et al. (2004) used a 9 mm wide blade, three noodles, crosshead speed = 0.45 mm/s, maximum deformation = 70%.
- Markowski et al. (2003) used a 10 mm wide blade, three noodles, crosshead speed = 0.4 mm/s, maximum deformation = 50%.

- Mohamed et al. (2005) used a 5 mm diameter plunger, five noodles, crosshead speed = 1 mm/s, maximum deformation = 70%.
- Tang et al. (1999) used a 25 mm diameter plunger, four noodles, crosshead speed = 0.2 mm/s, maximum deformation = 70%.
- Epstein et al. (2002) specified a 1 s hold time between compressions whereas Graybosch et al. (2004) specified a 3 s hold time. Other researchers did not specify what hold time was used.

In addition to the differences above, key aspects of procedure are often not specified even though they are known to influence textural quality including: cooking procedure, time of testing after cooking, noodle thickness and width, sheeting procedure, and resting time before TPA is performed (Miskelly 1996). All of these will influence TPA results, making comparisons between researchers difficult.

2.3.3 Colour measurement

Colour is probably the most important quality parameter for noodles because it is one of the first things a consumer will evaluate and will affect the decision to purchase the product, even if it is texturally acceptable. For noodles and pasta the L*, a*, and b* colour scale of the product is used as an objective evaluation of colour (Baik et al. 1995, Hatcher et al. 2004, Kruger et al. 1994a, Miskelly 1996, Morris et al. 2000, Park and Baik 2004a and b, Yun et al. 1997). The L* value measures the noodle brightness (L*=0 yields black and L*=100 indicates white), a* represents red-green chromaticity (negative values indicate green while positive values indicate red), and b* represents yellow-blue chromaticity (negative values indicate blue and positive values indicate yellow). There is little methodology in literature for measuring dried noodle colour with a colorimeter. Colour measurement is difficult with a dried product because of the uneven surface conditions and stiff shape. Park and Baik (2004a) measure noodle colour by grinding the dried noodle strands and measuring the powder through a transparent plastic dish. This method may be problematic because colour differences and brightness may not be uniform throughout the noodle cross section. Dexter et al. (1981) attached dried spaghetti strands to a white sheet to measure colour. This may not be practical with products that are not straight, as gaps between strands will affect the results. Kruger et al. (1998) detail the procedure for colour measurement of raw noodle sheets but make no mention of how it was done on dried noodle strands. A simple and repeatable method for dried noodle colour measurement needs to be developed.

2.4 Modelling of the drying process

2.4.1 Sorption behaviour

Moisture is held within a wet material in a variety of forms ranging from free moisture, through capillary and colloidal moisture, to physically adsorbed and chemically attached moisture (Potter and Beeby 1994). There is a pressure exerted between this moisture and the material. The stronger the moisture is bound to the material, the lower is the pressure exerted by the moisture. A material will loose moisture until the moisture in the material exerts the same pressure as the surroundings. In other words, the material will gain or lose moisture until it is in equilibrium with the relative humidity of the surroundings. In an air/vapour mixture this is determined by the amount of moisture in the surroundings denoted by the partial vapour pressure that it exerts (P_v), and the saturation vapour pressure of water at the same temperature (P_{sat}):

$$ERH = \frac{P_v}{P_{sat}} \times 100\% \qquad (2.1)$$

In a superheated steam environment, the vapour pressure of the system is equal to the operating pressure because the surroundings are composed solely of water vapour. For superheated steam, the ratio P_v/P_{sat} is known as the relative pressure.

In air systems at a fixed temperature the equilibrium moisture content (EMC) of a material will decrease with a decrease in relative humidity. The isotherms showing the sorption behaviour may be generated by plotting EMC of the material against the relative humidity at different temperatures. Many researchers have modelled these isotherms mathematically and the most common equations are summarised by Iglesias and Chirife (1982), Pabis et al. (1998), and Toledo (2007). In superheated steam at a fixed operating pressure (fixed P_v) the EMC of a product will decrease with increasing steam temperature (increasing P_{sat}). This has led others to produce isobars in superheated steam by plotting EMC against the temperature of the steam or against the relative pressure (Kauman 1956, Potter and Beeby 1994, Tang and Cenkowski 2001, Wimmerstedt and Hager 1996). Tang and Cenkowski (2001) are possibly the only ones to mathematically model the isobars in superheated steam. Two equations were proposed for EMC of spent grains in superheated steam. The first modelled EMC against steam temperature:

$$M_e = k \exp\left[n(T - 100)^m\right] \qquad (2.2)$$

and the second modelled EMC against the relative pressure:

$$M_e = k\exp\left(nP_r^m\right) \tag{2.3}$$

and k, m, and n are coefficients.

2.4.2 Diffusion model

During the constant rate period of drying the internal resistance to moisture diffusion is less than the external resistance to water vapour removal from the products surface. After the surface of the product begins to dry, corresponding to a critical moisture content of the product, the thermodynamic properties of the boundary layer do not affect the course of drying, and the internal resistance of the material to moisture transfer becomes the driving force in dehydration. Drying processes are often described mathematically based on the assumption that the knowledge of the overall moisture diffusivity is sufficient to predict the course of drying (Pabis et al. 1998). Knowledge of the overall moisture diffusivity allows for changes in the product dimensions without the redevelopment of the model. Moisture diffusion in the falling rate period is governed by Fick's second law:

$$\frac{\partial M}{\partial \theta} = \nabla\left(D_m \nabla M\right) \tag{2.4}$$

where D_m is dependant on moisture content or temperature. If D_m is assumed to be constant the above equation may be expressed as:

$$\frac{\partial M}{\partial \theta} = D_m \nabla^2 M \tag{2.5}$$

When the moisture content of a solid is below the critical moisture content (as it is in the falling rate period), moisture moves in the form of liquid water as well as water vapour (Pabis et al. 1998). Hence, the overall moisture diffusion coefficient is the sum of the liquid and vapour diffusion coefficients. To solve the above equations an appropriate geometric shape is assumed for the approximate representation of the product. Laplacian operators for Eq. 2.5 allow expansion into Cartesian, cylindrical, or spherical coordinates (Table 2.4). Equations for moisture content distribution and corresponding solutions are summarised in literature (Brooker et al. 1974, Crank 1975, Pabis et al. 1998).

Table 2.4. Laplacian operators for moisture content M in solids

Shape of Solid Body	Laplacian Operator on M	Coordinates
Parallelepiped	$\nabla^2 M = \frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} + \frac{\partial^2 M}{\partial z^2}$	Cartesian, three-dimensional
Infinite Bar	$\nabla^2 M = \frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}$	Cartesian, two-dimensional
Infinite Plate	$\nabla^2 M = \frac{\partial^2 M}{\partial x^2}$	Cartesian, one-dimensional
Cylinder	$\nabla^2 M = \frac{\partial^2 M}{\partial r^2} + \frac{1}{r}\frac{\partial M}{\partial r} + \frac{\partial^2 M}{\partial x^2}$	Cylindrical, two-dimensional
Infinite Cylinder	$\nabla^2 M = \frac{\partial^2 M}{\partial r^2} + \frac{1}{r}\frac{\partial M}{\partial r}$	Cylindrical, one-dimensional
Sphere	$\nabla^2 M = \frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}$	Spherical, one-dimensional

r = radius of a cylinder or sphere

Markowski et al. (2003) modeled noodles drying in superheated steam as a parallelepiped. For a parallelepiped of length $2l$, width $2w$, and thickness $2s$ Eq. 2.5 becomes:

$$\frac{\partial M}{\partial \theta} = D_m \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} + \frac{\partial^2 M}{\partial z^2} \right) \tag{2.6}$$

$$M = M(x, y, z, \theta) \quad -s \le x \le s \quad -w \le y \le w \quad -l \le z \le l$$

with the initial condition and the boundary condition of the first kind:

$$M(x, y, z, 0) = M_o$$

$$M(\pm s) = M(\pm w) = M(\pm l) = M_e \qquad \text{for} \qquad \theta > 0 \tag{2.7}$$

For an isotropic plate, D_m has the same value in all three directions. The solution for a parallelepiped can be written as the product of three infinite plates intersecting at a single point (Pabis et al. 1998). Similarly, the average moisture content in the parallelepiped can be written as the product of the solution for three infinite plates:

$$\frac{\overline{M}(\theta) - M_e}{M_o - M_e} = \frac{512}{\pi^6} \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \sum_{p=0}^{\infty} \beta_{n,m,p} \exp(-\theta \alpha_{n,m,p}) \tag{2.8}$$

where β and α with subscripts n, m, and p are coefficients given by Eqs. 2.9 and 2.10, respectively:

$$\beta_{n,m,p} = \frac{1}{(2n+1)^2 (2m+1)^2 (2p+1)^2} \tag{2.9}$$

$$\alpha_{n,m,p} = \frac{D_m \pi^2}{4} \left[\frac{(2n+1)^2}{s^2} + \frac{(2m+1)^2}{w^2} + \frac{(2p+1)^2}{l^2} \right] \tag{2.10}$$

When a parallelepiped is dried by convection, Eq. 2.8 may be reduced to only one term if $k \cdot \theta \ge 1.20$ (Pabis and Henderson 1961). Where k is the drying coefficient expressed as:

$$k = \frac{\pi^2}{4} D_m \left(\frac{1}{s^2} + \frac{1}{w^2} + \frac{1}{l^2} \right) \tag{2.11}$$

for a parallelepiped. If the overall moisture diffusion coefficient changes with moisture content, temperature, or both, then the diffusion equations should be derived from Eq. 2.4.

In addition to Markowski et al. (2003), many researchers have modeled the drying of products in superheated steam using models of diffusion. Taechapairoj et al. (2004) modeled rice and Tang and Cenkowski (2000) modeled cylindrical samples of potatoes as infinite cylinders. Prachayawarakorn et al. (2002 and 2004) modeled shrimp and soybeans as spheres. Braund et al. (2001) modeled tortilla chips and Caixeta et al. (2002) modeled potato chips as an infinite plate.

2.4.3 Semi-empirical and empirical models

Past research has shown that the drying of biological materials in superheated steam follows similar drying curves as those found in hot-air drying (Tang et al. 2005). Therefore, it is possible to apply a similar form of empirical equation for air drying to superheated steam drying. Semi-empirical models are based on diffusion theory and assume that the resistance to water diffusion occurs in the outer layer of the material (Pabis et al. 1998). One of the most common models based on Newton's law of cooling was suggested by Lewis (1921) and assumes a similarity between the cooling and drying of a solid body. The drying rate can then be described as:

$$\frac{d\overline{M}}{d\theta} = -k\left(\overline{M} - M_e\right) \qquad (2.12)$$

By integrating Eq. 2.12 for time from 0 to θ and the corresponding moisture content from M_o to M_e, a semi-empirical drying equation is obtained:

$$MR(\theta) = \exp(-k\theta) \quad (2.13)$$

where:

$$MR(\theta) = \frac{\overline{M}(\theta) - M_e}{M_o - M_e} \quad (2.14)$$

This model has widely been used to model the drying process but it tends to poorly model the initial stages of drying (Pabis 1998).

Taechapairoj et al. (2003) added a second exponential term to take into account for bed depth in thin layer drying:

$$MR(\theta) = a\exp(-k_1\theta) + b\exp(-k_2\theta) \quad (2.15)$$

where a, k_1, b, and k_2 are the drying coefficients varying with the drying conditions. The two-series exponential model was used to model a thin-layer fluidised bed of paddy neglecting the small initial moisture gain.

Many empirical models have been proposed based on Eq. 2.13 to improve the closeness of predicted results with experimental data. These have been summarised by Jayas et al. (1991). One commonly used model applied an exponential term to time θ (Page 1949):

$$MR(\theta) = \exp(-k\theta^n) \quad (2.16)$$

where n is a coefficient that depends on the product and drying conditions.

Over the course of drying the moisture ratio will vary from 1 at $\theta = 0$, $\overline{M}(\theta) = M_o$ to 0 at $\theta = \infty$, $\overline{M}(\theta) = M_e$. During superheated steam drying there is a small amount of moisture gained on the sample surface from steam condensation while the sample is warmed from room temperature to the steam saturation temperature. This time is short, usually 15 s or less (Markowski et al. 2003, Taechapairoj et al. 2003, Tang et al. 2005). As a result, the moisture ratio during this period becomes greater than 1. Tang et al. (2005) proposed adding an additional coefficient *a* to take into account the surface condensation in superheated steam drying:

$$MR(\theta) = a\exp\left(-k\theta^{n}\right) \tag{2.17}$$

Limitations to these semi and empirical models are that they are specific to the product that is being dried. Changes in size and properties will change the course of drying and new equations would have to be determined. As well, these models cannot predict the moisture profile within the product during drying. The benefits of these empirical models are the simplicity of their mathematical forms and the ease of fitting to experimental data with linear (if logarithmic scales are used) or non-linear regressions.

2.4.4 Heat and mass transfer models

Many researchers have modeled the drying of products in superheated steam by using heat and mass transfer theory. These models are often more complex than the diffusion, semi-empirical, and empirical models mentioned in the preceding chapter. Those models use material size or processing parameters only to describe the drying process (except for diffusion models which need the diffusion coefficient). Heat and mass transfer models often utilise several complex and larger equations to predict the drying process. What they do offer is more information about the temperature and moisture distribution during drying.

Elustondo et al. (2001) created a theoretical model that combined a dry layer and mass transfer model. The model was versatile as it featured dimensionless parameters to allow for the influence of shape, shrinkage, and elevation of boiling point. The model had several assumptions including; no structural or chemical changes, uniform shrinkage, and no change in shape. This limited the model's potential for the drying of foodstuffs as many of these assumptions cannot be satisfied. Elustondo et al. (2001) took the form of the theoretical model and made several simplifications to produce an empirical equation for drying.

Yang et al. (2001) produced a model based on heat and mass transfer equations. The unique aspect of their work was to take into account two dimensional shrinkage deformation whereas other similar models assumed volumetric or no shrinkage. Experimental results for cylindrical potato samples showed that axial and radial shrinkage during drying were different. The model which accounted for shrinkage was able to predict the moisture content, temperature, shape, and stress in the potato samples accurately.

Iyota et al. (2001) proposed a model based on heat and mass transfer that accounted for the initial condensation on the material during the initial stages of drying in superheated steam. The model predicted the drying history by using analytical solutions of one-dimensional unsteady heat conduction equations for several shapes. Material properties were assumed constant and were derived from the specific solid and water values with regard to moisture content. With this model Iyota et al. (2001) were successful in modeling the drying curves of potato slices with good agreement during the initial drying period.

Heinrich et al. (2002) presented a model that represented the drying process in superheated steam based on temperature profile of the material and by balancing the energy of all the components in a fluidised bed system. The model differentiates between the condensation phase, constant, and falling rate drying periods. The model only uses the physical characteristics and substance properties of the material (density, heat capacity, coefficient of thermal conductivity, particle diameter), the processing parameters, and apparatus dimensions. The limitations are that the model is only for discontinuous fluidised bed drying of batches of granular material. Other researchers have also developed models that are specific to the type of superheated steam dryer used (Blasco et al. 2001, Meunier and Munz 1986, Pakowski 2004, Tatemoto et al. 2003). No more will be said about such models because of their limitations to a specific dryer.

3 DESIGN OF A SUPERHEATED STEAM PROCESSING SYSTEM

As a developing field, superheated steam requires an investigatory period to test the fundamental drying kinetics of single particles or thin layers of materials. Knowledge gained during the investigatory period will show how materials dry in superheated steam, the effects of superheated steam processing on the quality, and allow for efficient design of full scale drying systems. At the University of Manitoba, the construction of the first laboratory scale superheated steam system occurred in 1994 and was used to determine drying characteristics, drying rates, and the effect of superheated steam on product quality in thin layers (Pronyk et al. 2004). The first system performed admirably but the need arose for a new system that would enable research to be conducted into new areas and allow for more flexibility, accuracy, and control in testing. Improvements over the old system were achieved with the construction of a new superheated steam system with new components, an optimized design, and additional instrumentation and process control features.

The new superheated steam system used in this study consists of a steam generator, a superheater, conveying pipelines, valves, drying chamber, instrumentation, and a condensation system (Fig. 3.1). The steam generator (1) functions to generate saturated steam for the system. The system uses an electric boiler (ES18, Sussman-Automatic Corp. Long Island City, NY, U.S.A.) with a steam capacity of 24.6 kg/h (54.2 lb/h) requires a 3 Phase, 208 V, 50 A power supply. The boiler operates on regular tap water because distilled, deionised, or reverse osmosis water is too aggressive on its carbon steel design. The maximum working pressure for the boiler is 621 kPa (90 psi), which is well above the maximum system operating pressure.

1. steam generator
2. globe valve
3. vacuum breaker
4. pressure regulator
5. gate valve
6. superheater
7. steam relief valve (414 kPa)
8. pressure gauge (415 kPa)
9. vortex meter
10. pressure transducer
11. thermoelectric probe
12. 3-way actuated valve
13. drying chamber
14. steam relief valve (103 kPa)
15. pressure gauge (100 kPa)
16. scale
17. fan
18. heat exchanger
19. check valve
20. process water tank
21. sparge tube
22. pump
23. pressure gauge (1100kPa)
24. 3-way valve

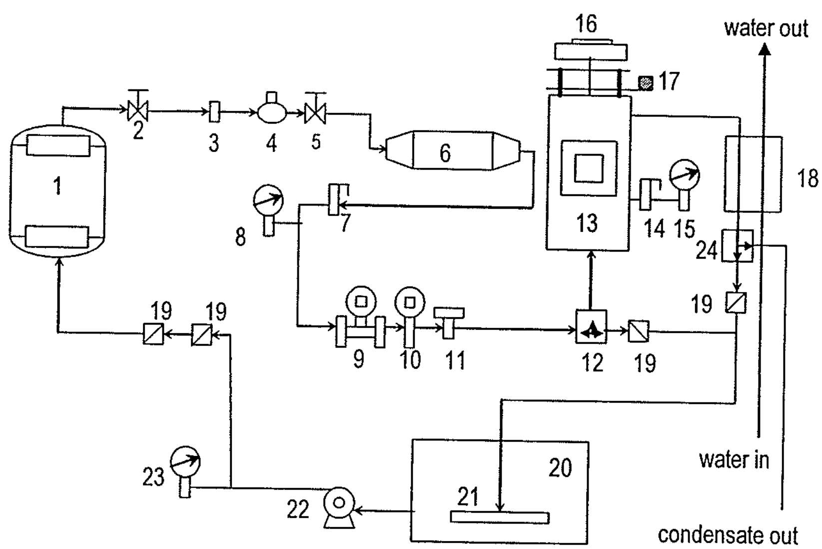


Fig. 3.1. Schematic of the superheated steam processing system.

The system piping transports the superheated steam between the necessary instrumentation and equipment. Steam is an aggressive corroding agent on regular steel, therefore, the system was designed with schedule 40, 316 stainless steel piping with a diameter of 12.7 mm (1/2 in). In case of an extreme build up in pressure, the system is designed with a steam relief valve (7) positioned before the chamber with a cracking pressure of 414 kPa (60 psi), the maximum pressure for the piping. All valves chosen for the system were sized to the piping specifications.

The first globe valve (2), which is specified by the boiler manufacturer, prevents steam from entering the system until warm-up is complete. A gate valve was positioned after the pressure regulator valve (4) to act as a flow regulatory valve for the superheated steam. Between the two valves is the vacuum breaker (3), which is required in the superheated steam system because air is drawn into the system after it is shut down. Breaking of the vacuum conditions is necessary to allow for the proper flow of steam in the system during operation. Without the vacuum breaker the flow of steam through the pipes may be prevented. The pressure regulator reduces the system pressure after the steam generator. This reduction in pressure causes the high pressure saturated steam to become low pressure superheated steam. Additional heat is provided to the steam by an industrial superheater (6) (SSH Series, Sussman-Automatic Corp. Long Island City, NY, U.S.A.) which has a maximum operating temperature of 400°C and requires a 3 Phase, 208 V, 12 A power supply. Steam flow rate in the system is measured with a vortex meter (9). Superheated steam exists in a region where temperature and pressure are no longer dependent properties and therefore other instrumentation must accompany the vortex meter to determine the flow rate. A pressure transducer (10), thermoelectric probe (11), and the vortex meter relay information to a flow computer (Compart DXF 351 Flow Computer, Endress Hauser GmbH, Weil am Rein, Germany) that amalgamates the individual readings to accurately provide a flow measurement for the superheated steam.

The superheated steam system is designed with a steam bypass that serves to divert the steam from the drying chamber during the warm-up and sample loading phases. To facilitate the bypass, a 3-way actuated valve (12) was selected. The 3-way actuated valve allows for a 3-way connection in the piping which is computer controlled. During warm-up and sample loading the steam is diverted back to the process water tank (20). To safely combine the exhaust steam with the process water, a sparge tube (21) is employed. The sparge tube is submerged in the water tank and dissipates the steam into the process water through 16, 2.4 mm holes. When a sample is loaded, or a user commands the computer, the 3-way actuated valve is turned to allow steam to pass into the drying chamber. By default the 3-way actuated valve is set to pass steam to the water tank for safety reasons.

The drying chamber (13) is designed with 12.7 mm (1/2 in) thick square tubing made of cold rolled steel that is coated with a Teflon PFA thermoplastic to protect against corrosion while meeting the temperature requirements of the chamber. The chamber designed to operate at near atmospheric pressure during testing. The drying chamber is tapped to accommodate the necessary thermocouple assemblies and various valves and pressure gauges. The drying chamber is separated into two parts (Fig. 3.2). The first chamber (Chamber 1) is in the lower portion and it is here that superheated steam enters through the system piping. The design intent is for the superheated steam to fill this lower chamber and be uniformly funnelled through the 89 mm (3.5 in) stainless steel pipe that connects the two chambers. The point at which the superheated steam leaves the connecting pipe, it enters the upper chamber (Chamber 2) (Fig. 3.2).

These two chambers are separated by a 6.3 mm (1/4 in) coated steel plate that sits on an edge surfaced with an industrial gasket to prevent superheated steam from bypassing the sample area. This connection between the two chambers is designed to accommodate a cylindrical sample holder in the stream of superheated steam. Operators have access to the upper chamber through a 152 x 152 mm door in the wall of the chamber which is sealed with a silicone rubber gasket and two clamps with a 120° sweep. To ensure a safe pressure is never exceeded in the drying chamber a second steam relief valve (14) with a cracking pressure of 103 kPa (15 psi) is attached. After the steam exits the drying chamber it passes through a flat-plate counter-current heat exchanger (MPN5X12-8, Wolseley, York, PA)(18). The heat exchanger condenses the exhaust superheated steam into liquid water. This condensate may be collected for further analysis by opening the 3-way valve (24) to the atmosphere or returned to the water tank and reused in the process by opening the valve to the tank.

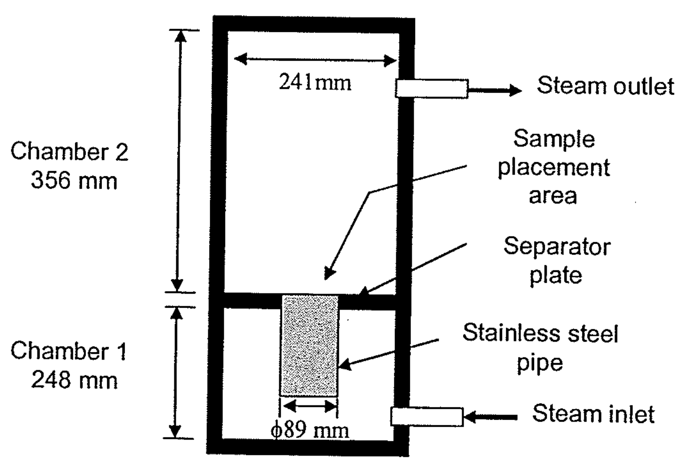


Fig. 3.2. Drying chamber of superheated steam drying system.

Process water is pumped from the water tank using a 250 W (1/3HP) impeller type pump (22) that is activated automatically to maintain the water level in the boiler. Along the line from the pump to the boiler, there are two check valves (19). These valves only allow unidirectional flow of the steam or water. These ensure the proper flow of the steam within the system, as well as protecting the water pump from the effects of water hammer between the pump and the boiler. A pressure gauge (22) indicates the water pressure during pump operation.

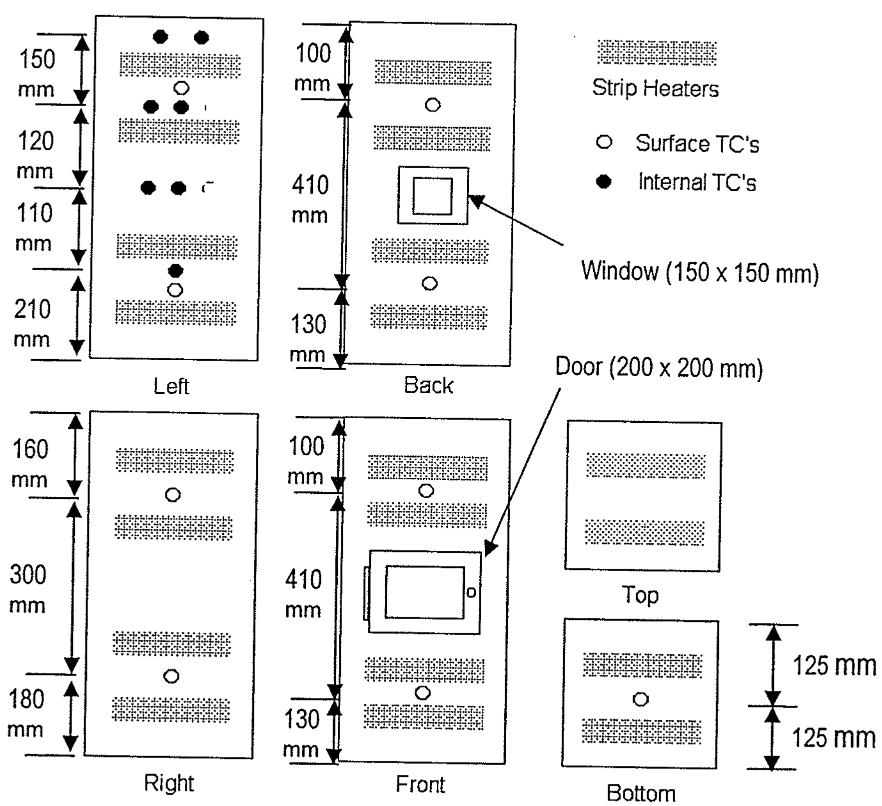


Fig. 3.3. Diagram of strip heater and thermocouple (TC) placement on exterior of the drying chamber (Gervais et al. 2004).

During operation, the outer surface of the drying chamber is heated by electric strip heaters, ensuring that the chamber walls operate at the same temperature as the superheated steam (Fig. 3.3). This creates adiabatic conditions inside the chamber, as the steam losses no heat through the chamber walls. The strip heaters are controlled in pairs by the computer control program and provide precision heating of the drying chamber. This ensures a uniform temperature distribution within the chamber at all times.

Monitoring of the system pressures are performed by three pressure gauges; two for the superheated steam (8 and 15) and one for the process water (23). The pressure gauges that measure the superheated steam pressure are selected to display pressures up to the safety relief valve's cracking pressure of 414 kPa (60 psi) and 103 kPa (15 psi) (steam relief valves 7 and 14 respectively in Fig 3.1). The process water gauge is selected based on the 690 kPa (100 psi) maximum operating pressure of the pump (supplied with the electric boiler).

Various thermocouple assemblies are required to measure temperatures throughout the superheated steam system and the sample (Fig. 3.3). The internal thermocouples are situated within the chamber such that temperature is measured on each side and from top to bottom. It this way an accurate temperature measurement and control of the heating in the chamber may occur. All the thermocouples are connected to a data acquisition system that transfers this temperature information to the control program that maintains the system at the operator's specifications. K-type thermocouples are selected as the primary thermocouple because they are typically used in heating applications.

Some of the testing performed in the superheated steam system will require mass measurements of samples. A digital electronic scale (16) (Model TR-403, Denver Instrument Co., Arvada, CO) with a 0.001 g accuracy is positioned above the drying chamber and the samples to be dried are hung with a thin wire from the scale. It is imperative that the wire, which passes through three plates before entering the drying chamber, is perfectly lined up through the holes. If the wire touches at any point the mass reading from the scale will not be accurate. A fan (17) blows air between two plates below the scale. This prevents the scale from getting damaged from the heat produced from the strip heaters attached to the top plate of the chamber.

The data acquisition and control system is tasked with monitoring and recording system outputs, as well as controlling the operation of the electrical components in the superheated steam system. There are three main components to this system, a data acquisition device, a desktop PC, and a panel of solid state relays used for activating and deactivating the main system components. Data acquisition and relay control is accomplished using an Agilent 34970A Data Acquisition/Switch Unit (Agilent Technologies, Palo Alto, CA) fitted with two 20 channel multiplexer modules and one 20 channel actuator module. The 21 thermocouples of the superheated steam system are connected to the multiplexer modules, leaving 19 channels open for future expansion. Each channel of the actuator module controls and switches a solid state relay (G3NA-210B 10A, Omron Canada Inc., Toronto, Canada) that is used to complete the main circuit that control the electrical components of the main system.

The superheated steam system requires a degree of automation and control that can not be accomplished by use of the data acquisition device alone. A desktop PC is linked to the data acquisition unit using a GPIB (IEEE-488) interface cable and PCI card. A custom program can send and receive data from this interface, and allows for software control of the superheated steam system. The PC also acquires data from the flow meter computer and the digital electronic scale via a RS-232 cable.

4 METHODS AND MATERIALS

4.1 Raw noodle preparation

4.1.1 Flour

Raw noodles were prepared from flour milled from the Canada Western Hard White (CWHW) wheat class (cultivar Snowbird). The wheat was milled at the Canadian International Grains Institute (CIGI) in Winnipeg, Manitoba, Canada following standard procedures for the production of straight-grade (75.2% extraction) noodle flour (Dexter and Tipples 1987). The flour had a protein content of 13.3% (14.1% moisture content, wet basis) and was used in the preparation of raw alkaline noodles. Rheological properties of the flour were determined by the Cereal Research Centre of Agriculture and Agri-Food Canada in Winnipeg, MB and are included in the Appendices (Table A1.1 and A1.2).

4.1.2 Laboratory noodle sheeter

A laboratory noodle sheeter constructed in the Department of Biosystems Engineering at the University of Manitoba based on a design by Kovacs et al. (2003) was used to create noodle sheets that were cut into strands to produce the raw noodles for experimentation (Fig. 4.1). The laboratory noodle sheeter, henceforth just called sheeter, has two sets of stainless steel rolls 25 and 75 mm wide, and 180 mm diameter powered by a 186 W (¼ HP) DC gear motor. For these experiments the 75 mm rolls were utilized.

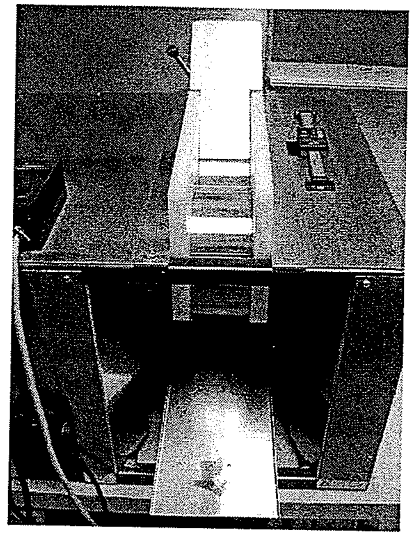


Fig. 4.1. Laboratory noodle sheeter (75 mm wide rolls).

4.1.3 Mixing and sheeting

A noodle sheet was prepared from raw dough following a similar procedure as described by Kovacs et al. (2003). In short, the noodle dough was mixed as a 100:34:1:1 ratio of flour, distilled water, alkaline salts (*Kansui*) (9:1 ratio of sodium and potassium carbonate), and table salt. An aqueous salt solution was prepared by combining 50 mL of solution containing 2.56 g sodium carbonate and 0.29 g of potassium carbonate with 50 mL of solution containing 2.85 g sodium chloride and mixing on a magnetic stirring plate until the salts were dissolved. A mixer (Kitchen-Aid, St Joseph, MI) with a flat beater was used to mix 120 g of flour with 41 mL of the aqueous salt solution for 5 min, forming a crumbly dough mixture of approximately 33% wb (wet basis) final moisture. The flour was deposited in the stainless steel bowl and the mixer was set to the lowest speed. The aqueous salt solution was slowly added over a period of approximately 30 s. At 1 min the mixer was stopped and the beater and bowl were scraped with a spatula and the dough mixed up to ensure even moisture distribution. The mixer was set to the second lowest speed and the dough was mixed vigorously for a period of 1 min. For the last 3 min of mixing the speed of the mixer was reduced to the lowest setting. Before the resulting crumbly dough mixture was deposited in the laboratory noodle sheeter, a 6.35 mm diameter (1/4 in) piece of rubber tubing was placed between the rolls to prevent the dough mixture from falling through the rolls. The dough mixture was then piled between the rolls of the sheeter (Fig. 4.2) and was firmly packed down with a wooden dowel. It was essential to firmly pack the dough otherwise the sheet would crumble and fall apart on the first pass. The dough mixture was passed through the rollers of the laboratory dough sheeting machine with an initial gap of 5 mm at 2 ¾ rpm to create a thick dough sheet. The sheet was then folded in half and passed through the rollers with a gap of 4 mm replicating the commercial laminating process. The sheet was then passed through the rollers two more times with the roller gaps set to 4 and 3 mm with each pass respectively. The roller speed was then increased to 4 1/3 rpm and the sheet was passed through four more times while reducing the roller gaps to 2, 1.5, 1.2, and 1 mm with each pass. The resulting sheet, 1.95 ± 0.16 mm thick (due to expansion) was cut into noodle strands 1.60 ± 0.04 mm wide with a pasta cutter (Shule Pasta Machine, Changzhou Shule Kitchen Utensils Co.,Ltd., Jiangsu China) with the edge noodles discarded. The cut noodles were wrapped in wax paper and stored in plastic bags to prevent moisture loss. The initial moisture content of the noodles was determined in triplicate following the AACC Approved Method 44-15A (AACC 2000).

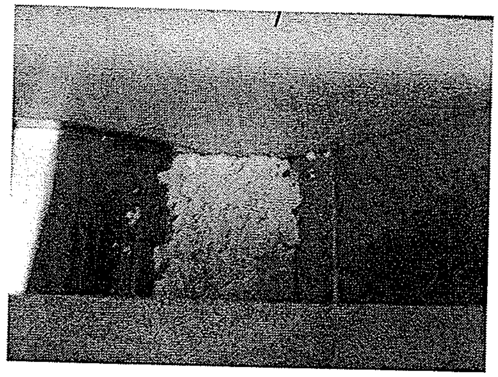


Fig. 4.2. Crumbly dough packed between rolls of noodle sheeter.

4.2 Instant noodle processing

4.2.1 Processing conditions

A superheated steam processing system (Fig. 4.3) developed in the Department of Biosystems Engineering at the University of Manitoba based on the system used by Tang and Cenkowski (2000) but further updated and improved by Gervais et al. (2004) was used to simultaneously dehydrate and cook the raw noodles to produce an instant product (Chapter 3). Experiments were conducted with superheated steam velocities of 0.5, 1.0, and 1.5 m/s ± 0.05 m/s in the drying chamber and at steam temperatures between 110 and 150°C ± 1.0°C in 5°C increments. Steam velocities were calculated using the mass flow rate read from the flow computer, the specific volume obtained from superheated steam tables (Irvine and Liley, 1984) for the processing temperature, and the cross-sectional area of the sample tray. Dehydration, internal temperature, and textural characteristics of noodles processed in superheated steam were studied in separate experiments.

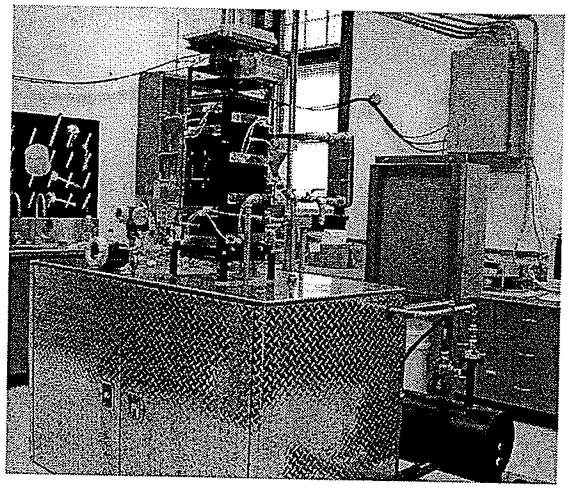


Fig. 4.3. Superheated steam processing system.

4.2.2 Mass measurement

The first series of experiments determined the dehydration kinetics of noodles by measuring the change in mass during steam processing. Approximately 4 to 6 g of noodles, 15 mm long were placed in a short cylindrical aluminium tray (Fig. 4.4a) hung in an aluminium holder (Fig. 4.4b) placed inside the drying chamber and suspended from a thin wire attached to an electronic balance (Model TR-403, Denver Instrument Co., Arvada, CO). The bottom of the tray was covered with an aluminium screen (0.25 mm diameter wire, 1.3 x 1.5 mm openings, 85% free cross-sectional area). Care was taken to ensure contact between noodle strands was minimised so that all noodles were equally exposed to the superheated steam. Mass changes were measured with 0.001 g accuracy and recorded every 2 s for the first 60 s, and every 5 s for the remainder of the experiment. Reduced recording intervals during the first 60 s were desired to record the initial period of condensation experienced in superheated steam drying. Short recording intervals increased the odds of successfully recording the initial moisture gain, which is often over within the first 60 s of drying (Markowski et al. 2003, Tang et al. 2005). Experiments continued until the mass remained constant. Six trials were run at each processing condition to ensure suitable replication as it was sometimes necessary to discard trials due to unforeseen events like the tray rubbing or sticking to the sides of the inlet tube.

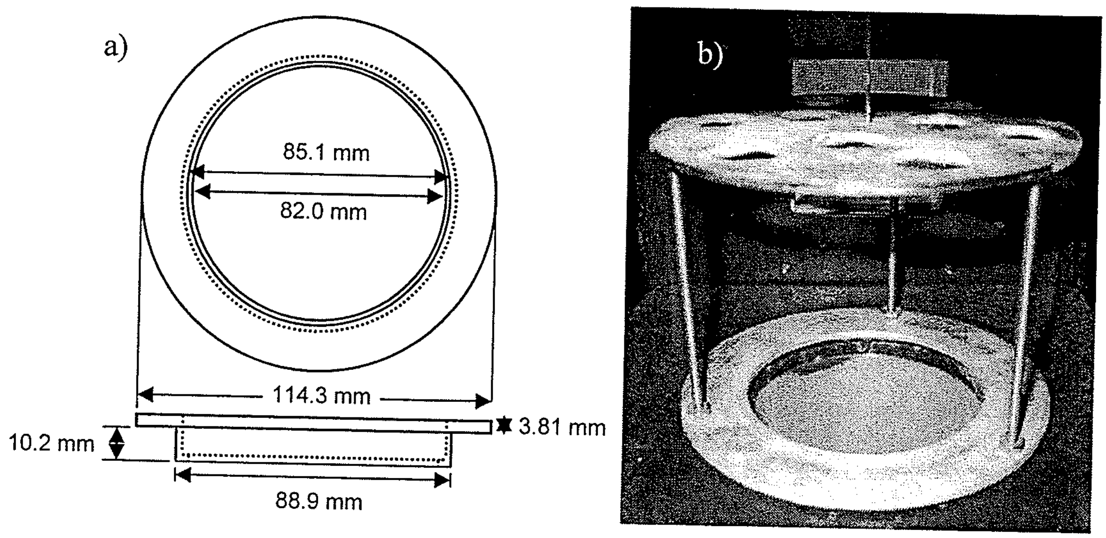


Fig. 4.4. Sample tray (a) and holder (b) used for mass measurement during superheated steam drying.

During processing, samples were affected by a lifting force caused by the upward flow of steam through the tray and sample. To account for the lifting force in calculations, separate experiments were conducted with pieces of aluminium of the same size and shape as noodles. Time averaged differences between the true sample mass and the mass measured during the flow of steam were taken as the lifting force. It was necessary during these experiments involving mass measurement to open the three-way valve after the heat exchanger to the atmosphere. If the valve was left opened to the water tank there was back pressure created by the water tank that caused a small pressure to build in the drying chamber (approximately 3.5 to 13 kPa depending on steam velocity). Throughout the experiment this pressure will vary slightly, decreasing as the experiment continues. This is caused by small changes in steam velocity, a delay of up to 5 s on the actuated valve to open, and a "plug" of air that enters the chamber when the sample is placed that must be displaced by the steam. This variation in pressure and steam velocity changes the lifting force and thus the mass measurement is affected. By opening the valve to the atmosphere the system is no longer operating as a closed system, but is now open to the atmosphere and the pressure in the chamber drops to zero. As a result there is less variation in the lifting force and a more accurate measure of the sample's mass is possible. Also, noodles were cut to a maximum length of 15 mm because noodles longer than 15 mm tended to curl up at higher temperatures and steam velocities. This meant that the cross-sectional area facing the flow of steam would change and there would be a corresponding change in the lifting force experienced. During experiments this was seen as an increase in sample mass caused by a reduction in lifting force due to a decrease in cross-sectional area (Appendix A, Fig. A1.1). To verify the results, the noodles were weighed before and after processing and the final moisture content was determined in triplicate by AACC method 44-15A (AACC 2000).

4.2.3 Temperature measurement

In the second series of experiments, only one noodle, 30 to 40 mm long was placed in the drying chamber with a needle temperature probe inserted near the geometric centre of the noodle. A 30-gauge, type T (copper-constantan) needle probe (Model

HYP-1, Omega, Stamford, CT) with a fast response rate and a temperature limit of 200°C was used (Fig. 4.5). Temperature was measured only by the very tip of the probe. To prevent conduction of heat down to the tip, the whole length of the probe (15.08 mm) was inserted into the noodle. Temperature measurements were recorded every 2 s and were carried out under the same drying conditions as in the experiments involving mass change measurements. Experiments continued until the temperature read from the probe was approximately constant. Five trials were run at each processing condition.

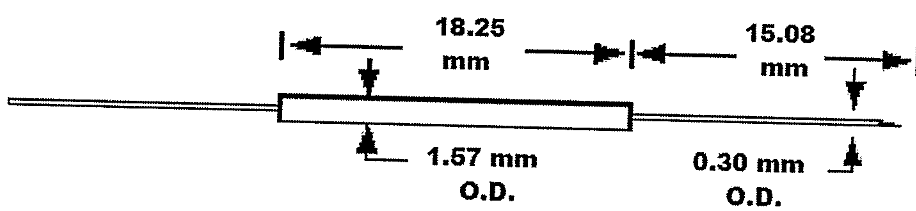


Fig. 4.5. Needle probe dimensions.

4.2.4 Processing of samples for quality evaluation

In the third series of experiments noodles were processed in superheated steam and samples were saved for quality evaluation. Noodles were processed under the same conditions as the mass change experiments. Processing times were determined from the mass change experiments by evaluating the time to reach the equilibrium moisture content from the drying curves. The time to reach equilibrium was then split into three equal periods (Time 1, Time 2, and Time 3, Table 4.1) to provide details about the change in quality during the course of processing. Approximately 28 noodles 30 to 40 mm long were placed in the sample tray, taking care to prevent noodles from touching each other as this could affect drying. Noodles were placed in a tray instead of hanging in order to minimize twisting during processing and to ensure that the whole noodle was treated to the same conditions as there may be slight variations in temperature with height in the chamber. These conditions could potentially affect the textural characteristics of the noodles. Three samples were processed at each condition for the textural profile analysis (TPA). In addition another three samples were processed and combined into one large sample which was evaluated for colour, maximum breaking stress, maximum cutting stress, and starch gelatinization.

4.2.5 Control samples

Textural characteristics of superheated steam processed instant noodles were compared to control samples and commercial products. Control samples were created by preparing fresh noodles according to the procedure already outlined. Samples were then steamed for 240 s in a food steamer (Salton, Lake Forest, IL) while hanging from a wire ring to ensure all noodles were equally exposed to the saturated steam environment. Fried instant noodles were processed in a 1000 mL beaker with 700 mL of canola oil to which 21 g of noodles were added for 2 min at 145°C. Samples were removed from the oil with a strainer and placed on paper to drain off excess oil. The fried instant noodles were then placed in a sealed plastic bag and stored in a freezer until the quality tests were performed. Air dried instant noodles were dehydrated in an oven (Thelco Laboratory Oven, Thermo Electron Corp., Mariette, OH) with hot air at

75°C for a period of 45 min. The same ring hanger used for steaming the noodles was also used to dry them in the oven. After drying, the noodles were stored in a sealed plastic bag in a freezer until the quality tests were performed. In addition to the control noodles produced from the same flour samples and recipe as the rest of the experiments, commercial products were purchased from the local supermarket.

Table 4.1. Processing plan for textural experiments. Time 1, Time 2, and Time 3 are at 1/3, 2/3, and 3/3 of the time for the noodles to reach equilibrium moisture content.

Temperature	Steam Velocity	Time 1 (s)	Time 2 (s)	Time 3 (s)
110°C	0.5 m/s	467	934	1400
	1.0 m/s	267	533	800
	1.5 m/s	233	466	700
115°C	0.5 m/s	367	733	1100
	1.0 m/s	233	466	700
	1.5 m/s	133	266	400
120°C	0.5 m/s	267	533	800
	1.0 m/s	200	400	600
	1.5 m/s	117	233	350
125°C	0.5 m/s	217	433	650
	1.0 m/s	167	333	500
	1.5 m/s	100	200	300
130°C	0.5 m/s	167	333	500
	1.0 m/s	133	266	400
	1.5 m/s	83	167	250
135°C	0.5 m/s	150	300	450
	1.0 m/s	117	233	350
	1.5 m/s	75	150	225
140°C	0.5 m/s	133	266	400
	1.0 m/s	100	200	300
	1.5 m/s	67	133	200
145°C	0.5 m/s	117	233	350
	1.0 m/s	83	167	250
	1.5 m/s	58	117	175
150°C	0.5 m/s	100	200	300
	1.0 m/s	67	133	200
	1.5 m/s	50	100	150

4.2.6 Cooking time

To determine optimum cooking time for the textural tests 6 g of noodle strands, 30 to 40 mm in length, were added to 300 mL of boiling water, purifird by reverse osmosis, in a 500 mL beaker. The optimum period was determined by the loss of the visible noodle core when squeezed between two Plexiglass plates. This was done for each of the processing conditions listed in Table 4.1. Results for the cooking time of the noodles tested are included in Appendix A (Tables A1.3 and A1.4). For the TPA and maximum cutting stress test, the noodles were cooked for the optimum period of time and then cooled in running tap water for 1 min. The drained noodles were stored in a sealed plastic bag at room temperature for 10 min before initiating the textural tests. Each specific texture test as be performed in triplicate at fixed 5 min intervals to ensure optimum reproducibility.

4.3 Factors affecting textural properties

4.3.1 Resting time for raw noodles

In addition to testing of textural properties over the course of drying, it was necessary to study the effects of noodle resting time. Textural properties of fresh noodles may change significantly over time before processing occurs but there is no information on this subject in the literature. It was necessary to determine how long a noodle sheet could be used before being discarded because of adverse changes. Information gained from these experiments was used to set a maximum time for use of a fresh noodle sample before it was discarded. Resting trials were conducted with raw noodles to serve as a control group to the processed noodles. A TPA was performed at 20 min intervals starting from the time the noodle sheet was prepared for a total of 200 min of resting time. A TPA is performed on cooked noodles, so at each time interval a sample of the raw noodles was boiled in water and the test conducted. Three trials were performed at each time interval.

4.3.2 Resting time for superheated steam processed noodles

The processing experiments were conducted at a temperature of 120°C, a steam velocity of 1.0 m/s, and a processing time of 8 min. The noodles were processed at intervals of 20 min starting from the time the noodle sheet was prepared for a total of 200 min of resting time. After processing in superheated steam, the samples were placed in a sealed plastic bag and stored in a freezer until the TPA was conducted. Three trials were run at each time interval.

4.3.3 Saturated steam pre-treatment

There was also a question about the need to process noodles in saturated steam before superheated steam processing. Commercial instant noodles are steamed before frying or air drying occurs to produce an instant product. This saturated steam processing helps to gelatinize starch and may affect textural characteristics of the final product. Processing in superheated steam is effective at gelatinizing starches as the temperatures experienced are sufficiently high enough to cause for gelatinization and the product has sufficient moisture (Cenkowski and Sosulski 1997, Taechapairoj et al. 2004). By not pre-steaming the noodles in saturated steam the drying kinetics of the noodles will be easier to ascertain. Still the effect of pre-steaming of superheated steam processed noodles and the affects on starch gelatinization and textural characteristics need to be determined. An experiment was conducted in the same manner as the time effect trial except after the noodles were arranged in the sample tray they were immediately placed into a food steamer (Salton, Lake Forest, IL) for 120 s. The food steamer was preheated prior to use to ensure samples were equally subjected equally to the pretreatment. After 120 s, the noodles were removed from the steamer and immediately placed into the superheated steam system. They were then processed under the same conditions in the time effect trial.

4.4 Quality evaluation

4.4.1 TPA

A texture analyzer (TA.XT2i, Texture Technology Co., Hamilton, MA) was used to conduct a double compression texture profile analysis (TPA) that simulated the first and second bites of cooked noodles. Tests were conducted with a 9 x 55 mm block attachment, compression speed of 0.4 mm/s, and compression depth of 1 mm, approximately one half of the thickness of the noodles (the noodles were approximated as square after cooking). Three noodles were placed on the textural analyzer perpendicular to the probe and touching one another to ensure that test results would be less affected by variances in individual noodle dimensions. The resulting TPA curves were analysed using Texture Expert software (Ver.1.22) and values for hardness, adhesiveness, springiness, chewiness, and resilience were obtained (Szczesniak 1963). Individual noodle width was determined by the measurement of three noodles using a calliper and calculated as the mean. Individual noodle thickness was determined from their force-deformation data.

4.4.2 Maximum cutting stress

Maximum cutting stress (MCS) was measured using the texture analyzer with fixtures and procedures similar to those described by Oh et al. (1983, 1985a). In short, three strands of the cooked noodles were placed on the sample holder and pressed crosswise at a speed of 0.4 mm/s by the Lexan blade attached to the analyzer. The blade had a 1 x 55 mm wide flat cutting edge. The blade traveled until the strain reached 99%. From the resulting force-deformation curve, the maximum force was used to calculate the maximum cutting stress (MCS) as:

$$MCS = f_{max} \left(w_n w_b\right)^{-1} \qquad (4.1)$$

4.4.3 Breaking stress

Breaking stress of the dried instant noodles was measured using the texture analyzer with fixtures and procedures similar to those described by Oh et al. (1985b). Noodle samples were first allowed to equilibrate at room temperature and humidity for several days before testing. This allowed all samples to be tested at the same equilibrium moisture content of 7% wet basis. A single dried noodle strand was tested in a three point bend/snap fixture (TA-92, Texture Technology Co., Hamilton, MA) compressed by a blade with a 1 x 55 mm flat cutting edge traveling at 4 mm/s to a distance of 6 mm and a span of 13 mm. Only a single noodle was tested because it would be impossible to ensure that multiple noodles would be contacted by the blade and break at the exact same time. All the tests were repeated five times at each condition, and the maximum breaking stress (BS) was calculated as:

$$BS = \frac{3f_{max}L}{2WT_n^2} \tag{4.2}$$

This formula assumes that: 1) the maximum stress during bending occurs at the mid point of the dried noodle strand, 2) the stress is compressive at the top half of the cross-sectional surface and is tensile at the bottom surface, 3) the cause of breakage is the tensile stress at the bottom surface rather than the compression at the top surface. Therefore:

$$\text{Tensile stress at midpoint} = \frac{\text{Moment (M)}}{\text{Modulus of cross section (Z)}} \tag{4.3}$$

where $M = f_{max}/2 \times L/2$, $Z = I/(2/T_n)$, I = moment of inertia = $WT_n/12$.

4.4.4 Color

Dried noodle colour was measured with a colorimeter (CR-410, KONICA MINOLTA, Tokyo, Japan). The colorimeter was set to the CIE 1931 Standard Observer and the "C" illuminant, which represents average daylight minus the ultraviolet component. The instrument was calibrated prior to use with a standardized disk provided by the manufacturer. Two possible methods for measuring colour of the dried noodle strands were evaluated. In the first, dried noodle strands were carefully stacked in layers within the granular attachment (CR-A50, KONICA MINOLTA, Tokyo, Japan) ensuring that as much area was covered and as much volume was consumed by the noodles as possible. A measurement was taken with the colorimeter and the sample was then removed from the granular attachment and the process repeated. In the second method dried noodles strands were laid out side to side as close as possible in a single layer. A measurement of this layer was then taken with the colorimeter. The noodles were then gathered and mixed so the process could be repeated. Results from the two methods were different, but the variation within the methods was small (Appendix A, Table A1.5). Using the granular attachment was deemed preferable to arranging the noodle strands side by side and taking a measurement with the colorimeter because of the ease and speed of measurement.

4.4.5 Starch Analysis

Starch analysis was conducted using a DSC 7 (PerkinElmer, Norwalk, CT) connected to a thermal analysis controller (TAC 7/DX, PerkinElmer, Norwalk, CT) that was controlled by a computer running Pyris software (V8.0, PerkinElmer, Norwalk, CT). Differential Scanning Calorimeter (DSC) analyses were performed on flour, raw noodles dough, and on the dehydrated instant noodles at a ramp rate of 10°C/min using nitrogen as the purge gas and ice water was used to cool the unit during operation. The baseline of the DSC was adjusted with empty furnaces to produce a nearly horizontal and flat line. To achieve a perfect baseline, a baseline file was created of this curve and used during all experiments. During experiments the baseline file curve is subtracted from the curve being generated to produce a truly flat and horizontal baseline. In addition, a two-point calibration was conducted with indium and zinc as the calibration materials before any experiments were conducted. Both samples were run separately and the melting temperature (onset) and transition energy were entered together into the calibration program. It is important not to enter them separately, or the calibration will not be true. As a final check the indium and zinc samples were run a second time after updating the calibration program. Results from the check were compared to the expected values (melting temperature and transition energy of 156.8°C and 28.2 J/g for indium and melting temperature of 419.5°C for zinc) and were found to be correct.

Powdered samples of approximately 5 to 12 mg weighed in the AD-4 autobalance (Perkin-Elmer, Norwalk, CT), were placed into hermetically sealed 60 μL stainless steel pans and tested in triplicate. Sample pans were first tarred against an empty dish and lid. The pan was then removed from the balance with tweezers as oil from the hand would interfere with the mass of the pan. Powdered sample was added to the pan which was then placed back into the autobalance were the mass was measured and recorded. The amount of moisture necessary to bring the sample up to 60% moisture content (wb) was calculated and then added with a 25 μL syringe (Microliter #702, Hamilton Co., Reno, NV). Moisturizing the samples to 60% (wb) was enough to enable the complete gelatinization of any starch (Cenkowski and Sosulski 1997). Sealed samples were tested against a reference containing an empty sample pan over a scanning range of 25 to 120°C. The onset temperature, peak temperature, and transition energy (enthalpy ΔH) of the amylopectin and amylose-lipid complex in the superheated steam dried noodles were determined from the resulting energy-temperature curves.

5 RESULTS AND DISCUSSIONS

5.1 Drying kinetics

5.1.1 Equilibrium moisture content (EMC) of Asian noodles

For the mass measurement trials, samples were dried in superheated steam at a constant temperature and velocity for sufficiently long time so that the mass changes were negligibly small. Six replicates were run, and the samples were combined after processing. The moisture content was determined from these combined samples by the AACC approved method 44-15A (AACC 2000) for each temperature and velocity. In air drying a material will lose moisture until the remaining moisture in the material exerts the same pressure as vapour in the surroundings. This is governed by the ratio of the vapour pressure, P_v, of the medium and the saturated vapour pressure of water at the same temperature, P_{sat}. In air systems this ratio is the equilibrium relative humidity (ERH) and in superheated steam the ratio is known as the relative pressure. The vapour pressure (P_v) in superheated steam is equal to the operating pressure of the system because the environment is completely composed of water vapour. For this superheated steam processing system the vapour pressure is 104.7 kPa because the system operates at a gauge pressure of approximately 3.4 kPa. Final EMC of a product should not be affected by steam velocity. The final moisture content (EMC) was taken as the averages of the moisture contents at each steam velocity at the same processing temperature (Appendix B1).

The noodles lost moisture with increasing steam temperature. The rate of decrease in moisture per unit temperature rise was greatest at the lowest steam temperatures (highest relative pressures). The EMC decreased 23% from 0.123 kg/kg db (dry basis) from 110°C to 115°C but only decreased 8.5% from 145°C to 150°C. It is easier to remove moisture at high relative pressure (low temperatures) because this is the portion of moisture held as free water within the product (Potter and Beeby 1994). As the relative pressure decreases, the free and capillary moisture is removed leaving the bound water held by molecular and chemical bonds. This will require much higher temperatures to remove these smaller, but tightly held portions of moisture in the product.

Tang and Cenkowski (2001) are possibly the only ones to mathematically model EMC isobars in superheated steam. Two equations were proposed for EMC of spent grains in superheated steam. The first modelled EMC against steam temperature:

$$\mathrm{M_e} = k \exp\left[a(\mathrm{T} - 100)^b\right] \tag{5.1}$$

and the second modelled EMC against the relative pressure:

$$\mathrm{M_e} = k \exp\left(a\mathrm{P_r}^b\right) \tag{5.2}$$

where *a, b,* and *k* are coefficients.

There are many equations used by researchers to describe EMC in air systems (Iglesias and Chirife 1982, Pabis et al. 1998, Toledo 2007). Equilibrium moisture content isotherms plotted against ERH are similar in shape to EMC isobars plotted against relative pressure in superheated steam (Potter and Beeby 1994, Tang and

Cenkowski 2001). The two dependant variables, ERH and relative pressure, are described by the ratio P_v/P_{sat}. The difference is that in air P_v is variable and P_{sat} is constant, and in superheated steam P_v is constant and P_{sat} is variable. Therefore, mathematically EMC equations for air systems plotted as isotherms could potentially be utilised as EMC equations for superheated steam plotted as isobars. Potential EMC equations include the Smith equation:

$$M_e = a - b\ln(1 - \mathrm{ERH}) \tag{5.3}$$

and the Oswin equation:

$$M_e = a\left(\frac{\mathrm{ERH}}{1 - \mathrm{ERH}}\right) + b \tag{5.4}$$

where a and b are coefficients. The Smith and Oswin equations are empirical and are among the more popular EMC equations (Toledo 1997). A theoretical EMC equation based on physical adsorption phenomena is the GAB (Guggenheim-Anderson-de Boer) equation (Toledo 1997):

$$M_e = \frac{a\,bk\ \mathrm{ERH}}{(1 - k\ \mathrm{ERH})(1 - k\ \mathrm{ERH} + \mathrm{b}k\ \mathrm{ERH})} \tag{5.5}$$

where a, b, and k are coefficients. The coefficient a is equivalent to the monolayer moisture value on a dry basis.

A non-linear regression procedure (Systat 2006) with P_r replacing ERH in the Smith, Oswin, and GAB equations was run in SigmaStat (Version 3.5, Systat Software Inc. Point Richmond, CA) to determine the coefficients in Eqs. 5.1 through 5.5. Results of the regression show that all equations fit the data with good accuracy because of the high R^2 values (Table 5.1). Isobars are plotted from Eqs. 5.2 through 5.5 using regression determined coefficients from Table 5.1 (Fig. 5.1). There is little difference between all of the equations although this may have changed if data was gathered for lower relative pressures (higher processing temperatures). The noodles could still experience moisture loss at lower relative pressures because even at 150°C the noodles still had an EMC of 4.3% db. Still, the noodles would not be expected to reach an EMC of zero because this is only experienced in granular or very porous materials (Chu et al. 1959, Potter and Beeby 1994, Tang and Cenkowski 2001).

From the results it is evident that isotherm equations for EMC in air systems may be utilised to model isobars in superheated steam systems. Further tests still need to be run to ascertain the effect of different system pressures on the EMC in superheated steam systems using isotherm equations.

Table 5.1. Results of non-linear regression for Eqs. 5.1 through 5.5.

Equation	Constants			R^2
	a	b	k	
Tang and Cenkowski (5.1)	-3.177	0.137	9.405	0.960
Tang and Cenkowski (5.2)	1.964	1.449	0.0354	0.962
Smith (5.3)	0.0232	0.0744		0.959
Oswin (5.4)	0.0749	0.483		0.958
GAB (5.5)	0.0464	9.330	0.871	0.955

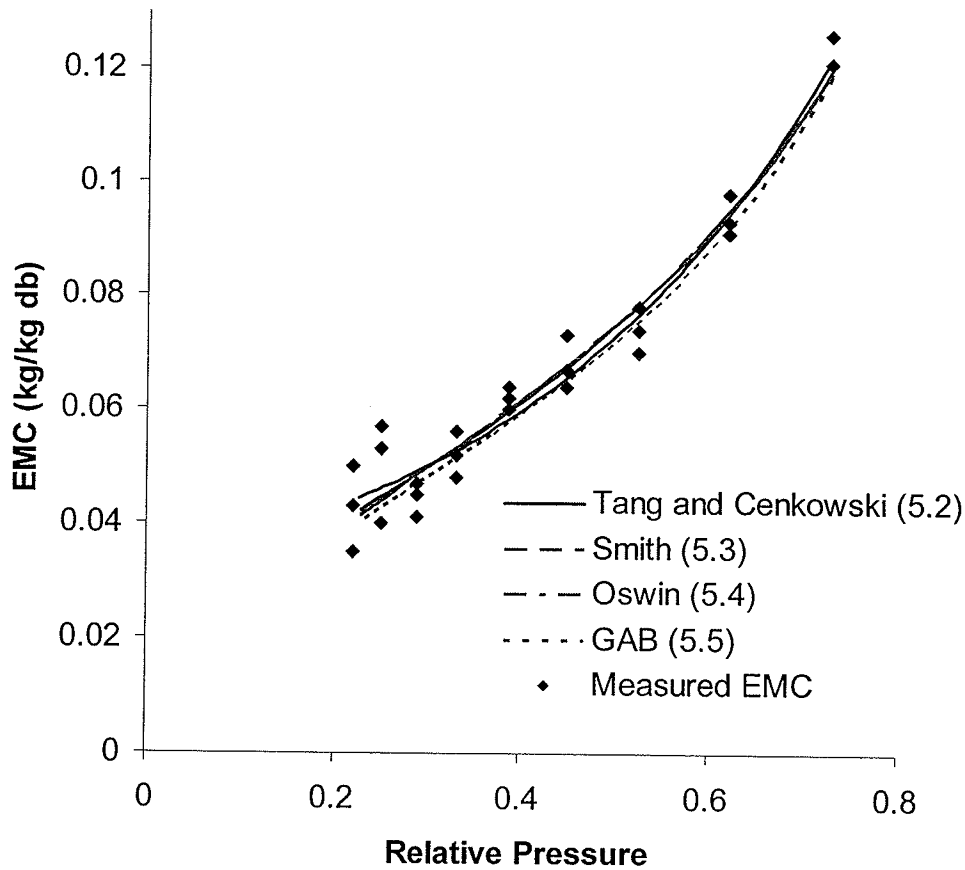


Fig. 5.1. Predicted and measured EMC of Asian noodles processed in superheated steam at 104.7kPa

5.2.2 Development of a drying model

Mass changes of the noodle samples recorded during the mass experiments were used with the initial moisture content and the EMC data from Appendix B1 to calculate the moisture ratio during processing under different conditions (Appendix B2). The first 20 s of data were eliminated for temperatures of 110, 120, 130, 140, and 150°C at a velocity of 1.0 m/s. When mass change experiments were first initiated, a thin rod was used to suspend the sample holder in which the sample tray was placed. During the first

20 s of processing, it was noticed from the data that the rod was contacting the sides of the holes in the plates on top of the chamber. At this point the rod was replaced with a thin wire and the problem was solved. A large amount of data was discarded, but the data for even temperatures at a velocity of 1.0 m/s were saved and used with the first 20 s removed to save time in running the experiments.

From the mass change data there are small discrepancies between the EMC and the time used for the texture tests. At the EMC the moisture ratio should be equal to zero, but in Appendix B2 at the time to reach the EMC from Table 4.1 there is often moisture left in the noodles (moisture ratio greater than 0). Equilibrium moisture content was determined from the combined final samples of the mass experiments by the oven drying method. This EMC was then used to calculate the moisture ratio from the mass changes recorded during superheated steam processing. Therefore, an average EMC was used for the moisture ratio when individual samples had different EMCs as measured from the mass changes. This produced some instances of moisture ratios above 0 (no more than 0.05) at the recorded time to dry. However, examination of the data suggests that little drying was occurring and the moisture ratio had become constant even if it did not reach 0.

The moisture ratio of a product should vary from 1 at the initial moisture content, to 0 at the EMC. Results from these experiments show that the moisture ratio is often above 1 during the initial stages of drying. This corresponds to the initial period of condensation on a product in superheated steam that ends when the product's temperature reaches the saturation temperature at the operating pressure of the system. The moisture ratio may stay above 1 for some time after this, depending on the amount of moisture gained, and the amount of evaporation from the product, which is dependant on the operating conditions. In these experiments the amount and duration of moisture gained was greatest at low superheated steam temperatures and velocities. At the lowest temperature and velocity, the amount of moisture gained was 0.64 to 0.97 g and the duration was 175 s until all of that moisture had been evaporated. A significant portion of this moisture was not gained by the noodles, but was deposited on the sample tray. The tray was machined from an aluminum cylinder and had a mass of 35.13 g, which is much more than the 4 to 6 g of noodles that were processed during each experiment. The high conductivity of aluminum would allow for the quick transfer of heat from the steam and the resulting condensation of the water on the tray. It was visually confirmed that large water droplets were present on the sample tray during the initial stages of processing. During this period the noodles were drying even as water was still present on the tray. This makes separation of noodle and tray drying difficult. It may be possible to determine the amount of moisture deposited on the tray and noodles separately using surface area, mass, and specific heat. There would still be difficulty determining the evaporation of moisture from the tray without running more experiments. At a velocity of 0.5 m/s and temperatures of 135°C and greater, the effect of initial condensation on drying is reduced to the first 25 s of processing. At velocities of 1.0 to 1.5 m/s the moisture condensed and was removed in a period of 2 to 4 s. For most processing conditions the condensation on the sample tray should not affect any mathematical model of noodle drying. Drying will be affected by condensation at a velocity of 0.5 m/s but the effects should be diminished at higher temperatures. As this condensation is difficult to separate, all data will be used in its raw form for modeling of the drying curves at 0.5 m/s. This will be a source of error in the models.

To model the mass changes during processing (drying curves), two mathematical models were considered. The first model, based on Newton's law of cooling (Lewis 1921), was chosen for its simplicity and common usage (Pabis et al. 1998). An additional coefficient a was added to take into account the surface condensation in superheated steam drying (Tang et al. 2005):

$$MR(\theta) = a\exp(-k\theta) \tag{5.6}$$

where MR is the moisture ratio defined as:

$$MR(\theta) = \frac{\overline{M}(\theta) - M_e}{M_o - M_e} \tag{5.7}$$

This model predicts the latter stages of drying better than the initial stages, so others have proposed further changes to Newton's model. These have been summarised by Jayas et al. (1991). One commonly used model applies an exponential term to time θ (Page 1949):

$$MR(\theta) = a\exp(-k\theta^{n}) \tag{5.8}$$

where n is a coefficient that depends on the product and drying conditions and a is a coefficient that takes into account surface condensation on the product (Tang et al. 2005).

A non-linear regression procedure (Systat 2006) with MR and θ as the regression variables was run in SigmaStat to determine the coefficients and drying coefficient k in Eqs. 5.6 and 5.8 for each processing temperature and velocity separately. From the regression results, Page's model (Table 5.2) fits the individual drying curves a little better than Newton's model (Table 5.3). For both models, the regression coefficient R^2 is in most cases 0.8 or higher, which indicates a very good fit of the equation to the data. Both models are most accurate during the latter stages of drying and do not accurately predict the initial condensation during superheated steam drying. Page's model was better at modeling the initial condensation period with values of coefficient *a* above 1 for most processing conditions. Newton's model returned values of *a* below 1 for 11 of 27 conditions, usually at velocities of 1.0 and 1.5 m/s (Table 5.3). These probably occurred because the length of the condensation period with moisture ratios above 1 was not long enough to influence the model.

Newton's and Page's models are excellent for modeling the noodles because they are not affected by any change in geometry of the noodles during processing. There is the potential for either shrinkage or expansion of noodles during superheated steam processing depending upon the ability of the steam to gently diffuse moisture out of the product, or to quickly cause the moisture to flash into steam creating pores and causing expansion. While both models are effective at predicting the drying of noodles for each superheated steam temperature and velocity, a single unifying equation would be of more use.

Table 5.2. Regression results for Page's model (Eq. 5.8).

Temperature °C	Velocity m/s	Coefficients			R^2
		a	k	*n*	
110	0.5	1.522	0.0015	1.092	0.981
110	1.0	1.058	0.0038	0.996	0.974
110	1.5	1.164	0.0285	0.718	0.864
115	0.5	1.368	0.0024	1.075	0.985
115	1.0	1.204	0.0123	0.860	0.987
115	1.5	1.026	0.0138	0.913	0.882
120	0.5	1.355	0.0021	1.159	0.986
120	1.0	0.986	0.0102	0.916	0.905
120	1.5	1.056	0.0361	0.759	0.820
125	0.5	1.149	0.0033	1.097	0.993
125	1.0	1.049	0.0536	0.667	0.943
125	1.5	1.363	0.0956	0.634	0.793
130	0.5	1.244	0.0041	1.136	0.989
130	1.0	1.011	0.0109	0.977	0.885
130	1.5	1.268	0.0358	0.812	0.951
135	0.5	1.113	0.0052	1.080	0.984
135	1.0	1.036	0.1070	0.582	0.936
135	1.5	1.167	0.0939	0.638	0.861
140	0.5	1.173	0.0033	1.195	0.989
140	1.0	0.934	0.0172	0.912	0.926
140	1.5	1.195	0.1310	0.597	0.777
145	0.5	1.115	0.0034	1.217	0.983
145	1.0	1.047	0.1140	0.577	0.913
145	1.5	1.247	0.1080	0.659	0.804
150	0.5	1.085	0.0056	1.156	0.996
150	1.0	0.963	0.0397	0.823	0.874
150	1.5	1.130	0.1240	0.644	0.880

Table 5.3. Regression results for Newton's model (Eq. 5.6).

Temperature °C	Velocity m/s	Coefficients		R^2
		a	k	
110	0.5	1.569	0.0027	0.980
110	1.0	1.056	0.0037	0.974
110	1.5	0.996	0.0054	0.852
115	0.5	1.402	0.0039	0.984
115	1.0	1.131	0.0055	0.984
115	1.5	0.987	0.0087	0.881
120	0.5	1.427	0.0054	0.983
120	1.0	0.939	0.0063	0.904
120	1.5	0.932	0.0105	0.811
125	0.5	1.188	0.0057	0.992
125	1.0	0.845	0.0086	0.923
125	1.5	1.076	0.0168	0.765
130	0.5	1.305	0.0085	0.987
130	1.0	0.997	0.0096	0.885
130	1.5	1.157	0.0146	0.944
135	0.5	1.149	0.0080	0.983
135	1.0	0.759	0.0123	0.896
135	1.5	0.933	0.0171	0.829
140	0.5	1.253	0.0092	0.985
140	1.0	0.880	0.0107	0.925
140	1.5	0.917	0.0211	0.731
145	0.5	1.197	0.0103	0.978
145	1.0	0.770	0.0135	0.872
145	1.5	1.015	0.0243	0.777
150	0.5	1.146	0.0121	0.994
150	1.0	0.857	0.0169	0.868
150	1.5	0.904	0.0266	0.847

From the regression results it was noted that coefficients *a* and *n*, and the drying coefficient k for Page's model followed no discernable trends for steam temperature and velocity (Appendix B3). For Newton's model coefficient *a* approximately decreased, and drying coefficient k increased approximately linearly with an increase in steam temperature and velocity (Appendix B3). Therefore, the coefficients for Newton's model were regressed further based on steam temperature and velocity:

$$a = (a_1 T_s + a_2)(a_3 V_s + a_4) \quad (5.9)$$

$$k = (k_1 T_s + k_2)(k_3 V_s + k_4) \quad (5.10)$$

where a_1, a_2, a_3, a_4, k_1, k_2, k_3, and k_4 are coefficients. Results of the non-linear regression to determine the coefficients for Eqs. 5.9 and 5.10 are presented in Table 5.4. The high R^2 value for the drying coefficient k indicates that the regression equation accurately fits the data. Coefficient a has a much lower R^2 value probably due to the different amounts of condensation on the sample tray, depending on processing conditions. Appendix B3 shows that at 1.0 and 1.5 m/s a is approximately constant and equal for the two velocities (Fig. B3.4b). At 0.5 m/s, a is larger and has a decreasing trend with temperature.

Table 5.4. Results for second regression of coefficients a and k from Newton's equation based on steam temperature and velocity.

Parameter	Coefficient	Regression Value	R^2
a	a_1	-0.469	0.54
	a_2	142.97	
	a_3	-0.00375	
	a_4	0.0167	
k	k_1	0.16	0.944
	k_2	-15.73	
	k_3	0.00173	
	k_4	0.000419	

Finally, by inserting Eqs. 5.9 and 5.10 into Eq. 5.6 the moisture ratio can be predicted based solely on steam temperature, velocity, and processing time (Figs. 5.2 to 5.10). Results show that the higher the steam temperature, the quicker the noodles dried.

Increasing the steam velocity also resulted in quicker drying at the same temperature. This phenomenon occurs in superheated steam but does not occur in hot air (Tang and Cenkowski 2000, Tang et al. 2000, Tang et al. 2005). By increasing the steam velocity from 0.5 m/s to 1.0 m/s, drying time to equilibrium is reduced by 25 to 40%. If the velocity is increased from 0.5 m/s to 1.5 m/s, the overall drying time is reduced by 50% or more.

Agreement between predicted and measured values is excellent for all velocities at temperatures between 110 to 125°C, except for 1.0 m/s at 125°C. From 130 to 150°C and at a steam velocity of 0.5 m/s there is still excellent agreement. But, at a steam velocity of 1.5 m/s, early and late stages of the drying curve are accurately predicted but drying is over predicted during the mid stage. At temperatures of 125, 135, and 145°C the early stage of drying is not accurately predicted. Examination of the drying curves show that there may be some problems with the measured values. In the early stage of drying the measured values decrease rapidly at a steep slope and then sharply change to a more gradual slope. This is not seen at other velocities where the drying curves tend to be smoother over all stages of drying. These phenomena were not present at temperatures of 120, 130, 140, and 150°C at a velocity of 1.0 m/s. At these temperatures the sample tray was still hung from the scale with a rod instead of a thin wire. When the thin wire was used there was more room in the top plate of the chamber to allow moisture to escape. This would sometimes allow water droplets to form on the wire above the hole in the top plate. These droplets would sometimes form a meniscus of water in the hole that would interfere with mass measurement. It may be possible that a velocity of 0.5 m/s was not great enough to force enough moisture out and a velocity of 1.5 m/s was great enough to blow the water droplets away so that mass measurement was not affected in the same way.

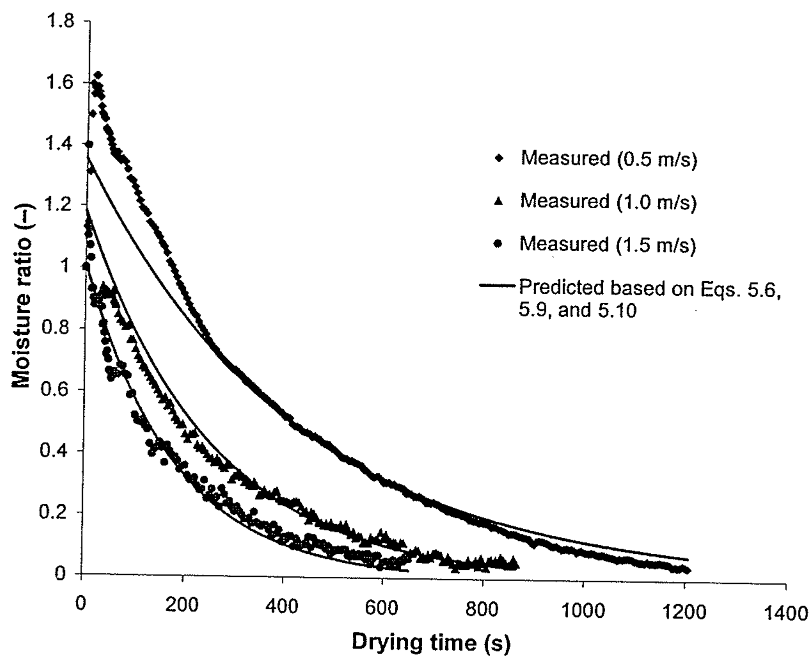


Fig. 5.2. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 110°C and velocities of 0.5, 1.0, and 1.5 m/s.

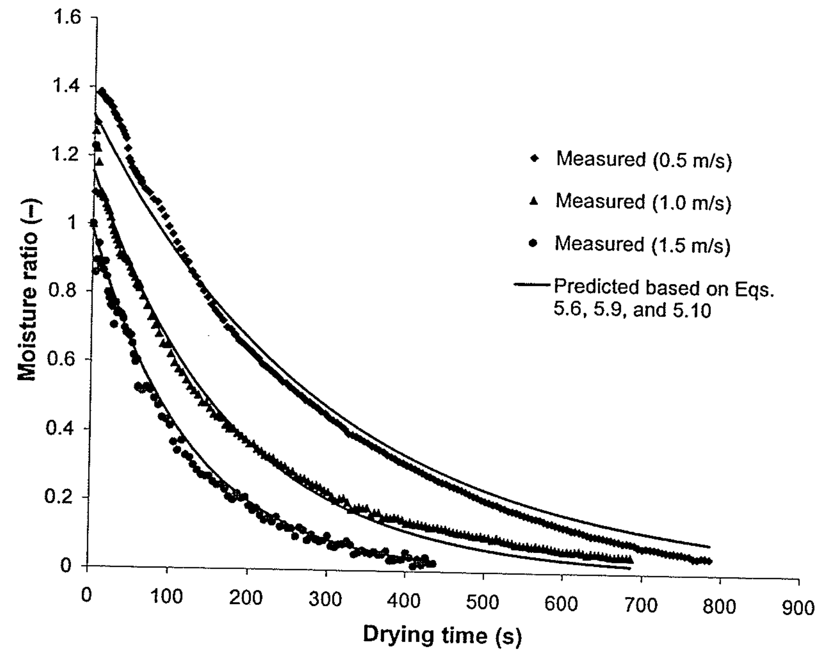


Fig. 5.3. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 115°C and velocities of 0.5, 1.0, and 1.5 m/s.

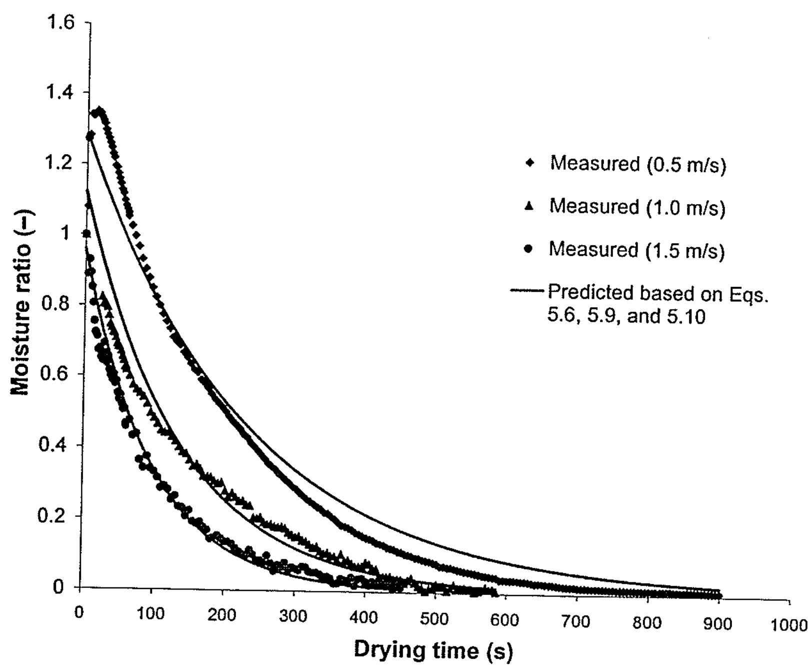


Fig. 5.4. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 120°C and velocities of 0.5, 1.0, and 1.5 m/s.

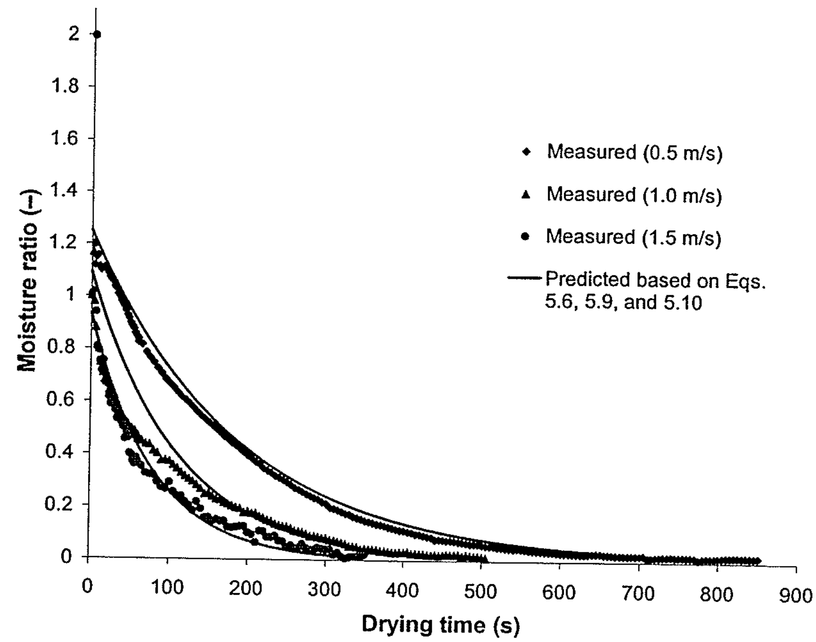


Fig. 5.5. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 125°C and velocities of 0.5, 1.0, and 1.5 m/s.

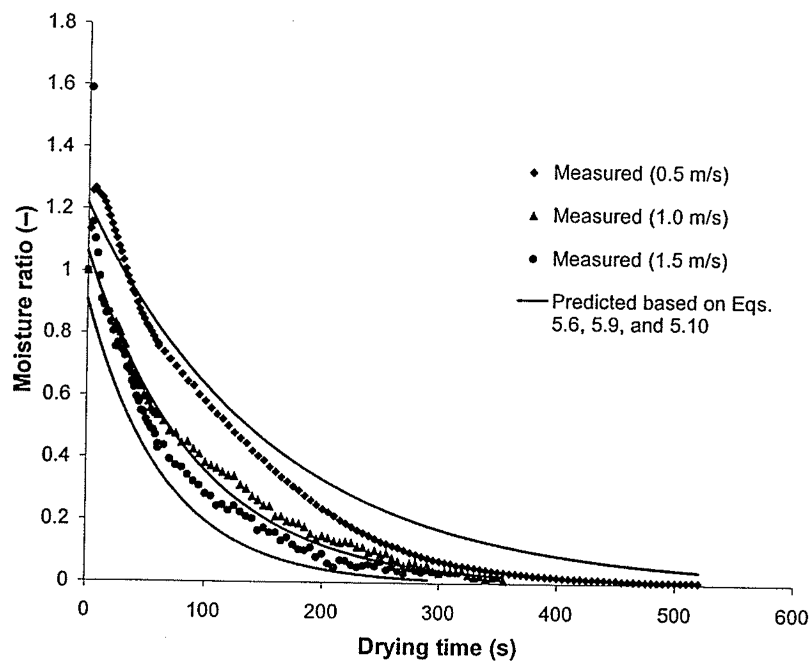


Fig. 5.6. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 130°C and velocities of 0.5, 1.0, and 1.5 m/s.

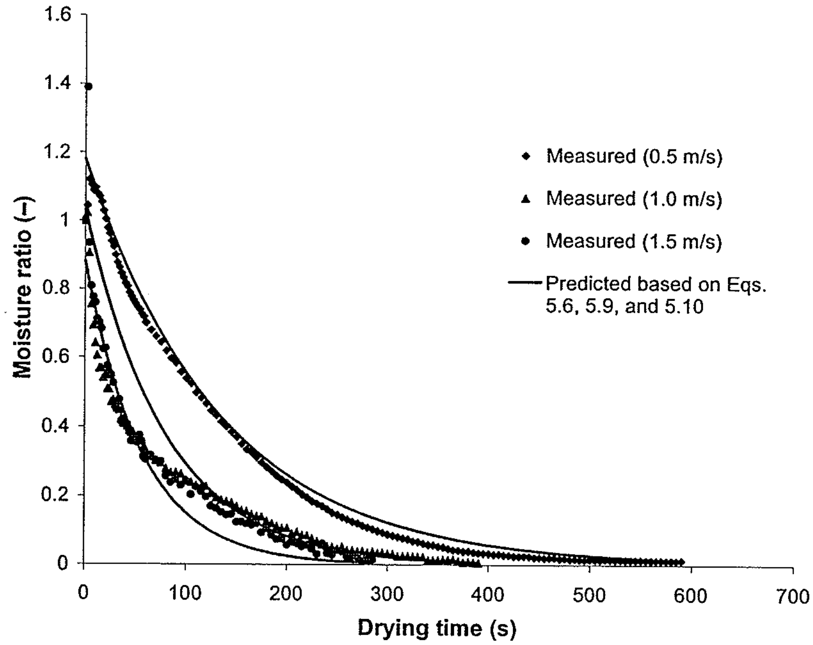


Fig. 5.7. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 135°C and velocities of 0.5, 1.0, and 1.5 m/s.

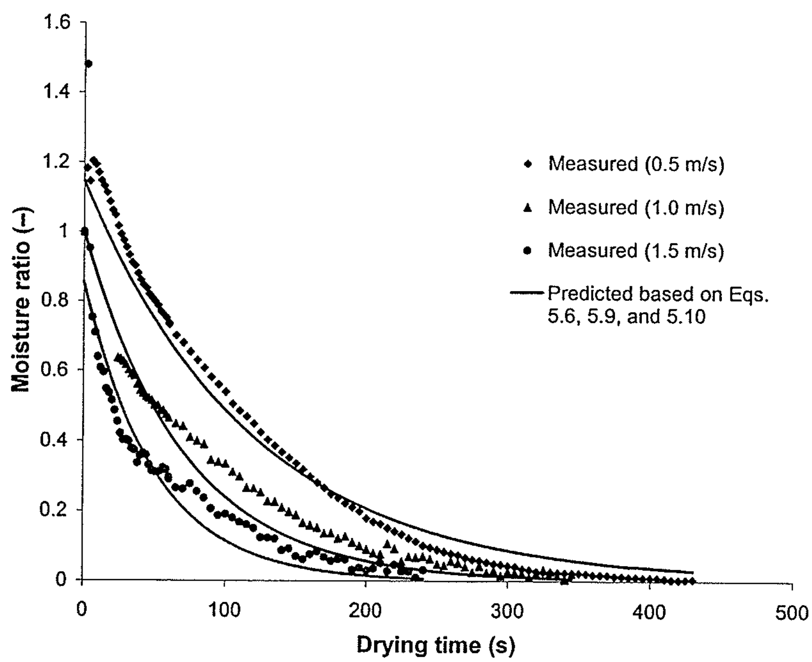


Fig. 5.8. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 140°C and velocities of 0.5, 1.0, and 1.5 m/s.

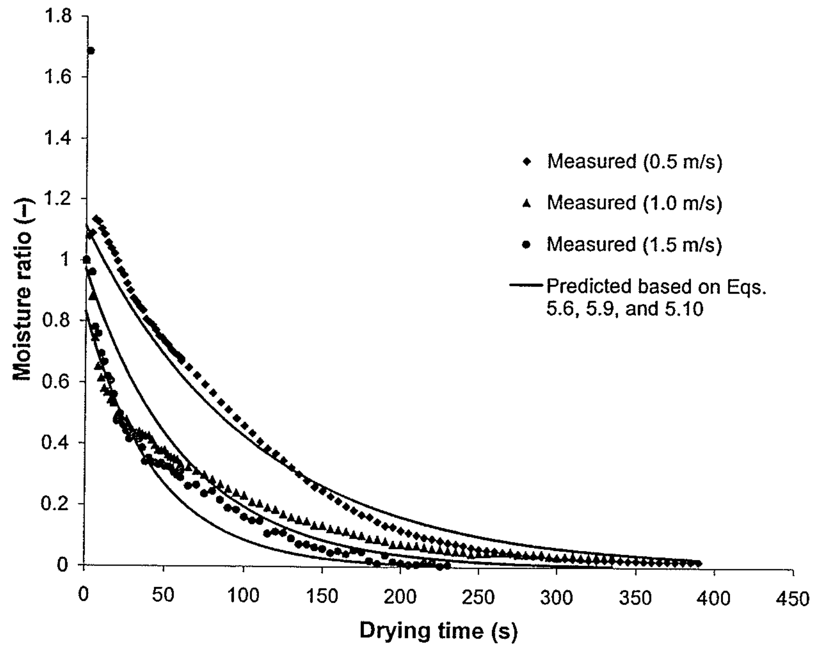


Fig. 5.9. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 145°C and velocities of 0.5, 1.0, and 1.5 m/s.

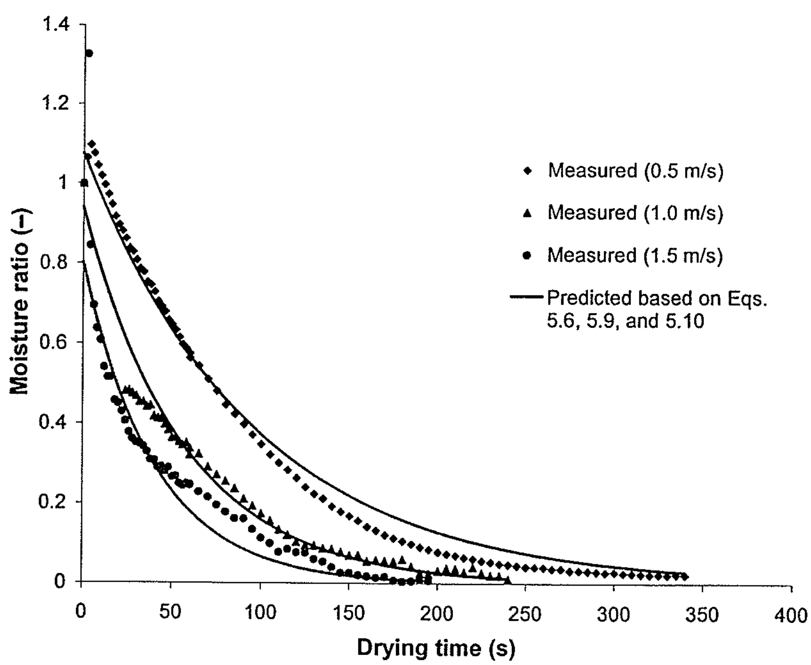


Fig. 5.10. Comparison of predicted results and measured values of moisture ratio for noodles processed in superheated steam at 150°C and velocities of 0.5, 1.0, and 1.5 m/s.

5.2.3 Drying rate

The drying rate of the noodles in superheated steam may be calculated from the drying curve. The drying rate is defined as the change in moisture content per unit time and may be calculated by differentiating the equation for the drying curve (Eq. 5.6):

$$\frac{dM}{d\theta} = -a\,k(M_o - M_e)\exp(-k\theta) \tag{5.11}$$

Coefficients from Table 5.2, EMC data from Appendix B1, and experimentally measured moisture contents were used to produce drying rate curves for all processing conditions (Figs. 5.11 to 5.19).

From the graphs it can be seen that there was a constant rate drying period for all temperatures at a steam velocity of 1.5 m/s. Concurrently, there was no constant rate drying period at a steam velocity of 0.5 m/s. At a steam velocity of 1.0 m/s, a constant rate drying period was shown at temperatures of 115, 125, 135, and 145°C. There was no constant rate period shown at other temperatures as the first 20 s of drying data was eliminated for these temperatures because of the rod contacting the sides of the holes in the top plate of the chamber. The constant drying rate period (when present) occurred only for a short length of time, so eliminating 20 s of moisture data eliminated the time at which it occurred. Also, at a velocity of 0.5 m/s it is possible that the initial large amount of condensation on the sample tray is also masking the constant rate period. From Figs. 5.11 to 5.19, lower steam velocities result in lower drying rates, which are also reported in the literature (Tang and Cenkowski 2000, Tang et al. 2000, Tang et al. 2005). If a constant rate drying period is present at higher velocities with corresponding higher drying rates, then the constant rate period must also be present at lower velocities. The constant drying rate period ends at a critical moisture content that should not be influenced by medium velocity. Therefore, at lower medium velocities it should take longer to reach the critical moisture content and the constant rate period should be present on the graphs. Further testing with sample trays that don't accumulate large amounts of condensation is necessary to confirm this.

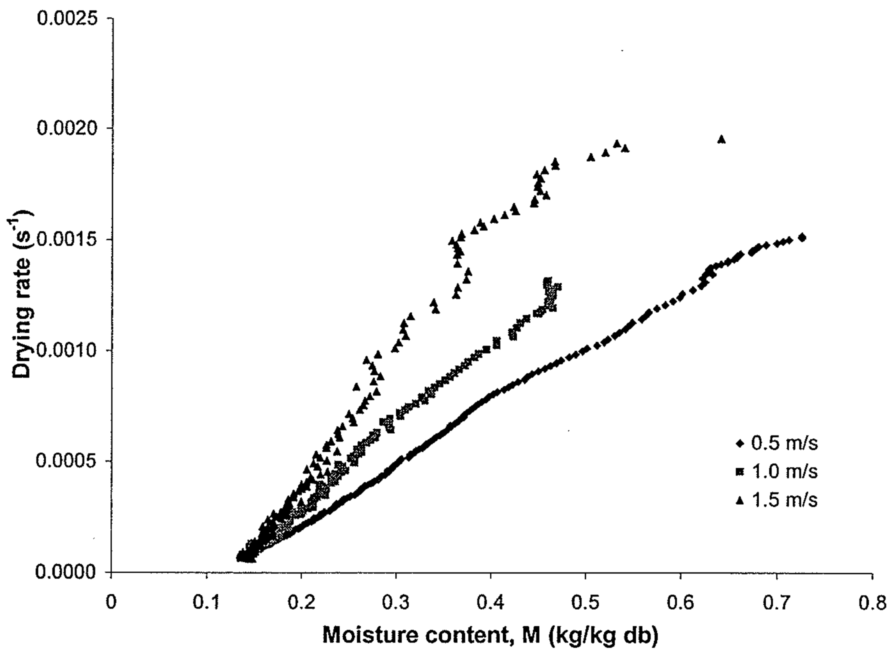


Fig. 5.11. Predicted drying rates for noodles processed in superheated steam at 110°C and velocities of 0.5, 1.0, and 1.5 m/s.

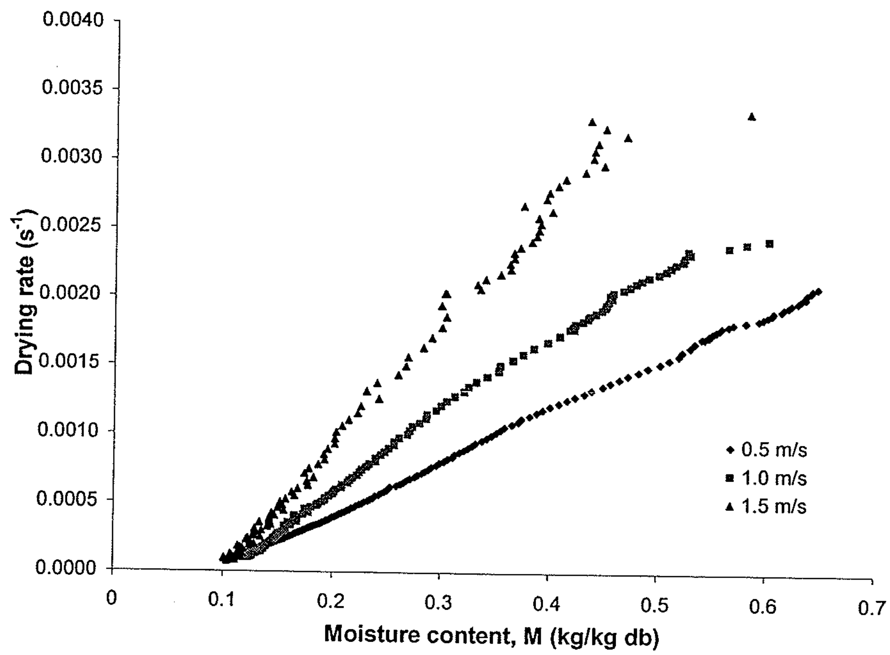


Fig. 5.12. Predicted drying rates for noodles processed in superheated steam at 115°C and velocities of 0.5, 1.0, and 1.5 m/s.

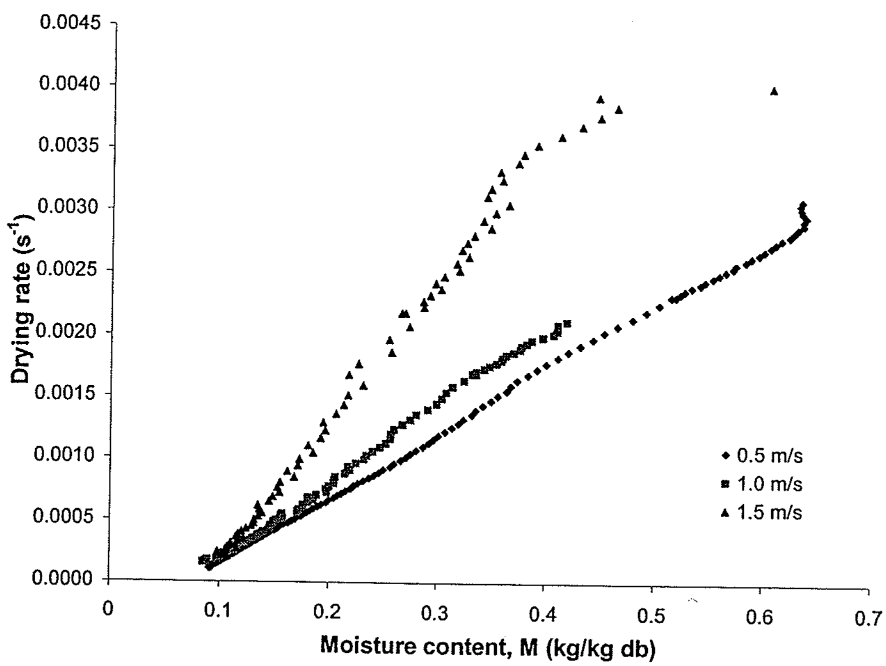


Fig. 5.13. Predicted drying rates for noodles processed in superheated steam at 120°C and velocities of 0.5, 1.0, and 1.5 m/s.

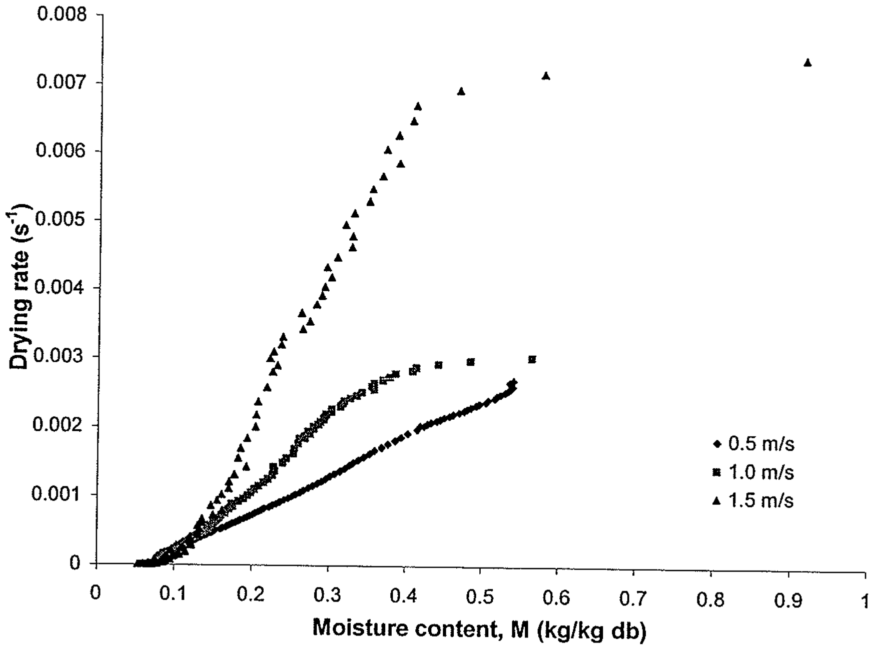


Fig. 5.14. Predicted drying rates for noodles processed in superheated steam at 125°C and velocities of 0.5, 1.0, and 1.5 m/s.

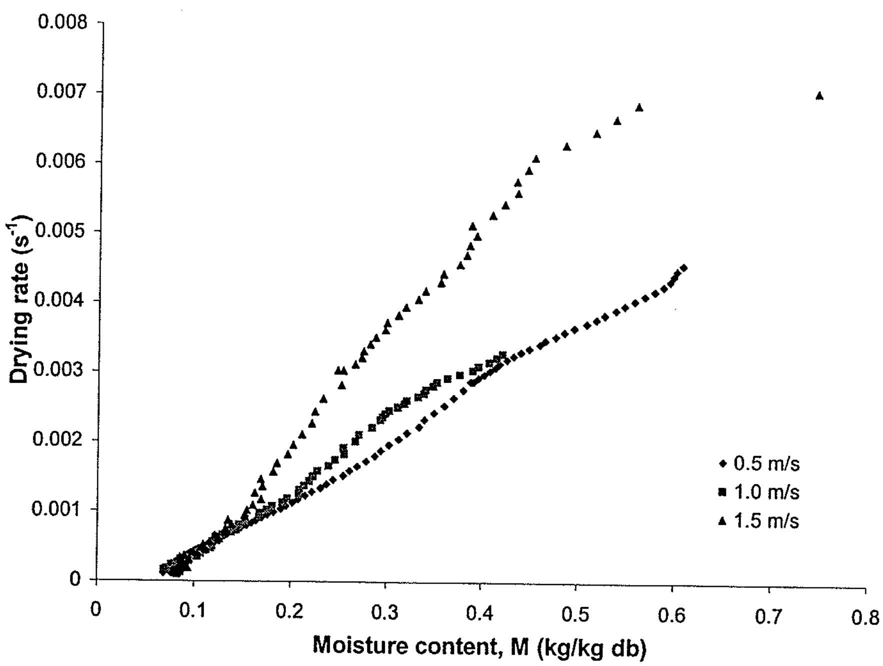


Fig. 5.15. Predicted drying rates for noodles processed in superheated steam at 130°C and velocities of 0.5, 1.0, and 1.5 m/s.

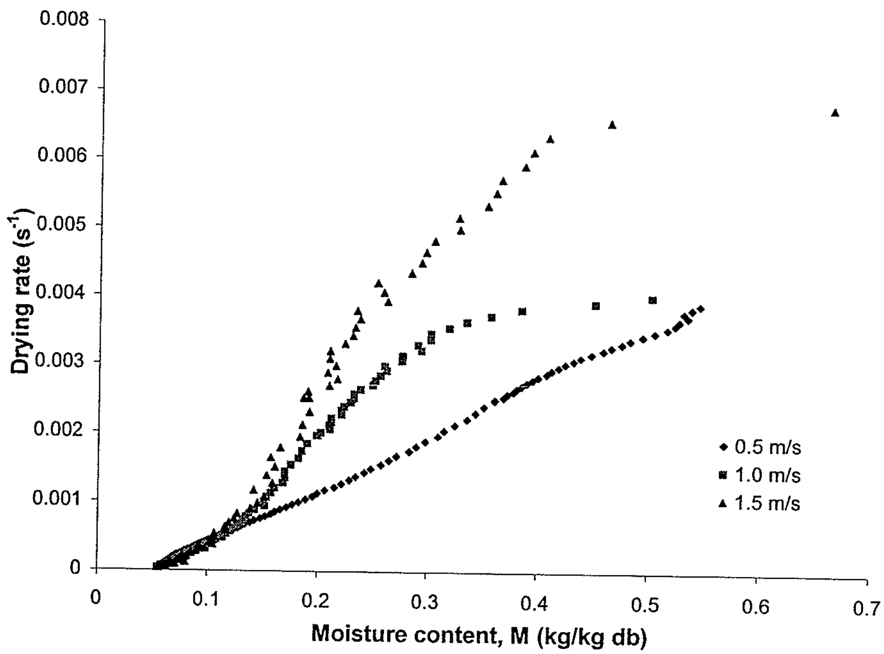


Fig. 5.16. Predicted drying rates for noodles processed in superheated steam at 135°C and velocities of 0.5, 1.0, and 1.5 m/s.

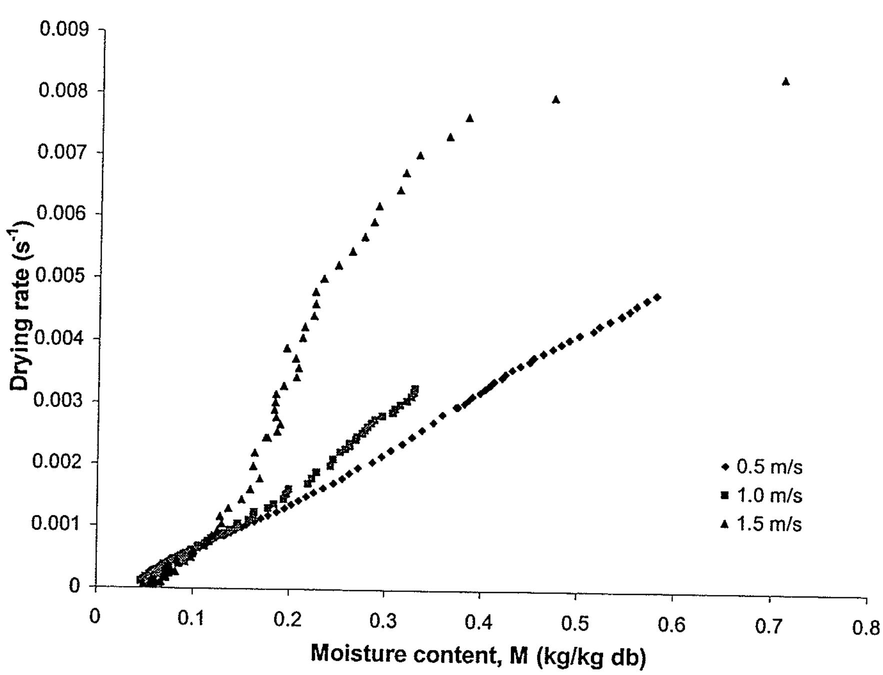


Fig. 5.17. Predicted drying rates for noodles processed in superheated steam at 140°C and velocities of 0.5, 1.0, and 1.5 m/s.

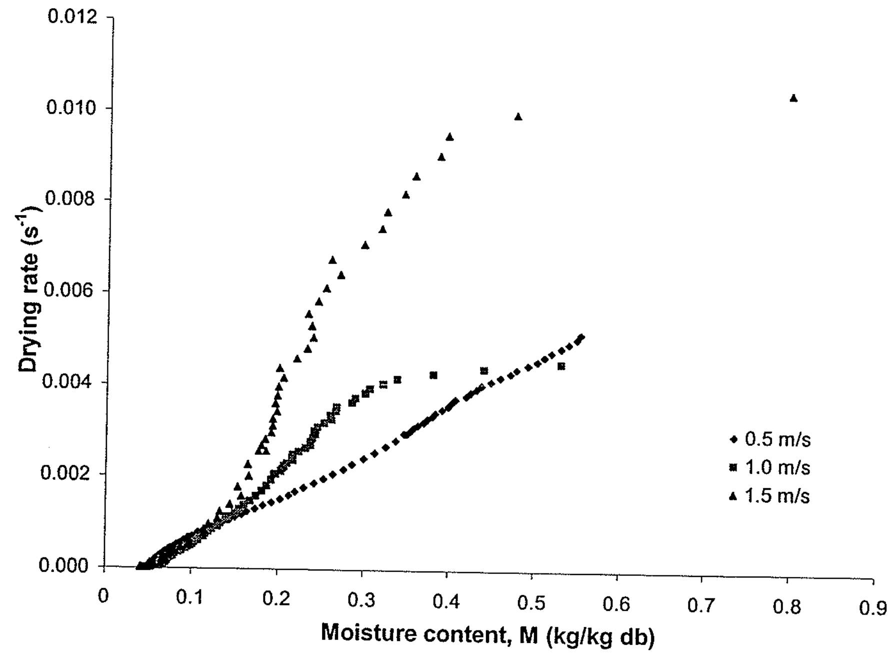


Fig. 5.18. Predicted drying rates for noodles processed in superheated steam at 145°C and velocities of 0.5, 1.0, and 1.5 m/s.

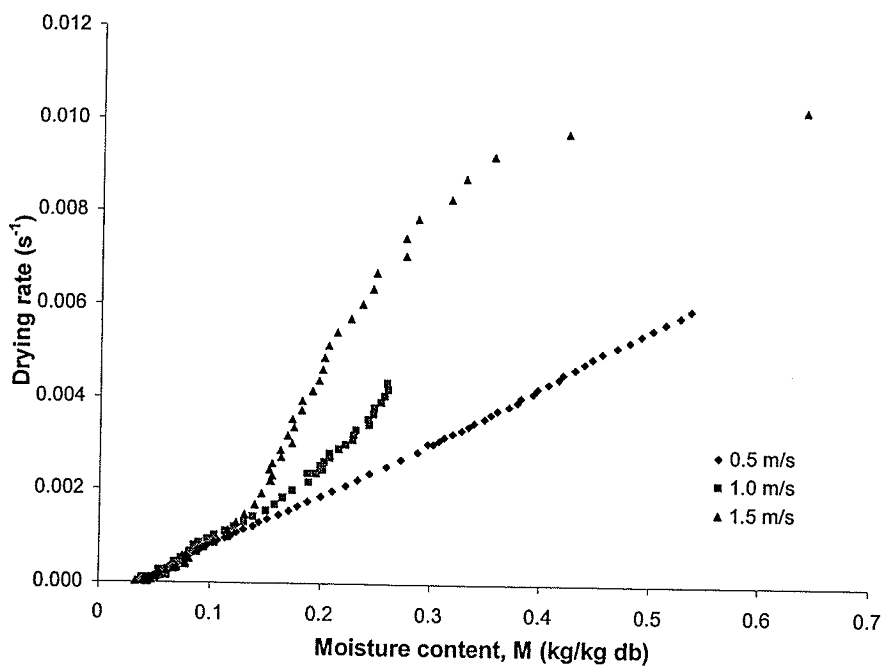


Fig. 5.19. Predicted drying rates for noodles processed in superheated steam at 150°C and velocities of 0.5, 1.0, and 1.5 m/s.

From Figs. 5.11 to 5.19 there is a critical moisture content of approximately 0.35 to 0.43 kg/kg db where the constant rate drying period ends and the falling rate drying period begins. The noodles begin with an initial moisture content of 0.49 kg/kg db which is very near the critical moisture content measured in these experiments. This means that there are very few data points between the start of drying until the critical moisture is reached. This may affect the accuracy with which the critical moisture content is determined. A critical moisture content of approximately 0.3 kg/kg db is seen from the drying rates of noodles processed in superheated steam at 130 and 140°C in experiments by Markowski et al. (2003). They found no constant rate drying period for noodles processed at 110 and 120°C.

5.2.4 Internal noodle temperature

Internal temperature changes of noodles processed in superheated steam were measured with a needle probe inserted at their geometric center (Figs. 5.20 to 5.24). Internal temperature of the noodles rapidly rose to the saturation temperature and gradually increased to near the steam processing temperature. The saturation temperature in these experiments is slightly greater than 100°C (saturation temperature at atmospheric pressure) because a slight pressure of 3 to 13 kPa (gauge) developed in the drying chamber depending on the superheated steam velocity. During the temperature experiments, the three-way valve downstream of the heat exchanger was left open to the water tank. This caused a small pressure to build in the drying chamber, which increased with increasing steam velocity. There is also the possibility that there is an internal pressure created by evaporation within the product (Tatemoto et al. 2003). This pressure is more pronounced at higher velocities because of increased heat transfer rates.

From the graphs it appears that there is a distinct constant drying rate period. This constant level of temperature during drying is reported in literature for a wide range of products dried in superheated steam (Braund et al. 2001, Heinrich et al. 2002, Looi et al. 2002, Tatemoto et al. 2003). Markowski et al. (2003) did not experience the same trend for their experiments with Asian noodles. In their case there was a rapid increase to the saturation temperature but then the temperature kept rising almost linearly to the processing temperature. The same trend was experienced in these experiments when a 30 gauge thermocouple was used as in Markowski's experiments instead of the needle probe. Inserting the 30 gauge thermocouple wire into the noodle caused a deformation around the insertion point. This allowed superheated steam to penetrate to the thermocouple tip during processing. The needle probe was able to penetrate without deforming the noodle.

In these experiments the internal temperature stayed approximately constant at the saturation temperature for nearly 200 s at 110°C but decreased to 50 s at 150°C. An increase in steam velocity shortened this period and noodles came to the medium temperature much faster. The temperature measured in the constant period slowly increased, whereas in literature for superheated steam drying the temperature stays almost constant before it starts to rise. The size of the noodles in these experiments was quite small, so it is possible that conduction down the length of the probe could be significant. Looi et al. (2002) estimated that the energy conducted along the thermocouple wires could account for as much as 5% of the total energy delivered to the centre of a 1 cm diameter brick sphere. They concluded that it is not easy to translate this energy into a measure of temperature. When compared to the drying rate curves from the previous section the constant rate drying period suggested by the temperature curves is much longer and well defined for all processing conditions.

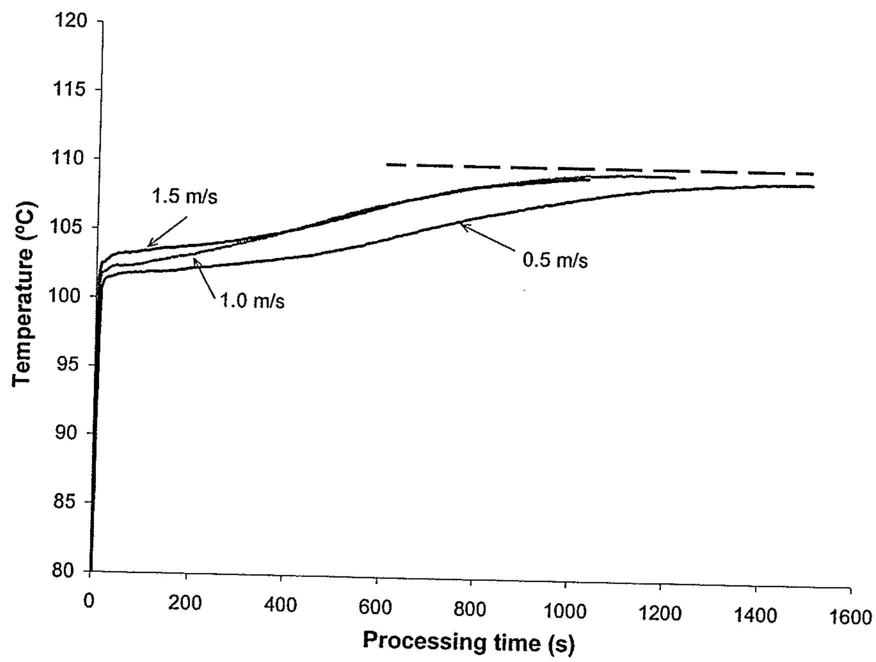


Fig. 5.20. Internal temperature measured near the geometric centre for noodles processed in superheated steam at 110°C and velocities of 0.5, 1.0, and 1.5 m/s (— — — medium temperature).

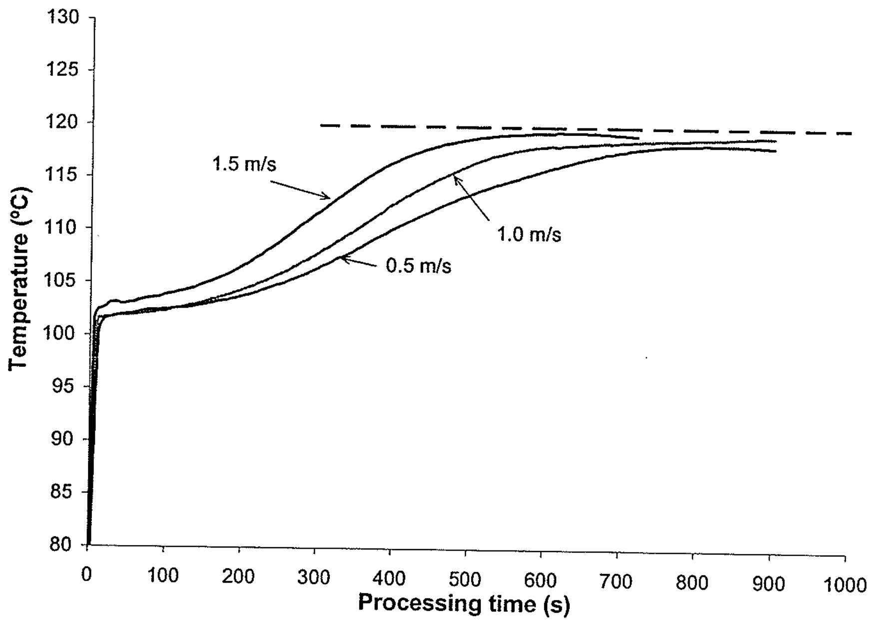


Fig. 5.21. Internal temperature measured near the geometric centre for noodles processed in superheated steam at 120°C and velocities of 0.5, 1.0, and 1.5 m/s (——— medium temperature).

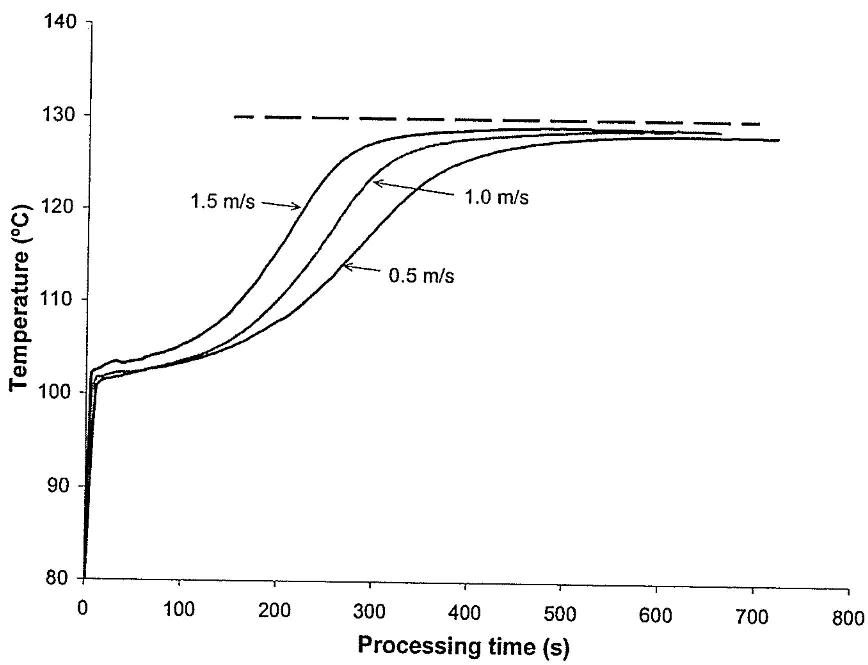


Fig. 5.22. Internal temperature measured near the geometric centre for noodles processed in superheated steam at 130°C and velocities of 0.5, 1.0, and 1.5 m/s (——— medium temperature).

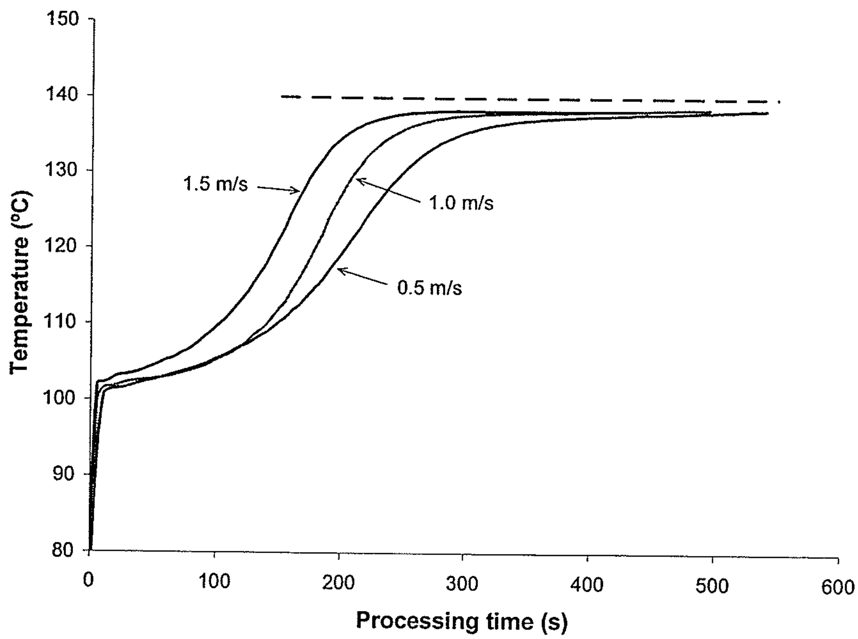


Fig. 5.23. Internal temperature measured near the geometric centre for noodles processed in superheated steam at 140°C and velocities of 0.5, 1.0, and 1.5 m/s (— — — medium temperature).

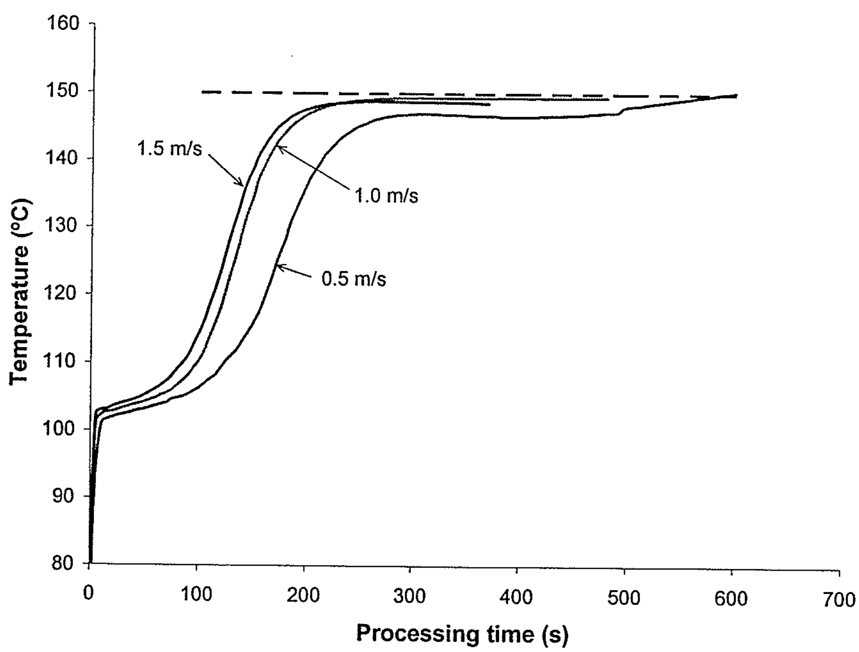


Fig. 5.24. Internal temperature measured near the geometric centre for noodles processed in superheated steam at 150°C and velocities of 0.5, 1.0, and 1.5 m/s (— — — medium temperature).

5.3 Factors affecting textural properties

5.3.1 Resting time for raw noodles

Textural properties of fresh noodles may change substantially over time before processing occurs, but there is no information on this subject in the literature. It was necessary to determine how long a noodle sheet could be used before being discarded because of adverse changes. Information gained from these experiments was used to set a maximum time for use of a fresh noodle sample before it was discarded. A TPA was performed at 20 min intervals starting from the time the noodle sheet was prepared, for a total of 200 min of resting time (Table 5.4). Data obtained from the Texture Expert software were first analyzed using a one-way analysis of variance (ANOVA) using SigmaStat (Version 3.5, Systat Software Inc. Point Richmond, CA). If differences between treatments were found, then a pairwise multiple comparison procedure using Fisher's LSD (least significant difference) was run to ascertain which treatments were significantly different from each other.

Of all the textural properties, adhesiveness was the only one not significantly affected by resting time ($p > 0.05$) for raw noodles. The other textural properties showed some variability, but in most cases did not exhibit any discernable trends (Table 5.5). The main exception is for cohesiveness, where values were approximately equal for the first 60 min and then shifted downward for the last 140 min of testing. Still, the difference between these two periods is only 1.7%, which given the nature and variability found in the noodle sheet is not substantial. Springiness and chewiness started at a high value and then slightly decreased and became nearly constant. When time zero was removed there was no significant difference ($p > 0.05$) for these textural parameters for the remainder of the testing time. Springiness is a measure of elasticity and the noodles at 0 min rest time would not be expected to have had sufficient time for gluten development. As well, uniform hydration of the noodles may not have been completed, resulting in a greater hardness and a noodle that requires more energy to chew. Resilience was not significantly different at longer resting times, but early differences were mostly due to large values at 20 and 60 min resting time. Hardness showed the most variation, with an LSD of 28.9, but did not show a particular trend in the data. Variation is in the order of 14% between the highest and lowest values of hardness for all periods of resting time. When looking at sheet to sheet variation in hardness, the differences were found to be as low as 5%, but as high as 29% (Table 5.6). Similar results are seen for other textural properties when the sheet to sheet variations in results are examined. Manufacture of the raw noodle sheet will affect the results of the TPA. There are always going to be small variations in thickness of the noodle dough after sheeting. Variation measured in these experiments can be in the order of 0.2 mm in thickness which may not seem significant, but it actually represents a 10% change in size of the noodles. In conclusion, if the noodles are allowed to rest for at least 20 min there are no significant changes in textural properties of raw noodles for at least 200 min.

Table 5.5. Textural properties from TPA tests of unprocessed raw noodles at various dough resting times.

Resting Time (min)	Adhesiveness (g•s)	Springiness	Cohesiveness	Chewiness (g)	Resilience	Hardness (g)
0	-17.9^{a}	0.975^{a}	$0.532^{b,c}$	228.4^{a}	$0.364^{b,c}$	440.4^{a}
20	-19.9^{a}	$0.968^{a,b,c}$	0.542^{a}	$218.4^{a,b,c,d}$	0.386^{a}	$416.4^{a,b,c,d,e}$
40	-16.3^{a}	$0.972^{a,b}$	$0.529^{b,c,d}$	$203.9^{d,e}$	$0.341^{c,d}$	$396.5^{d,e}$
60	-17.4^{a}	$0.969^{a,b}$	0.535^{b}	201.5^{e}	$0.375^{a,b}$	389.1^{e}
80	-18.2^{a}	$0.965^{b,c}$	0.521^{e}	$222.4^{a,b}$	0.335^{d}	443.8^{a}
100	-17.2^{a}	$0.968^{a,b,c}$	$0.529^{b,c,d}$	$206.3^{c,d,e}$	$0.345^{c,d}$	$403.1^{b,c,d,e}$
120	-19.4^{a}	0.960^{c}	$0.523^{d,e,f}$	$213.8^{a,b,c,d,e}$	$0.341^{c,d}$	$425.6^{a,b,c}$
140	-16.4^{a}	$0.970^{a,b}$	$0.528^{c,d,e}$	$203.9^{d,e}$	$0.354^{b,c,d}$	$398.5^{c,d,e}$
160	-17.3^{a}	$0.964^{b,c}$	$0.522^{e,f}$	$211.4^{b,c,d,e}$	$0.349^{c,d}$	$420.4^{a,b,c,d}$
180	-15.0^{a}	$0.970^{a,b}$	$0.524^{d,e,f}$	203.1^{e}	$0.353^{b,c,d}$	$399.5^{c,d,e}$
200	-16.9^{a}	$0.966^{b,c}$	$0.527^{c,d,e,f}$	$218.6^{a,b,c}$	$0.358^{b,c,d}$	$429.5^{a,b}$
LSD		0.008	0.006	14.6	0.024	28.9

Means followed by the same superscript letter are not significantly different at $\alpha = 0.05$ level
LSD = least significant difference ($\alpha = 0.05$)

Table 5.6. Hardness values of cooked raw noodles measured on three different noodle sheets dough resting times of 0 to 200 min.

Resting Time (min)	Sheet 1		Sheet 2		Sheet 3	
	avg	std dev	avg	std dev	avg	std dev
0	462.6	7.6	409.0	14.6	449.8	14.5
20	397.6	5.8	371.8	8.6	479.8	28.2
40	422.2	10.1	379.6	2.3	387.6	23.2
60	382.9	9.1	370.1	8.1	414.3	4.2
80	500.6	18.6	416.6	13.3	414.1	49.1
100	396.8	43.1	416.4	11.4	396.1	25.5
120	454.1	8.0	409.2	11.3	408.1	23.2
140	411.9	26.0	375.2	1.8	408.3	13.7
160	437.3	24.1	410.0	8.0	413.8	7.8
180	410.4	21.0	390.1	29.6	398.1	15.4
200	415.2	19.1	455.3	14.4	418.2	31.1

5.3.2 Resting time for superheated steam processed noodles

When noodles were processed in superheated steam at 120°C, a steam velocity of 1.0 m/s, and a processing time of 8 min, the textural parameters adhesiveness, springiness, and cohesiveness were not significantly affected by resting time ($p > 0.05$)(Table 5.7). The other textural properties showed small amounts of variability, but in most cases did not exhibit any discernable trends. In most cases it was only a single value that influenced the results. The value for hardness at 20 min resting time was much lower than at all other resting times. When it is removed there is no significant difference among the resting times ($p > 0.05$). This in turn had an effect on the chewiness of the noodles because hardness is a factor in calculating chewiness. If chewiness at 20 min resting time is removed then there is no significant difference between the remaining resting times ($p > 0.05$). Finally, the only significantly different value for resilience occurs at a resting time of 120 min. This is probably an anomaly in the data because values after 120 min resting time are the same as those before. To eliminate any influence of resting time on the textural properties of noodles it was decided to rest the noodle sheet for 40 min before processing samples for texture. This agrees with literature which recommends resting raw noodles for at least 40 min before processing (Hou and Kruk, 1998). It is then possible to use the same noodle sheet for a total of 200 min after it is made without changes in its textural properties.

Table 5.7. Textural properties from TPA tests of superheated steam processed noodles with various dough resting times before processing.

Resting Time (min)	Adhesiveness (g•s)	Springiness	Cohesiveness	Chewiness (g)	Resilience	Hardness (g)
20	-6.4^{a}	0.981^{a}	0.549^{a}	313.8^{d}	$0.495^{a,b}$	581.7^{c}
40	-5.8^{a}	0.983^{a}	0.542^{a}	$366.3^{a,b,c}$	0.503^{a}	$687.8^{a,b}$
60	-2.4^{a}	0.988^{a}	0.550^{a}	350.1^{c}	0.517^{a}	$645.2^{b,c}$
80	-5.1^{a}	0.984^{a}	0.550^{a}	$352.8^{b,c}$	0.506^{a}	$652.6^{a,b}$
100	-3.9^{a}	0.986^{a}	0.549^{a}	$369.6^{a,b,c}$	0.504^{a}	$682.8^{a,b}$
120	-6.4^{a}	0.981^{a}	0.538^{a}	$363.4^{b,c}$	0.479^{b}	$687.6^{a,b}$
140	-4.4^{a}	0.987^{a}	0.541^{a}	$382.5^{a,b}$	0.510^{a}	715.7^{a}
160	-2.3^{a}	0.981^{a}	0.556^{a}	$372.8^{a,b,c}$	$0.495^{a,b}$	$683.2^{a,b}$
180	-2.7^{a}	0.991^{a}	0.567^{a}	395.7^{a}	0.514^{a}	$709.1^{a,b}$
200	-4.4^{a}	0.982^{a}	0.549^{a}	$374.6^{a,b,c}$	0.502^{a}	$694.9^{a,b}$
LSD				31.9	0.022	68.1

Means followed by the same superscript letter are not significantly different at $\alpha = 0.05$ level
LSD = least significant difference ($\alpha = 0.05$)

5.3.3 Saturated steam pre-treatment

Commercial instant noodles are steamed before either frying or air drying occurs to produce an instant product. This saturated steam processing helps to gelatinize starch and may have an effect on the textural characteristics of the final product. Pre-treated with saturated steam (PSS) noodles were compared to the averages of the raw noodle and superheated steam processed (SHP) from the preceding sections. Based on the results for raw and SHP noodles, TPA values were averaged over the last 160 min of resting time (Table 5.8). The effects of saturated steam pre-treatment could then be ascertained.

Table 5.8. Average results of the texture profile analysis of raw, superheated steam processed (SHP), and pre-treated with saturated steam (PSS) noodles.

Textural Property	Raw[a]		SHP[a]		PSS[b]	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Adhesiveness (g•s)	-17.1	1.2	-4.2	1.5	-4.2	3
Springiness	0.967	0.004	0.985	0.003	0.975	0.011
Cohesiveness	0.526	0.004	0.549	0.009	0.539	0.0065
Chewiness (g)	209.4	7.5	369.8	14.1	417.5	60.9
Resilience	0.35	0.012	0.503	0.011	0.467	0.025
Hardness (g)	411.8	18.5	684.3	23.1	746.5	66.2

[a] n = 27
[b] n = 18

There are many differences between the raw noodles and the processed samples, but fewer differences between the SHP and PSS noodles. Processed noodles were more firm (higher hardness), less sticky (decreased adhesiveness), more elastic (increased springiness and resilience), and would be more difficult to masticate between the teeth (increased chewiness). The increase in chewiness was mostly due to the increase in hardness as cohesiveness was similar for all three treatments. When the processed samples are compared, there was no statistical difference in the adhesiveness and springiness properties between PSS and SHP noodles ($P > 0.05$). However, hardness and chewiness were higher in the PSS noodles, while cohesiveness was lower. Measurement of noodle dimensions after superheated steam processing indicated that PSS noodles were approximately 5% smaller than SHP noodles. The increased diameter of the noodles processed using just superheated steam may have been caused by a "puffing" effect which takes place near the beginning of processing. When the noodles are first placed in the chamber, the temperature of the noodle rises very quickly

(Chapter 5.2.4) and this may cause the moisture in the noodle to flash to steam. This will create many pores of steam that will cause the noodles to puff out and create a less dense noodle. In the case of PSS noodles, moisture is absorbed very quickly near the surface of the noodle during the pretreatment, and when the sample is placed in the superheated steam chamber, the increased amount of moisture causes the noodle to dry more slowly and evenly creating a denser noodle. The increase in density could potentially cause the increase in hardness and chewiness of the PSS noodles.

Commercial instant noodles are steamed before frying or air drying occurs to help gelatinize starch in the final product. Starch analysis was conducted using a differential scanning calorimeter (DSC) to determine the amount of gelatinization. The degree of starch gelatinisation in instant noodles is typically 80 to 90%, depending on the product (Hatcher 2001, Hou 2001). Processing in superheated steam is effective at gelatinizing starches as the temperatures experienced are high enough to allow for gelatinization and the product has sufficient moisture (Cenkowski and Sosulski 1997, Taechapairoj et al. 2004). Results showed that while starch gelatinization increased from raw to processed noodles for both starch types, differences between PSS and SHS noodles ($p < 0.05$) were only found in the amylopectin (Table 5.9). The PSS noodles had a lower enthalpy, ΔH, indicating that there was more starch gelatinization during processing. The absolute difference in enthalpies of 0.03 and 0.11 J/g for amylopectin and amylose-lipid respectively, found between SHS and PSS is extremely small. This is especially true when compared with differences of approximately 6.08 and 0.42 J/g for amylopectin and amylose-lipid respectively, between raw and processed noodles. Results show that the combined gelatinization of amylopectin and amylose-lipid is 87% for SHS noodles and 89% for PSS, indicating that the superheated steam processing was successful in gelatinizing starch. This indicates that the pre-treatment with saturated steam for 120 s prior to superheated steam processing has only minimal effects on the total starch gelatinization in the noodles and will likely not affect the starch properties of the final cooked product in any significant way.

Table 5.9. Starch analysis of flour and noodles from three processing procedures.

	Amylopectin			Amylose-Lipid		
Treatment	Onset Temperature (°C)	ΔH (J/g)	Peak Temperature (°C)	Onset Temperature (°C)	ΔH (J/g)	Peak Temperature (°C)
flour	56.1 ± 0.6	6.83 ± 0.27	62.0 ± 0.4	80.8 ± 0.8	1.48 ± -0.18	92.8 ± 2.5
raw	61.0 ± 0.2	5.54 ± 0.18	67.3 ± 0.2	92.5 ± 1.0	1.01 ± 0.20	103.1 ± 1.4
SHP	75.0 ± 0.7	0.33 ± 0.02	80.9 ± 0.1	90.6 ± 1.2	0.61 ± 0.20	102.5 ± 0.2
PSS	77.5 ± 1.4	0.30 ± 0.02	81.7 ± 0.9	95.1 ± 1.4	0.50 ± 0.22	103.0 ± 0.6

Values are mean of triplicate ± standard deviation

The effects of saturated steam pre-treatment on the textural properties and starch gelatinization of noodles processed in superheated steam at 120°C and 1.0 m/s were minimal. At other temperatures and steam velocities the effects may be more pronounced, but not enough to add the extra complexity to the processing procedure. It was therefore decided not to use the saturated steaming pre-treatment in the experimental procedure for the texture trials.

5.4 Quality evaluation

5.4.1 TPA

Alkaline noodles prepared from Canada Western Hard White (CWHW) wheat (cultivar Snowbird) were processed in superheated steam under various conditions. A TPA was conducted on samples dried to 1/3, 2/3, and 3/3 of the EMC and on a sample of raw unprocessed noodles (Appendix B4). The flour used in these experiments is of higher protein content (13.3%) than traditionally used for Asian noodles, but would make for a firm noodle preferred in some markets (Hatcher 2001, Hou 2001). In general, noodles should be firm yet elastic, chewy, have good cohesion, and not be too sticky (Hatcher 2001, Kim 1996, Markowski et al. 2003, Park and Baik 2004a and b).

A Pearson Product Moment Correlation (Systat 2006) was conducted on the results of the TPA (Table 5.10). Unlike a regression analysis, which predicts the value of a dependent variable from an independent variable, a Pearson Product Moment Correlation does not assign dependency and only quantifies the strength of association between variables. This method was chosen over a regression because it is unknown how the various TPA parameters are affected by steam temperature, velocity, and processing time. Correlation coefficients vary between +1 and -1, where +1 indicates a strong correlation with both variables increasing together, -1 indicates a strong correlation with one variable decreasing as the other increases, and 0 indicates no correlation. In general a correlation coefficient between -0.20 and 0.20 is not strong enough to be considered meaningful in previously published noodle research (Epstein et al. 2002, Graybosch et al. 2004). The correlation coefficient is applicable to the whole set of data and does not make inferences about any one set of processing conditions.

Table 5.10. Pearson Product Moment Correlation coefficients for textural properties from the TPA of noodles processed in superheated steam at various velocities, processing times, and temperatures.

	Processing Variables					
	Velocity		Processing Time		Temperature	
Textural Property	Correlation Coefficient	*P* value	Correlation Coefficient	*P* value	Correlation Coefficient	*P* value
Adhesiveness (g•s)	-0.196	< 0.001	0.444	< 0.001	-0.439	< 0.001
Springiness	-0.115	0.002	0.196	< 0.001	-0.270	< 0.001
Cohesiveness	-0.135	< 0.001	0.479	< 0.001	-0.379	< 0.001
Chewiness (g)	-0.291	< 0.001	0.721	< 0.001	0.202	< 0.001
Resilience	-0.208	< 0.001	0.609	< 0.001	-0.413	< 0.001
Hardness (g)	-0.267	< 0.001	0.661	< 0.001	0.285	< 0.001

Adhesiveness, which is a measure of how sticky the noodles are, decreased with temperature (more sticky) and increased with processing time (less sticky). The correlation of adhesiveness with velocity was too weak to be considered meaningful. Noodles from these experiments are less sticky than noodles processed in superheated steam by Markowski et al. (2003). They achieved adhesiveness values of approximately -12.1 to -17.4 g•s for noodles processed at 110 and 120°C for 5 to 15 min at 0.2 m/s using the same TPA procedure. Values from these experiments are in the range of -1.2 to -3.9 g•s at nearly the same processing conditions, except for a greater steam velocity of 0.5 m/s. However, the correlation coefficient does indicate that adhesiveness will decrease slightly with an increase in velocity. The only other difference was the noodles used by Markowski et al. (2003) were larger. This would increase the contact area of the noodles with the probe during the TPA and could account for the larger values for adhesiveness. Markowski et al. (2003) also did not find a significant time effect on adhesiveness but were only evaluating a limited number of processing conditions. This would not be enough to ascertain the trends found by this larger and more complete study.

Springiness, a measure of the elasticity of the noodles, was not always measured correctly by the Texture Expert software. Values for springiness were often determined to be greater than 1, which would indicate that after the first compression the noodles would expand to a greater size. Examination of the raw data indicated that due to noise in the curve, the program would not correctly measure where the TPA curve crossed the x-axis. The point would often be set before it actually happened, so springiness values would be greater than they actually were. Length 2 was thus manually read from the raw data to correctly calculate springiness. Results show that springiness was not affected by velocity and processing time. Temperature had a slightly stronger influence on springiness with a correlation coefficient of -0.270. However, the difference in springiness between 110°C and temperatures of 140 to 150°C is only 2%. In general, none of the processing conditions in these experiments has a large enough effect to be of any real importance. When the average of springiness for all superheated steam processing conditions is compared to springiness for the raw noodles the difference is also only 2%. Markowski et al. (2003) also concluded that there were no differences in noodle springiness due to superheated steam processing.

Cohesiveness, which is the strength of the internal bonds or ability of the noodle to stick together, was not affected by steam velocity. Cohesiveness increased with processing time and decreased with temperature. When the data was examined closely, cohesiveness was not significantly different ($p > 0.05$) at 1/3 and 2/3 of the time to dry to EMC but increased in the final stages of drying. Cohesiveness decreased for temperatures of 110 to 120°C and then became nearly constant. When compared to the raw noodles, cohesiveness of superheated steam processed samples were approximately 3.5% lower.

Resilience, which is a measure of recoverable energy after compression, was not affected by steam velocity. Resilience increased with an increase in processing time. The increase was 6.5% from 1/3 to 2/3 of the time to EMC and 8.6% from 2/3 to 3/3 of the time to EMC, for an overall increase of nearly 15%. Resilience decreased with an increase in temperature for each processing time and velocity. Overall the decrease from 110 to 150°C could be as high as 20%, although there was substantial variability at different temperatures. The resilience of superheated steam processed noodles is greater than the resilience of the raw noodles, except for noodles processed at temperatures greater than 125°C and at a velocity of 1.5 m/s. Results for temperature effects on resilience differ in these experiments from those of Markowski et al. (2003) who found that resilience increased from 110 to 120°C. As there were only two processing temperatures examined, it was not possible to determined if this was a trend or a random result.

Hardness, which is a measure of the firmness of the noodle, was greatly affected by processing time and to a lesser extent by steam velocity and temperature. Hardness increased with an increase in processing time. The increase was 21.1% from 1/3 to 2/3 of the time to EMC and 15.3% from 2/3 to 3/3 of the time to EMC, for an overall increase of nearly 34.0%. An increase in steam velocity from 0.5 to 1.5 decreased hardness by an average of 13.2%. Hardness increased with an increase in temperature for each processing time and velocity. Overall the increase from 110 to 150°C for each set of processing conditions was between 20 and 35%. As with resilience there was considerable variability in the value of hardness at different temperatures. Hardness in processed noodles was nearly twice as high on average when compared to raw noodles.

Chewiness, which is the energy required to break down the noodles to a swallowing state, was greatly affected by processing time and to a lesser extent by steam velocity and temperature. The effects of processing conditions were almost identical for chewiness as they are for hardness. As chewiness is a function of hardness and other textural properties (Szczesniak 1963) this result was reasonable. Chewiness increased by an average of 21.9% from 1/3 to 2/3 of the time to EMC and 18.0% from 2/3 to 3/3 of the time to EMC, for an overall increase of nearly 39.5%. Increasing velocity from 0.5 m/s to 1.5 m/s decreased chewiness by an average of 14.3%. Chewiness also increased with an increase in temperature for each processing time and velocity. The increase with processing time and decrease with velocity for chewiness is greater than that of hardness. This is because of the influence of cohesiveness and resilience, which both increase with processing time and decrease with velocity, in the calculation of chewiness. Chewiness increased with temperature an average of 10 to 32% for each set of processing conditions. As with hardness and resilience, there is a lot of variability in chewiness from temperature to temperature. Markowski et al. (2003) found that the raw control noodles had the highest value for chewiness whereas in these experiments chewiness of the raw noodles was much lower than the processed noodles.

5.4.2 Maximum cutting stress

Maximum cutting stress (MCS) was measured to characterise the texture of cooked noodles during cutting. An ideal noodle should display a good "bite" as indicated by a high MCS (Markowski et al. 2003). Figs. 5.25 to 5.27 show the MCS of noodles processed under various conditions. In general, steam velocity had no effect on MCS of noodles. There was a small increase in MCS with an increase in processing time at a velocity of 0.5 m/s. This influence started to diminish at 1.0 m/s and all but disappeared at 1.5 m/s. The MCS was not significantly different ($p > 0.05$) at temperatures of 120 to 150°C. At 110°C the MCS was approximately 28% lower at 35.1 g/mm^2 than the 44.9 g/mm^2 average of the other temperatures. Raw control noodles had a MCS of 23.44 ± 1.6 g/mm^2, which was similar to Markowski et al. (2003) who found the MCS of their raw noodles to be 24.31 g/mm^2. They also found that MCS was highest in the raw noodles when compared to the superheated steam processed samples. This is opposite to the findings here where the raw noodles have a lower MCS than all of the superheated steam processed samples. It is unknown why these results differ but higher values for MCS are consistent with increased hardness values from the TPA tests.

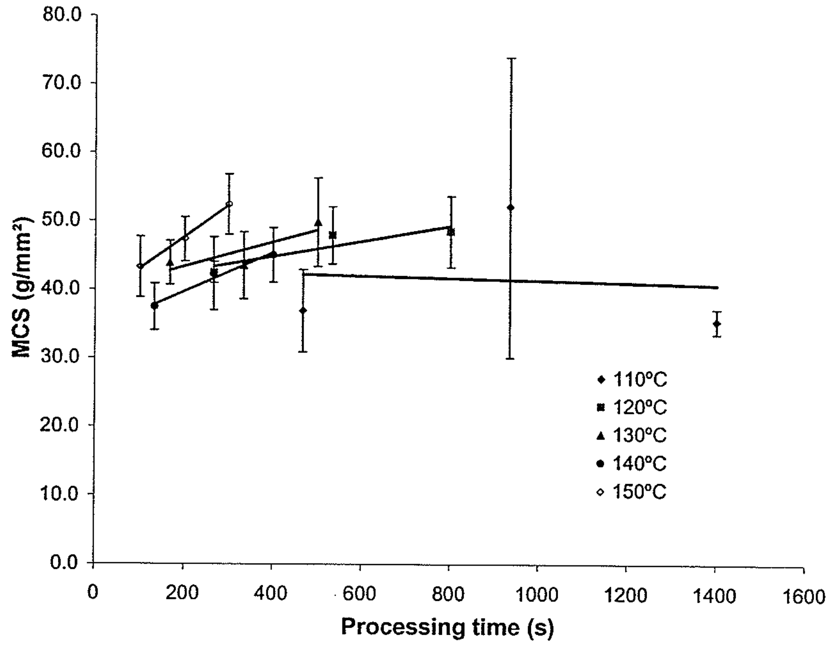


Fig. 5.25. Maximum cutting stress of noodles processed in superheated steam at a velocity of 0.5 m/s and temperatures of 110, 120, 130, 140, and 150°C.

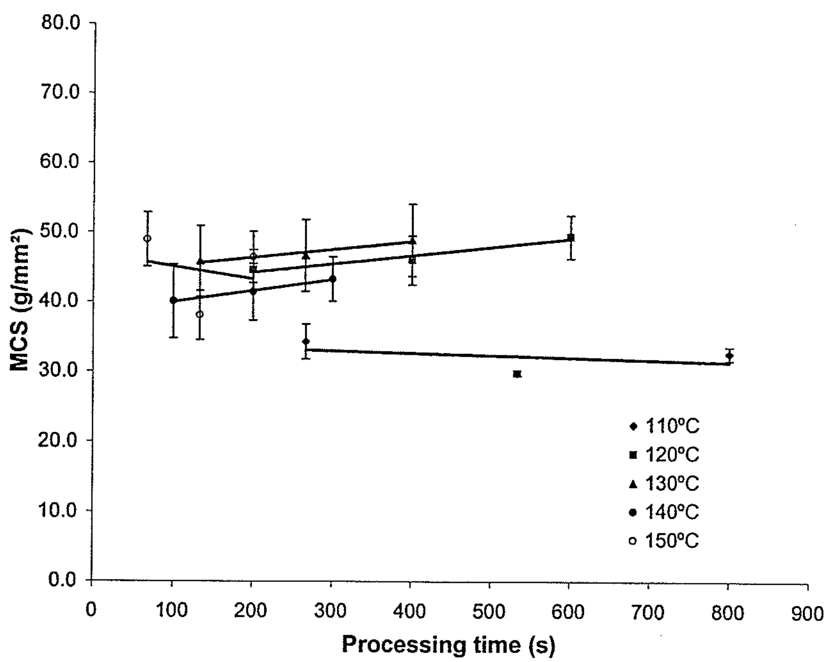


Fig. 5.26. Maximum cutting stress of noodles processed in superheated steam at a velocity of 1.0 m/s and temperatures of 110, 120, 130, 140, and 150°C.

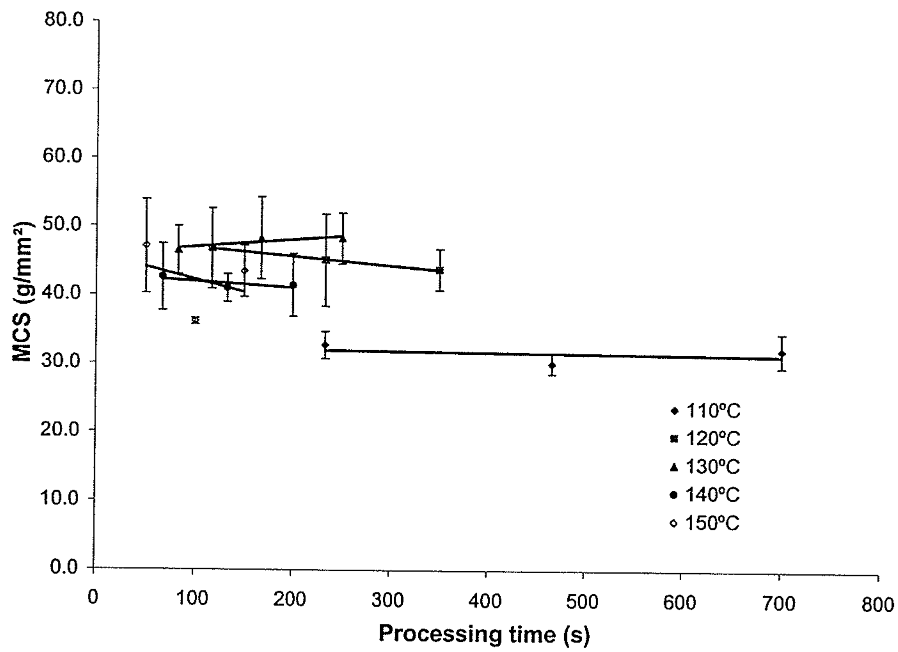


Fig. 5.27. Maximum cutting stress of noodles processed in superheated steam at a velocity of 1.5 m/s and temperatures of 110, 120, 130, 140, and 150°C.

5.4.3 Breaking stress

One of the aspects of quality that is of primary concern to the commercial noodle manufacturer is the breaking strength of the noodles (Markowski et al. 2003). Large amounts of breakage from handling during packaging and shipping would create a commercially unacceptable product. Results obtained for breaking stress (Figs. 5.28 to 5.30) were analyzed using an ANOVA procedure (Systat 2006) with velocity, temperature, and processing time as factors. If differences between treatments were found, then a pair-wise multiple comparison procedure using the Holm-Sidak method was run to ascertain which factors affected the breaking stress. Samples that were processed at lower temperatures and for shorter periods of time still contained substantial amounts of moisture. These noodles were quite elastic and soft. All breaking stress tests were therefore conducted on samples that were allowed to equilibrate at room temperature and humidity for several days before testing. This eliminated the elasticity in the noodles and allowed all samples to be tested at the same equilibrium moisture content of 7% wet basis.

Results show that velocity was not a significant factor ($p > 0.05$) on the breaking strength of noodles. Temperature was only significant ($p < 0.05$) at 110 and 120°C and breaking stress decreased with increasing temperature. Breaking stress was statistically the same at temperatures of 130, 140, and 150°C. It is possible that due to the high temperatures at 130°C and above, the water in the noodles flashes to steam during the initial stages of processing. This would create many pores that would lower the strength of the dried noodles. Noodles processed at 130, 140, and 150°C had significantly larger dried dimensions than noodles processed at 110 and 120°C (Appendix B5). This would indicate a puffing of the noodles due to the flashing of moisture to vapour and the possible creation of pores. However, this would have to be proven by determining the porosity of individual noodles or by taking images of noodle cross sections to check for the creation of pores. Processing time was not a significant factor ($p > 0.05$) at a velocity of 0.5 m/s. At 1.0 m/s, processing time was significant ($p < 0.05$) only at 110°C and at 1.5 m/s it was significant ($p < 0.05$) at 110 and 120°C. In these cases breaking stress decreased with increased processing time.

Work done by Markowski et al. (2003) on noodles dried in superheated steam between 110 and 140°C found that the strength of noodles decreased with both temperature and processing time. This differs from the results from these experiments that found processing time was often not significant and there was no change in strength at temperatures of 130°C and higher. However, Markowski et al. (2003) do not specify how their testing was completed. There is no mention of the span used in the determination of their breaking strength. As well, they claim to follow the procedure of Oh et al. (1985b), yet report their findings as a breaking strength with units of Newtons. The only way to obtain this result is to not use Eq. 4.2 and just report the maximum force supported by the noodle strand before breaking. This would ignore the influence of small size differences between noodle strands on the force it would take to break the noodles. Or perhaps Markowski et al. (2003) made an error in the units that were reported.

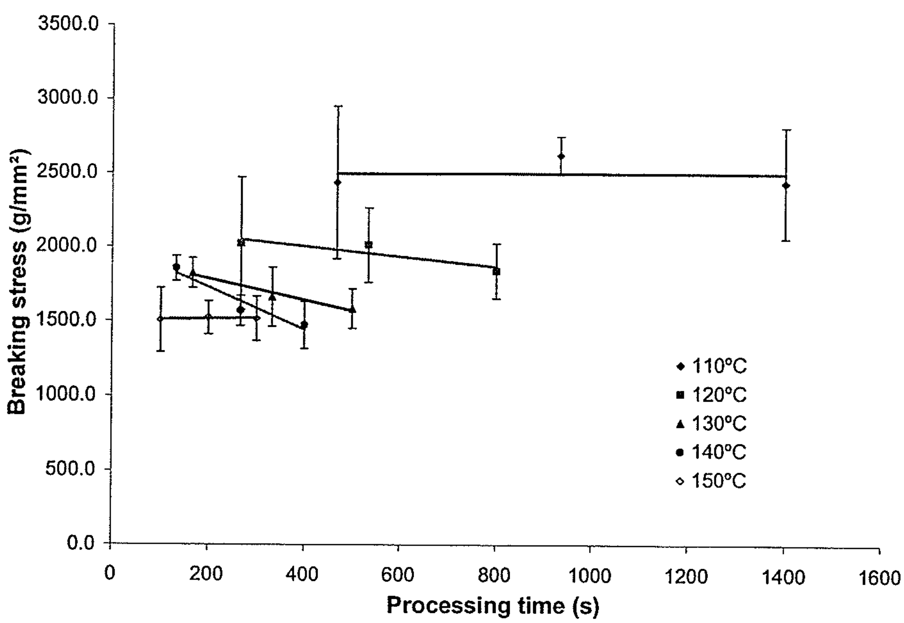


Fig. 5.28. Breaking stress of noodles processed in superheated steam at a velocity of 0.5 m/s and temperatures of 110, 120, 130, 140, and 150°C.

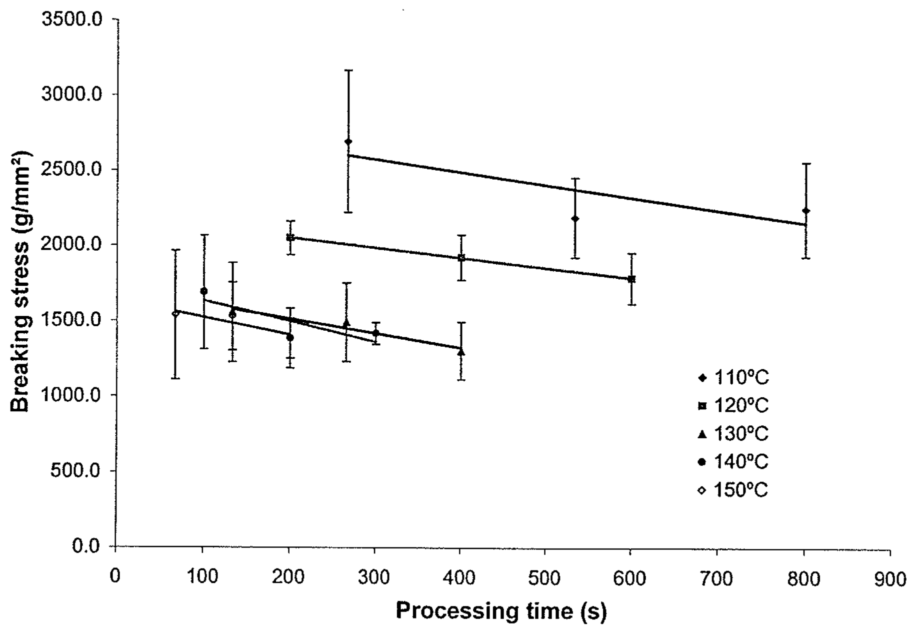


Fig. 5.29. Breaking stress of noodles processed in superheated steam at a velocity of 1.0 m/s and temperatures of 110, 120, 130, 140, and 150°C.

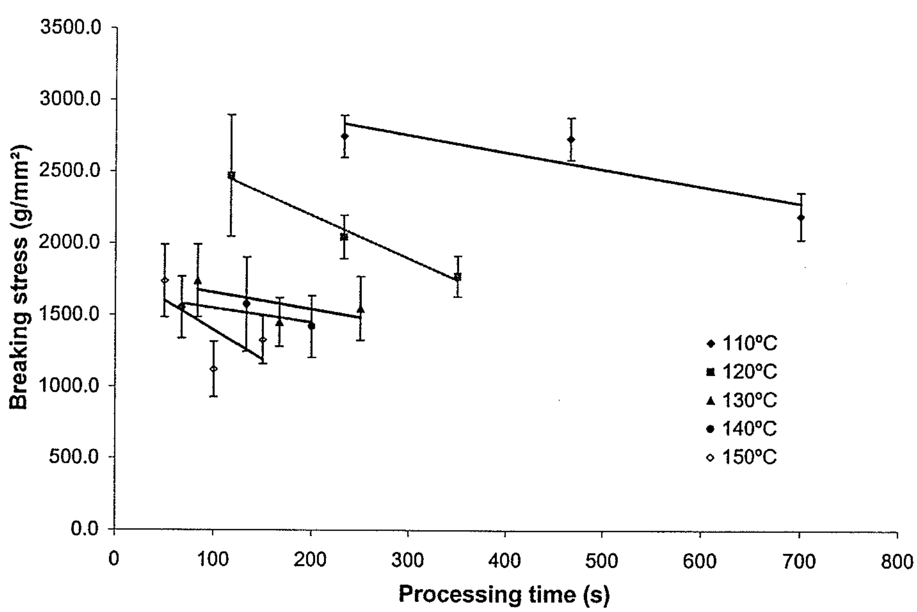


Fig. 5.30. Breaking stress of noodles processed in superheated steam at a velocity of 1.5m/s and temperatures of 110, 120, 130, 140, and 150°C.

5.4.4 Colour

Colour is one of the most important quality parameters for noodles because it is the first item a consumer will evaluate. Colour will affect the decision to purchase the product, even if it is texturally acceptable. After processing in superheated steam, the L*, a*, and b* values were read using a colorimeter with a granular attachment (Table 5.11). Values of L* decreased with an increase in processing time while values of a* increased with processing time. With an increase in steam velocity the opposite occurred, where L* increased while a* decreased. The yellowness of the noodles (b* values) was not significantly affected ($p > 0.05$) by steam temperature or velocity, but there was an increase with processing time. An increase in temperature would normally decrease L* and increase a* because noodles have a tendency to become brown at higher steam temperatures (Markowski et al. 2003). This was not the case in these experiments as the noodles became slightly brighter and did not brown as much at higher temperatures. This is explained by the fact that while steam temperature plays a large role in noodle browning, processing time is the most important factor. Markowski et al. (2003) processed noodles for arbitrary periods of time so that noodles spent more time in the superheated steam than would be necessary to dry them. As a result the noodles were over-processed. Noodles created in these experiments were only processed long enough to reduce the moisture to the EMC, which is often less than the acceptable 12% of the commercial product. This meant that as steam temperatures rose, the noodles dried faster and the processing times could be reduced to prevent noodle browning.

Table 5.11. Colour values (L*, a*, b*) of noodles processed in superheated steam at 110 to 130°C at various velocities and processing times.

Temperature (°C)	Velocity (m/s)	Processing Time (s)	L* Avg	L* Std Dev	a* Avg	a* Std Dev	b* Avg	b* Std Dev
110	0.5	467	68.5	0.4	1.4	0.2	25.1	0.2
110	0.5	934	58.8	0.7	5.8	0.1	21.9	0.4
110	0.5	1400	55.9	0.2	6.2	0.1	21.2	0.2
110	1	267	70.2	0.4	-0.1	0.1	24.1	0.2
110	1	533	66.3	0.2	3.6	0.1	24.3	0.2
110	1	800	61.8	0.4	5.4	0.1	23.3	0.4
110	1.5	233	71.6	0.5	-0.9	0.2	23.7	0.3
110	1.5	466	63.4	0.5	2.7	0.1	25.1	0.4
110	1.5	700	57.7	0.4	5.7	0.1	23.7	0.2
115	0.5	367	68.7	0.2	0.4	0.1	25.6	0.1
115	0.5	733	57.1	0.4	5.3	0.1	23.5	0.2
115	0.5	1100	55.4	0.5	6.7	0.1	23.4	0.3
115	1	233	70.4	0.5	-1.2	0.1	25.0	0.2
115	1	466	60.6	0.6	4.6	0.1	25.7	0.5
115	1	700	55.9	0.3	7.1	0.1	24.2	0.2
115	1.5	133	72.0	0.6	-2.2	0.2	22.9	0.1
115	1.5	266	67.1	0.4	0.7	0.1	26.1	0.3
115	1.5	400	61.5	0.3	4.1	0.1	25.8	0.1
120	0.5	267	69.1	0.4	-1.1	0.1	24.3	0.3
120	0.5	533	61.0	0.2	4.8	0.1	26.0	0.2
120	0.5	800	55.3	0.3	7.4	0.1	24.3	0.2
120	1	200	72.1	0.4	-1.6	0.1	24.7	0.2
120	1	400	62.8	0.3	4.4	0.1	27.1	0.3
120	1	600	57.4	0.3	6.7	0.1	25.3	0.2
120	1.5	117	73.0	0.4	-2.2	0.1	23.1	0.1
120	1.5	233	67.4	0.3	0.7	0.1	25.9	0.2
120	1.5	350	62.0	0.5	4.5	0.1	26.5	0.4
125	0.5	217	65.1	0.3	1.8	0.2	27.1	0.1
125	0.5	433	63.4	0.7	3.3	0.1	26.7	0.4
125	0.5	650	56.8	0.6	6.6	0.1	25.2	0.5
125	1	167	71.5	0.4	-1.9	0.1	23.4	0.1
125	1	333	63.0	0.3	3.8	0.1	26.9	0.3
125	1	500	57.0	0.3	6.8	0.1	25.6	0.2
125	1.5	100	72.2	0.3	-2.2	0.1	22.7	0.2
125	1.5	200	69.7	0.2	-0.7	0.1	25.2	0.1
125	1.5	300	62.1	0.2	4.6	0.1	27.2	0.3
130	0.5	167	70.5	0.5	-1.3	0.1	24.1	0.1
130	0.5	333	63.5	0.3	3.4	0.1	27.3	0.2
130	0.5	500	59.7	0.7	5.9	0.1	26.6	0.5
130	1	133	71.2	0.7	-1.5	0.1	23.3	0.4
130	1	266	64.1	0.8	3.6	0.2	27.4	0.3
130	1	400	61.8	0.6	4.9	0.1	26.9	0.2
130	1.5	83	70.6	0.7	-1.8	0.1	21.7	0.3
130	1.5	167	72.2	0.3	-1.0	0.1	24.8	0.1
130	1.5	250	66.5	0.2	2.4	0.1	27.2	0.2

Table 5.11 (cont'd). Colour values (L*, a*, b*) of noodles processed in superheated steam at 135 to 150°C at various velocities and processing times.

Temperature (°C)	Velocity (m/s)	Processing Time (s)	L* Avg	L* Std Dev	a* Avg	a* Std Dev	b* Avg	b* Std Dev
135	0.5	150	68.3	0.3	-1.3	0.1	24.0	0.2
135	0.5	300	63.0	0.4	3.4	0.2	27.2	0.3
135	0.5	450	61.0	0.8	5.1	0.2	27.1	0.5
135	1	117	71.7	0.4	-1.9	0.1	22.9	0.1
135	1	233	66.8	0.5	1.9	0.1	27.5	0.3
135	1	350	63.1	0.5	4.3	0.1	27.2	0.3
135	1.5	75	73.4	0.6	-1.8	0.1	21.7	0.2
135	1.5	150	71.2	0.7	-0.4	0.1	24.8	0.3
135	1.5	225	68.4	0.3	1.6	0.1	25.7	0.1
140	0.5	133	69.8	1.2	-1.8	0.1	22.8	0.5
140	0.5	266	65.3	0.4	2.5	0.1	27.3	0.2
140	0.5	400	61.8	0.5	4.7	0.1	27.1	0.5
140	1	100	72.4	0.3	-2.0	0.1	21.7	0.2
140	1	200	69.7	0.3	0.2	0.1	25.8	0.2
140	1	300	58.2	0.6	6.0	0.1	25.9	0.5
140	1.5	67	71.5	0.7	-1.5	0.1	21.8	0.2
140	1.5	133	68.7	0.8	-0.3	0.2	24.5	0.2
140	1.5	200	63.2	0.5	3.9	0.1	26.6	0.3
145	0.5	117	67.5	0.6	-1.3	0.1	22.1	0.4
145	0.5	233	61.7	0.6	3.2	0.1	26.0	0.4
145	0.5	350	60.3	0.5	4.9	0.1	25.9	0.5
145	1	83	71.2	0.9	-2.0	0.1	20.7	0.3
145	1	167	67.0	1.0	0.9	0.3	25.5	0.4
145	1	250	62.9	0.9	3.8	0.2	25.9	0.6
145	1.5	58	70.2	1.3	-1.4	0.1	17.9	0.3
145	1.5	117	67.4	0.7	0.4	0.1	24.9	0.4
145	1.5	175	62.0	1.2	4.6	0.1	26.5	0.7
150	0.5	100	70.0	0.9	-1.6	0.1	21.4	0.4
150	0.5	200	65.5	0.8	1.8	0.2	26.0	0.7
150	0.5	300	63.3	0.3	4.0	0.1	26.2	0.3
150	1	67	70.4	1.0	-2.0	0.1	20.2	0.6
150	1	133	67.1	0.6	-0.2	0.1	23.6	0.5
150	1	200	64.6	0.7	2.7	0.2	26.0	0.6
150	1.5	50	75.4	0.6	-1.1	0.1	19.9	0.2
150	1.5	100	73.7	0.5	-0.4	0.1	22.5	0.2
150	1.5	150	62.2	1.2	3.6	0.1	25.9	0.4

The raw noodle sheet had values of 75.9 ± 0.4, -0.5 ± 0.1, and 22.2 ± 0.3 for L*, a*, and b*, respectively. In nearly all cases, superheated steam processed noodles were less bright (lower L* values) than the raw noodle sheet. On the other hand, processed noodles had a stronger yellow colour than the raw noodle sheet. A distinct yellow colour in alkaline noodles is a desirable quality characteristic (Hatcher 2001, Hou

2001). In many cases values of a* were adversely affected by processing. This is not surprising as a* is an indication of noodle browning. The browning of noodles during processing may be the result of several factors. The first and least likely is enzymatic browning due to polyphenol oxidases (PPO), which catalyse the oxidation of phenolic compounds in the presence of oxygen. Browning due to PPO can occur in pasta and noodles especially at high temperatures (Feillet et al. 2000, Kruger et al. 1994b). However, results are inconclusive as to the influence of PPO in the browning when compared to other sources (Feillet et al. 2000). In superheated steam PPO should be even less of a factor in browning because of the lack of oxygen in the process. Oxygen is only present in the drier at the start of processing when a sample is loaded. The more likely source of browning is due to a Maillard reaction, which is a non-enzymatic browning that is the result of reactions between free amino groups of amino acids and reducing sugars that give rise to a brown "melanoidin pigment". Maillard reactions also give rise to distinct tastes as in toasted bread. When noodles browned in these experiments there was a distinct taste like that of a pretzel. Maillard reactions occur in pasta drying at temperatures greater than 80°C and moistures less than 15% (Resmini and Pelligrino 1994) and this causes an increase in redness (increased a*) (Feillet et al. 2000). There were improvements to a* at higher temperatures that were probably due to the shorter processing times. These are potentially the noodles that would be most acceptable to consumers.

5.4.5 Starch analysis

Starch is composed of branched (amylopectin) and linear (amylose-lipid complex) chains of molecules. In most wheat the ratios are in the order of 70:30 to 80:20 amylopectin to amylose (Bushuk and Rasper 1994). A waxy, or partially waxy wheat like Snowbird has a larger amount of amylose than a non-waxy wheat. Measurements of the enthalpy (ΔH), onset, and peak temperatures for amylopectin and amylose starch were conducted for superheated steam processed noodles (Table 5.12). These were compared to fried and air dried control samples and the flour and raw noodle sheet used in noodle preparation (5.13). Results indicate that the ratio of amylopectin to amylose is only 80:20 for this particular sample of Snowbird, which is the same as a non-waxy wheat. This is possible because Snowbird is a new variety that has not been grown in large enough quantities to enable segregation into different protein or quality streams (Anonymous 2004).

Superheated steam processing resulted in a reduction in enthalpy and an increase in onset and peak temperatures. This is potentially the result of modification of starch during a heat moisture treatment at high temperatures and semi-dry conditions (Stute 1992). This does not affect gelatinization but does affect the swelling properties of starch granules. Markowski et al. (2003) concluded that starch modification was occurring due to a loss in ability of starch granules to swell, indicated by a 20% reduction in thickness of cooked noodles that had been processed at 140°C. This reduction in cooked noodle dimensions was not seen in these experiments (Appendix B5). In nearly all cases cooked noodle dimensions of superheated steam processed samples were greater than the raw control noodles. This may have occurred due to pore formation from the puffing effect. The percentage increase in dimensions from dried to cooked superheated steam noodles was less than unprocessed to cooked raw noodles. But, this was only significant for noodle thickness and may be the result of the potentially increased porosity of the noodles allowing swelling of the starch granules without any dimension changes. The effect of alkaline salts on the starch granules is also a possible source of differences. Alkaline treatment of starches will increase the gelatinization temperature but not affect the enthalpy at gelatinization (Gunaratne and Corke 2007). The enthalpy was affected so this cannot be the only factor affecting the starch. It is probable that starch is gelatinizing and thus the enthalpy is decreasing. Taechapairoj et al. (2004) used scanning electron microscopy to examine starch granules in rice dried in superheated steam. They found that starch granules swelled and absorbed surrounding moisture, and thus starch gelatinization occurred. So, while it is not possible to say without further testing, it is probable that changes in starch during superheated steam processing for these experiments is due to gelatinization, perhaps with some modification of starch due to heat-moisture and alkaline treatments.

Table 5.12. Starch analysis of superheated steam processed noodles.

Temperature	Velocity	Processing Time	Amylopectin			Amylose–Lipid		
(°C)	(m/s)	(s)	onset (°C)	peak (°C)	ΔH (J/g)	onset (°C)	peak (°C)	ΔH (J/g)
110	0.5	467	78.1 ± 0.4	82.4 ± 0.5	0.91 ± 0.20	96.0 ± 1.5	103.6 ± 3.8	0.54 ± 0.37
110	0.5	934	80.1 ± 0.2	83.8 ± 0.6	0.57 ± 0.06	95.2 ± 2.0	105.0 ± 1.4	0.60 ± 0.14
110	0.5	1400	80.3 ± 1.5	83.8 ± 0.3	0.30 ± 0.03	98.9 ± 1.0	104.4 ± 1.4	0.46 ± 0.27
110	1.5	233	80.6 ± 1.0	83.6 ± 0.2	0.33 ± 0.06	94.7 ± 0.3	104.5 ± 0.5	1.04 ± 0.60
110	1.5	466	79.0 ± 1.0	83.4 ± 0.1	0.45 ± 0.11	94.6 ± 0.8	104.6 ± 0.6	0.54 ± 0.18
110	1.5	700	77.7 ± 1.6	81.9 ± 0.3	0.66 ± 0.08	94.9 ± 1.5	104.7 ± 1.6	0.81 ± 0.23
120	0.5	267	78.8 ± 0.7	82.3 ± 0.4	0.73 ± 0.12	97.1 ± 2.3	105.9 ± 2.7	0.26 ± 0.12
120	0.5	533	78.0 ± 0.3	82.2 ± 0.2	0.92 ± 0.04	97.1 ± 1.6	105.2 ± 2.0	0.72 ± 0.56
120	0.5	800	76.4 ± 0.8	81.5 ± 0.4	1.39 ± 0.14	95.8 ± 1.0	104.8 ± 0.1	1.00 ± 0.20
120	1.5	117	78.9 ± 0.4	82.6 ± 0.4	0.46 ± 0.05	95.6 ± 0.9	103.3 ± 1.3	0.81 ± 0.14
120	1.5	233	77.4 ± 1.3	81.7 ± 0.2	0.64 ± 0.05	95.7 ± 1.2	103.3 ± 1.3	0.58 ± 0.21
120	1.5	350	77.0 ± 1.1	82.0 ± 0.4	0.70 ± 0.06	94.2 ± 2.2	105.3 ± 1.0	0.76 ± 0.17
130	0.5	167	78.0 ± 0.3	81.8 ± 0.1	0.68 ± 0.12	93.3 ± 1.7	103.0 ± 0.8	0.76 ± 0.20
130	0.5	333	78.8 ± 0.7	83.4 ± 0.1	0.45 ± 0.10	98.0 ± 0.9	103.2 ± 1.8	0.46 ± 0.37
130	0.5	500	79.1 ± 0.5	83.1 ± 0.4	0.45 ± 0.04	99.8 ± 2.3	104.8 ± 0.1	0.74 ± 0.53
130	1.5	83	76.6 ± 1.7	82.7 ± 0.7	0.58 ± 0.06	96.4 ± 1.7	103.5 ± 0.5	1.04 ± 0.16
130	1.5	167	77.9 ± 1.5	83.1 ± 0.6	0.65 ± 0.09	95.1 ± 4.4	102.7 ± 1.3	0.75 ± 0.26
130	1.5	250	78.5 ± 1.2	83.2 ± 0.4	0.64 ± 0.11	100.6 ± 1.4	103.5 ± 2.7	0.42 ± 0.31
140	0.5	133	77.9 ± 0.4	82.2 ± 0.1	0.72 ± 0.05	97.6 ± 1.4	104.7 ± 0.8	0.88 ± 0.34
140	0.5	266	75.6 ± 1.3	81.6 ± 0.6	1.30 ± 0.20	98.3 ± 2.4	104.8 ± 0.1	0.59 ± 0.17
140	0.5	400	78.0 ± 0.5	82.5 ± 0.3	0.90 ± 0.07	99.8 ± 0.9	105.0 ± 0.3	0.57 ± 0.37
140	1.5	67	78.4 ± 0.6	82.4 ± 0.9	0.63 ± 0.09	97.0 ± 4.7	103.8 ± 2.3	0.86 ± 0.40
140	1.5	133	77.4 ± 0.2	82.1 ± 0.1	1.01 ± 0.14	100.1 ± 4.7	104.2 ± 2.3	0.42 ± 0.27
140	1.5	200	77.8 ± 0.6	82.0 ± 0.5	0.85 ± 0.19	95.7 ± 1.6	104.7 ± 0.7	1.28 ± 0.16
150	0.5	100	75.8 ± 1.3	81.4 ± 0.4	1.46 ± 0.10	98.3 ± 1.6	105.0 ± 0.3	1.06 ± 0.12
150	0.5	200	77.0 ± 0.5	81.8 ± 0.1	1.18 ± 0.03	98.9 ± 3.4	105.0 ± 0.3	0.67 ± 0.33
150	0.5	300	75.8 ± 1.1	80.9 ± 0.1	1.58 ± 0.10	99.9 ± 2.2	105.4 ± 0.1	0.88 ± 0.20
150	1.5	50	76.4 ± 1.2	80.9 ± 0.1	0.65 ± 0.02	96.9 ± 2.4	103.4 ± 1.1	0.74 ± 0.21
150	1.5	100	77.4 ± 1.2	81.9 ± 0.1	0.45 ± 0.06	95.6 ± 0.9	100.6 ± 3.0	0.73 ± 0.16
150	1.5	150	77.2 ± 0.7	81.9 ± 0.9	0.60 ± 0.10	93.1 ± 3.6	104.1 ± 0.7	0.66 ± 0.23

Values are mean of triplicate ± standard deviation

Table 5.13. Starch analysis of control noodles and flour.

Material	Amylopectin			Amylose–Lipid		
	onset (°C)	peak (°C)	ΔH (J/g)	onset (°C)	peak (°C)	ΔH (J/g)
Flour	60.4 ± 0.6	66.0 ± 0.2	6.31 ± 0.94	93.2 ± 1.3	100.4 ± 1.3	1.26 ± 0.44
Raw Noodle	61.0 ± 0.2	67.3 ± 0.2	5.54 ± 0.18	92.5 ± 1.0	103.1 ± 1.4	1.01 ± 0.20
Fried	79.3 ± 0.7	83.0 ± 0.8	0.18 ± 0.04	92.6 ± 2.0	102.6 ± 0.1	0.64 ± 0.25
Air Dried	79.3 ± 1.6	83.4 ± 0	0.67 ± 0.13	101.5 ± 1.1	104.1 ± 1.8	0.45 ± 0.28

Values are mean of triplicate ± standard deviation

At all superheated steam processing conditions there was significant starch gelatinization when compared to the raw control noodles and flour. There was not a significant difference ($p > 0.05$) between the raw noodles and flour, indicating that no gelatinization occurred during mixing and sheeting. Also, there was no difference ($p > 0.05$) between the amylose starch components for the different superheated steam processing conditions. For amylopectin there was not much of an effect due to processing time. There was a general increase in gelatinization with velocity and a decrease with an increase in temperature. On average, the difference in gelatinization of amylopectin was as low as 19% at 110°C and as high as 60% at 150°C between steam velocities of 0.5 and 1.5 m/s. At the same velocity, amylopectin gelatinization was greatest at 110°C and lowest at 140 and 150°C. It is probable that higher steam velocities and temperatures caused moisture to leave the noodles more rapidly and help prevent the gelatinization of the starch molecules.

When superheated steam processed noodles are compared to fried and air dried control samples, there are no significant differences ($p > 0.05$) in gelatinization of amylose. For amylopectin the differences between superheated steam processed and fried controls are significant ($p < 0.05$) at all processing conditions, whereas there are no differences ($p > 0.05$) between the superheated steam processed samples and the air dried controls except for a few processing conditions. Combined gelatinization of both amylopectin and amylose was 89.2% for fried control noodles, 85.2% for air dried control noodles, and an average of 80.5% for all superheated steam processed samples.

5.5 Optimum processing conditions

There is little information in the literature about what constitutes an acceptable instant noodle. Several researchers have dried or created instant Asian noodles (Kim 1996, Markowski et al. 2003, Oh et al. 1985b, Park and Baik 2004 a and 2004b, Wills and Wootton 1997). However, procedures for determining quality are not standardized between the different researchers, making comparisons difficult. As well, many of the researchers were evaluating new technology (Markowski et al. 2003) or evaluating flour and the effects of different components on noodle quality (Oh et al. 1985b, Park and Baik 2004a and 2004b). In these cases only general inferences could be made about the consumer acceptability of the noodles because no study of commercial product quality was made.

To ascertain the commercial acceptability of superheated steam processed instant noodles, a sampling of commercial products was undertaken. In all, a sampling of instant noodle products from six different manufacturers was evaluated for colour, texture, and breaking strength. In all cases the major ingredients were flour and salts although many products had additional ingredients including starch and eggs (Appendix B6). One major ingredient for all commercial products that was not present in the superheated steam processed instant noodles is oil from the frying process. This may have an effect on the taste of the product, but was not studied for this project.

Noodle colour is perhaps the most important aspect of quality for commercial noodles. If colour is not acceptable, consumers are not likely to purchase an instant noodle product. Measurement of commercial noodle colour indicated that noodles should be bright, with L* values greater than 63, should not have any browning, indicated by a* values less than 0, and should have a good yellow colour, indicated by b* values above 20 (Table 5.14). Six Fortune noodles had a b* value of 17.1, which is less than all the other noodles. These noodles were noticeably white, indicating that they were probably an Udon noodle and not an alkaline noodle. The raw noodle sheet and air dried instant control noodles displayed good colour values. Fried control noodles had low brightness and high values of browning. This was probably due to the methodology used to fry the noodles. There were many instances of superheated steam processed noodles displaying acceptable colour values (Appendix B6). However, many of these noodles had moisture contents above the acceptable storage limit of 12% (Kim 1996). There were still several superheated steam processing conditions that produced acceptable colour values and had moisture at or below the safe storage limit (Table 5.15). Acceptable colour values were achieved at higher temperatures in conjunction with high steam velocities. In all but one case (150°C, 1.0 m/s, 133 s) only noodles processed at 1.5 m/s dried sufficiently, and were exposed to superheated steam for a short enough period of time, to prevent browning from occurring.

Table 5.14. Colour values (L*, a*, b*) of control and commercial instant noodles.

	L*		a*		b*	
	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
Noodle Sheet	75.9	0.4	-0.5	0.1	22.2	0.3
Air Dried Control	71.0	0.5	-1.6	0.1	23.6	0.2
Fried Control	63.1	0.9	3.5	0.1	30.0	0.4
Rosan	64.2	3.3	-1.1	0.7	38.9	2.3
Nong Shim	73.3	0.5	-2.4	0.1	26.3	1.2
No Name	65.8	3.0	1.4	0.6	20.3	1.5
Noodle Time	76.4	0.5	-1.4	0.4	27.4	0.7
Six Fortune	76.3	0.8	-0.1	0.1	17.1	1.0
Farkay	70.8	0.7	-2.3	0.1	29.8	1.0

Table 5.15. Superheated steam processed noodles with acceptable colour values and a moisture content below 12% db.

Temperature (°C)	Velocity (m/s)	Processing Time (s)	L*		a*		b*	
			Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
125	1.5	200	69.7	0.2	-0.7	0.1	25.2	0.1
130	1.5	167	72.2	0.3	-1.0	0.1	24.8	0.1
135	1.5	150	71.2	0.7	-0.4	0.1	24.8	0.3
140	1.5	133	68.7	0.8	-0.3	0.2	24.5	0.2
150	1	133	67.1	0.6	-0.2	0.1	23.6	0.5
150	1.5	100	73.7	0.5	-0.4	0.1	22.5	0.2

A TPA was conducted for the commercial and control noodles and results compared to the superheated steam processed noodles with acceptable colour values (Table 5.16). Dimensions varied from noodle to noodle making direct comparisons difficult, as there is no information on the effects of product dimensions on TPA results. Nong Shim, No Name, Noodle Time, and Farkay noodles were quite close in width and thickness to the superheated steam processed noodles (less than 10% variation) while Rosan and Six Fortune noodles were both wider and thinner. Results were analyzed using a one-way analysis of variance (ANOVA) using SigmaStat (Version 3.5, Systat Software Inc. Point Richmond, CA). If differences between treatments were found, then a pairwise multiple comparison procedure using the Holm-Sidak method to ascertain which treatments were significantly different from each other. Results of the TPA show that commercial and superheated steam processed noodles have similar values for adhesiveness. Only the air dried control and the 150°C, 1.0 m/s, 133 s superheated steam processed samples were different ($p < 0.001$). Both samples were stickier than the rest of the noodles. Springiness was not significantly different ($p < 0.001$) for all noodles. Cohesiveness was also not

Table 5.16. Results of TPA conducted for commercial and control noodles and superheated steam processed noodles with acceptable colour values.

Processing Condition	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	st dev
Air Dried Control	-19.6	1.5	0.971	0.007	0.516	0.009	273.7	6.2	0.366	0.016	546.2	12.1
Fried Control	-9.9	0.4	0.982	0.005	0.501	0.005	442.8	52.9	0.379	0.012	902.8	64.2
Rosan	-8.9	1.9	0.976	0.035	0.516	0.008	197.6	13.9	0.349	0.016	392.4	20.2
Nong Shim	-1.5	1.7	0.931	0.031	0.530	0.026	190.3	24.0	0.423	0.029	387.1	57.4
No Name	-5.1	3.4	0.957	0.009	0.513	0.025	236.7	19.8	0.436	0.031	482.3	28.8
Noodle Time	-3.4	1.7	0.976	0.013	0.549	0.004	214.6	36.4	0.456	0.063	401.0	74.9
Six Fortune	-9.3	2.5	0.934	0.013	0.521	0.010	282.4	16.8	0.421	0.035	580.2	24.4
Farkay	-6.8	1.4	0.961	0.007	0.547	0.002	351.6	17.0	0.423	0.015	668.8	34.2
125°C, 1.5 m/s, 200 s	-4.6	2.6	0.966	0.017	0.523	0.004	368.4	11.9	0.453	0.017	729.6	21.3
130°C, 1.5 m/s, 167 s	-5.9	1.7	0.939	0.020	0.516	0.007	348.7	18.1	0.411	0.016	720.2	34.3
135°C, 1.5 m/s, 150 s	-3.4	1.4	0.961	0.059	0.512	0.009	294.0	21.6	0.434	0.027	598.1	43.3
140°C, 1.5 m/s, 133 s	-8.9	3.2	0.971	0.048	0.513	0.008	330.6	24.7	0.422	0.033	665.1	50.9
150°C, 1.0 m/s, 133 s	-12.8	4.6	0.975	0.019	0.526	0.006	320.1	20.0	0.438	0.037	624.0	34.2
150°C, 1.5 m/s, 100s	-7.4	1.4	0.960	0.015	0.515	0.005	252.8	16.3	0.431	0.011	511.1	27.4

different except for the Noodle Time and Farkay commercial noodles, which had higher values than the rest of the noodle samples. Resilience was also the same except for the air dried control and Rosan commercial noodles. Resilience was lower in both cases. In general hardness and chewiness differed between noodles although superheated steam processed noodles were more firm and chewy than the commercial noodles. These results show that all superheated steam processed noodles with acceptable colour values have textural properties that are the same or close to commercial instant noodles.

Breaking strength of noodles is also a key aspect of commercial acceptability. Consumers will not wish to purchase a product with excessive breakage from handling and packaging. Only two commercial products were evaluated for breaking stress because it was impossible to obtain a long enough sample to conduct a test from brick instant noodle products. Results show that air dried control noodles had a much higher breaking stress than the fried control and commercial products (Table 5.17). Breaking stress of superheated steam processed noodles with acceptable colour values were in the same range as the fried control and commercial products (Chapter 5.4.3). Values ranged from a low of 1121 ± 194 g/mm² for noodles processed at 150°C, 1.5 m/s, for 100 s to a high of 1575 ± 329 g/mm² for noodles processed at 140°C, 1.5 m/s, for 133 s. Superheated steam processed instant noodles have the same chance of breaking as the commercial products tested.

Table 5.17. Breaking stress of control and commercial noodles.

Noodle	Breaking Stress (g/mm^2)	
	Avg	Std Dev
Air Dried Control	3496	674
Fried Control	1537	107
Rosan	1278	249
Farkay	1299	283

The instant noodles created for this project had cooking times only slightly longer than the commercial products (Appendix A). In addition, there were no occurrences of bubbles on the surface of any noodles processed in superheated steam at any processing condition. Bubbles on the noodle surface are not a desired trait for instant noodles (Park and Baik 2004b).

6 CONCLUSIONS

It was proven that it is possible to create an acceptable instant noodle by simultaneous drying and cooking in superheated steam. The general conclusions of this work are:

The sorption behavior of noodles processed in superheated steam were modeled by isobars using two equations for superheated steam and three isotherm equations for air with relative pressure replacing relative humidity. All equations modeled the EMC data well and isotherm equations can be used to model isobars in superheated steam by replacing relative humidity with relative pressure. The EMC approached 4.3% db at 150°C and would be expected to decrease further at higher temperatures although it would not be expected to reach 0%.

Measurement of the internal temperature of the noodles showed a rapid rise to the saturation temperature and a gradual increase to near the steam temperature after a constant temperature period. This constant period, which denotes the constant drying rate period, was nearly 200 s at 110°C but decreased to 50 s at 150°C. An increase in steam velocity shortened this period and noodles came to the medium temperature much faster.

At a velocity of 0.5 m/s and temperatures of 135°C and greater the effect of initial condensation on drying was reduced to the first 25 s of processing. At velocities of 1.0 to 1.5 m/s the condensed moisture was removed in 2 to 4 s. The higher the steam temperature the quicker the noodles dried. Increasing the steam velocity also resulted in quicker drying at the same temperature. By increasing the steam velocity from 0.5 m/s to 1.0 m/s, drying time to equilibrium is reduced by 25 to 40%. If the velocity is increased from 0.5 m/s to 1.5 m/s, the overall drying time is reduced by 50% or more.

Newton's and Page's drying equations were proposed to model the drying of noodles undergoing superheated steam processing. For both models the regression coefficient R^2 was 0.8 or better for most processing conditions. The models are most accurate during the latter stages of drying and do not accurately predict the initial condensation period during superheated steam drying. Coefficients determined by non-linear regression for both equations were further regressed to determine the effects of steam temperature and velocity. Coefficients for Page's model followed no discernable trends for steam temperature and velocity. For Newton's model, coefficient a decreased and drying coefficient k increased following a linear trend with an increase in steam temperature and velocity. Using the regression equations for coefficients a and k, the moisture ratio was predicted based on steam temperature, velocity, and processing time. Prediction of drying was best at low temperatures and steam velocity.

Drying rates were determined from differentiation of the drying equation. There was a constant rate drying period for all temperatures at a steam velocity of 1.5 m/s but there was no constant rate drying period at a steam velocity of 0.5 m/s because of condensation on the sample tray. At a steam velocity of 1.0 m/s, a constant rate drying period was shown at temperatures of 115, 125, 135, and 145°C but not at other temperatures because the first 20 s of drying data was eliminated due to errors in mass measurement. The constant rate drying period suggested by the temperature curves is much longer and well defined for all processing conditions than from the drying curves.

If raw noodles are allowed to rest for at least 20 min there are no significant changes in textural properties of raw noodles for at least 200 min. If noodles are processed in superheated steam, noodle sheets should be rested for 40 min after which time there are no significant changes in textural properties. There was no difference in the adhesiveness and springiness properties between saturated steam pre-treated noodles and superheated steam processed noodles. However, hardness and chewiness were higher in the saturated steam pre-treated noodles while cohesiveness was lower. This was due to a puffing effect in noodles with no pre-treatment causing a less dense noodle that was not as hard. Pre-treatment with saturated steam for 120 s prior to superheated steam processing has only minimal effects on the total starch gelatinization in the noodles as the combined gelatinization of amylopectin and amylose-lipid is only 2% greater for noodles with the saturated steam pre-treatment.

Textural properties of adhesiveness, springiness, cohesiveness, chewiness, resilience, and hardness determined from a TPA were generally unaffected by steam velocity. All properties but springiness increased with an increase in processing time. Increasing temperature decreased adhesiveness, springiness, cohesiveness, and resilience but increased hardness and chewiness to a small degree. Maximum cutting stress and breaking stress were not affected by steam velocity. There were also no differences in maximum cutting stress at temperatures of 120°C and greater and at 130°C and greater for breaking stress.

Noodle colour was affected by the superheated steam processing conditions. Values of L* (brightness) decreased with an increase in processing time while values of a* (redness) increased with processing time. With an increase in steam velocity the opposite occurred where L* increased while a* decreased. The yellowness of the noodles (b* values) were not significantly affected ($p > 0.05$) by steam temperature or velocity but there was an increase with processing time. Browning of noodles ($a^* > 0$) is likely due to the Maillard reaction.

Superheated steam processing resulted in a reduction in enthalpy and an increase in onset and peak temperatures of amylopectin and amylose starches. This was due to gelatinization of the starch molecules. There was no difference between the amylose starch components for the different superheated steam processing conditions. For amylopectin there was not much of an effect due to processing time. There was a general increase in gelatinization with velocity and a decrease with an increase in temperature. Combined gelatinization of both amylopectin and amylose was 89.2% for fried control noodles, 85.2% for air dried control noodles, and an average of 80.5% for all superheated steam processed samples.

Measurement of commercial noodle colour indicated that noodles should be bright, with L* values greater than 63, should not have any browning, indicated by a* values less than 0, and should have a good yellow colour, indicated by b* values above 20. Noodles processed at 125°C, 1.5 m/s, for 200 s, 130°C, 1.5 m/s, for 167 s, 135°C, 1.5 m/s, for 150 s, 140°C, 1.5 m/s, for 133 s, 150°C, 1.0 m/s, for 133 s, and 150°C, 1.5 m/s, for 100 s had acceptable colour values and moisture at or below the safe storage limit. Results showed that these noodles had textural properties and breaking strengths that were the same or close to commercial instant noodles. These conditions are the optimum to produce a noodle that has physical and textural properties that would be acceptable to consumers.

7 RECOMMENDATIONS FOR FUTURE RESEARCH

During experimentation there were several problems encountered while taking mass measurements with the scale outside of the drying chamber. The wire from which the sample tray was suspended would contact the sides of the hole in the top plate and thus affect mass measurement. As well, the hole allows steam to escape the chamber. This steam may condense and form a water meniscus around the wire in the hole and thus interfere with the mass measurements. A new system should be developed to be contained within the chamber, with no moving parts exiting the chamber. This would improve the mass data collected and help to improve the mathematical models produced from the data.

For experiments involving mass measurement a new sample tray must be designed to minimize moisture condensation during the initial warm up phase. Only by doing this can a true picture of the whole drying process be obtained at low temperatures and flow rates.

Further work on sorption models need to be conducted. Other system pressures need to be utilized to ascertain the effects of P_v on sorption modeling. This would help to confirm whether isotherm equations for air systems can be used for superheated steam systems if relative humidity is replaced by relative pressure.

Procedures for conducting a TPA are not standard from researcher to researcher. Effects of differences in test procedures like crosshead speed, probe size and shape, hold time between compressions, and number of noodles on the values of TPA properties need to be studied. As well, effects of product size differences on the values of TPA properties also need to be studied. Knowledge of these effects may allow comparison of results from researcher to researcher, or for products of non-uniform dimensions.

Breaking stress and size changes in superheated steam processed noodles may be due to a puffing phenomenon. When the noodles are first placed in the chamber the temperature of the noodle rises very quickly and this may cause the moisture in the noodle to flash to steam. This will create many pores of steam that will cause the noodles to puff out and create a less dense noodle. Internal porosity may be determined experimentally by taking images of noodle cross sections by scanning electron microscopy.

During these experiments only one protein content and one cultivar of a single wheat variety was tested. These will have an effect on the textural properties of noodles. Different protein contents and wheat varieties need to be tested to determine if an acceptable instant noodle can be obtained from other flours.

Now that optimum processing conditions of instant noodles processed in superheated steam have been found, a human sensory panel should be formed to judge the noodles and compare them to commercial products.

8 REFERENCES

AACC. 2000. Method 44-15A: Moisture-air-oven methods. In *Approved Methods of the AACC.* 10th ed. St. Paul, Minn.: American Association of Cereal Chemists.

Anonymous. 2004. On the white track: New Canadian hard white wheat getting customers' attention. *Institute Images* 12(2): 6-9.

Baik, B.K., Z. Czuchajowska and Y. Pomeranz. 1994. Role and contribution of starch and protein contents and quality to textural profile analysis of oriental noodles. *Cereal Chemistry* 71: 315-320.

Baik, B.K., Z. Czuchajowska and Y. Pomeranz. 1995. Discoloration of dough for oriental noodles. *Cereal Chemistry* 72: 198-205.

Bailey, M. 2002. Canada market development reports: Asian appeal. GAIN Report #CA2024. Washington, DC; USDA Foreign Agricultural Service.

Bainbridge, J.R. and K. Satchwell. 1947. Experiments in Fleissner drying Victorian brown coal. *Fuel* 26(2): 28-38.

Basel, L. and E. Gray. 1962. Superheated solvent drying in a fluidized bed. *Chemical Engineering Progress* 58(6): 67-70.

Blasco, R., R. Vega and P.I. Alvarez. 2001. Pneumatic drying with superheated steam: Bi-dimensional model for high solid concentration. *Drying Technology* 19(8): 2047-2061.

Bourne, M.C. 1978. Texture profile analysis. *Food Technology* 32(7): 62-66, 72.

Braund, L.M., R.G. Moreira and M.E. Castell-Perez. 2001. Mathematical modeling of impingement drying of corn tortillas. *Journal of Food Engineering* 50: 121-128.

Brooker, D.B., F.W. Bakker-Arkema, and C.W. Hall. 1974. *Drying Cereal Grains*. Westport, CT: AVI Publishing Company Inc.

Bushuk, W. and V.F. Rasper. 1994. *Wheat: Production, Properties and Quality*. Glasgow, UK: Blackie Academic & Professional.

Caixeta, A.T., R. Moreira, and M.E. Castell-Perez. 2002. Impingement drying of potato chips. *Journal of Food Process Engineering* 25: 63-90.

Cenkowski, S. and F.W. Sosulski. 1997. Physical and cooking properties of micronized lentils. *Journal of Food Process Engineering* 20: 249-264.

Chen, Z. W. Wu and P.K. Agarwal. 2000. Steam drying of coal. Part 1. Modeling the behaviour of a single particle. *Fuel* 79: 961-973.

Chou, S.K. and K.J. Chua. 2001. New hybrid drying technologies for heat sensitive foodstuffs. *Trends in Food Science & Technology* 12: 359-369.

Chu, J.C., S. Finelt, W. Hoerrner and M.-S. Lin. 1959. Drying with superheated steam-air mixtures. *Industrial and Engineering Chemistry* 51(3): 275-280.

Chu, J.C., A.M. Lane and D. Conklin. 1953. Evaporation of liquids into their superheated vapors. *Industrial and Engineering Chemistry* 45: 1586-1591.

Cooley, A.M. and I. Lavine. 1933. Development of Dakota lignite. VIII. Oil-steam atmosphere for dehydrating Dakota Lignite. *Industrial and Engineering Chemistry* 25(2): 221-224.

Crank, J. 1975. *The Mathematics of Diffusion*. Oxford: Oxford University Press.

CWB. 2007. Canadian Wheat Board 2006-2007 Variety Survey Results. http://www.cwb.ca/public/en/farmers/surveys/variety/2007/, (2007/03/03).

Dexter, J.E. and K.H. Tipples. 1987. Wheat milling at the Grain Research Laboratory: Part 2. Equipment and procedures. *Milling* 180:16, 18-20.

Dexter, J.E., R.R. Matsuo and B.C. Morgan. 1981. High temperature drying: Effect on spaghetti properties. *Journal of Food Science* 46: 1741-1746.

Elustondo, D., M.P. Elustondo and M.J. Urbicain. 2001. Mathematical modeling of moisture evaporation from foodstuffs exposed to subatmospheric pressure superheated steam. *Journal of Food Engineering* 49: 15-24.

Elustondo, D.M., A.S. Mujumdar and M.J. Urbicain. 2002. Optimum operating conditions in drying foodstuffs with superheated steam. *Drying Technology* 20: 381- 402.

Epstein, J., C.F. Morris and K.C. Huber. 2002. Instrumental texture of white salted noodles prepared from recombinant inbred lines of wheat differing in the three granule bound starch synthase (waxy) genes. *Journal of Cereal Science* 35: 51-63.

Feillet, P., J. Autran and C. Icard-Vernière. 2000. Pasta brownness: An assessment. *Journal of Cereal Science* 32: 215-233.

Friedman, H.H., J.E. Whitney, and A.S. Szczesniak. 1963. The texturometer: A new instrument for objective texture measurement. *Journal of Food Science* 28: 390-396.

Gervais, M., C. Pronyk, J. Bunn and S. Cenkowski. 2004. Design and performance of a laboratory scale superheated steam processing system. 2004 North Central ASAE/CSAE Conference. September, 2004. Winnipeg, MB.

Graybosch, R., N. Ames, P.S. Baenzinger and C.J. Peterson. 2004. Genotypic and environmental modification of Asian noodle quality of hard winter wheats. *Cereal Chemistry* 81(1): 19-25.

Gunaratne, A. and H. Cooke. 2007. Effect of hydroxypropylation and alkaline treatment in hydroxypropylation on some structural and physicochemical properties of heat-moisture treated wheat, potato and waxy maize starches. *Carbohydrate Polymers* 68: 305-313.

Hatcher, D.W. 2001. Asian noodle processing. In *Cereals Processing Technology*, ed. G. Owens, 131-157. Cambridge, England: Woodhead Publishing.

Hatcher, D.W., S.J. Symons and U. Manivannan. 2004. Developments in the use of image analysis for the assessment of oriental noodle appearance and colour. *Journal of Food Engineering* 61: 109-117.

Huang, T., C. Ho and H. Fu. 2004. Inhibition of lipid oxidation in pork bundles processing by superheated steam frying. *Journal of Agricultural and Food Chemistry* 52: 2924-2928.

Hausbrand, E. 1912. *Drying by Means of Air and Steam* (Translated from German by A.C. Wright). London, England: Scott, Greenwood & Son.

Hayashi, H. 1989. Drying technologies of foods – Their history and future. *Drying Technology* 7(2): 315-369.

Heinrich, S., M. Ihlow, M. Henneberg, M. Peglow, E. Machnow and L. Mörl. 2002. Studies of steam drying in a fluidized bed. *Drying Technology* 20(1): 175-194.

Hou, G. 2001. Oriental noodles. *Advances in Food and Nutrition Research* 43: 141-193.

Hou, G. and M. Kruk. 1998. Asian noodle technology. Volume XX, Issue 12. American Institute of Baking, Manhattan, KS. 10p.

Iglesias, H.A. and J. Chirife. 1982. *Handbook of Food Isotherms: Water Sorption Parameters for Food and Food Components*. New York, NY: Academic Press Inc.

Irvine Jr., T.F., and Liley, P.E. 1984. *Steam and Gas Tables with Computer Equations*. Orlando, FL: Academic Press Inc.

Ishikawa, A., N. Kuroda and A. Kato. 2004. In situ measurement of wood moisture content in high-temperature steam. *Journal of Wood Science* 50: 7-14.

Iyota, H., N. Nishimura, M. Yoshida and T. Nomura. 2001. Simulation of superheated steam drying considering initial steam condensation. *Drying Technology* 19(7): 1425-1440.

Janto, M., S. Pipatsattayanuwong, M.W. Kruk, G. Hou and M.R. McDaniel. 1998. Developing noodles from US wheat varieties for the Far East market: sensory perspective. *Food Quality and Preference* 9(6): 403-412.

Jayas, D.S., S. Cenkowski, S. Pabis, and W.E. Muir. 1991. Review of thin-layer drying and wetting equations. *Drying Technology* 9(4): 551-588.

Kaner, O. 1920. *Engineering* 110: 821-822. (Cited by Potter and Beeby 1994)

Kauman, W.G. 1956. Equilibrium moisture content relations and drying control in superheated steam drying. *Forest Products Journal* 6: 328-332.

Keey, R.B. 1980. Theoretical foundations of drying technology. In *Advances in Drying: Volume 1*, ed. A.S. Mujumdar, 1-22. New York, NY: Hemisphere Publishing Corporation.

Kiiskinen, H.T. and K.E. Edelmann. 2002. Superheated steam drying of paper web. *Developments in Chemical Engineering & Mineral Processing* 10(3/4): 349-365.

Kim, S.K. 1996. Instant noodles. In *Pasta and Noodle Technology*, eds. J.E. Kruger, R.B. Matsuo and J.W. Dick, 195-225. St. Paul, MN: American Association of Cereal Chemists, Inc.

Kollmann, F.F.P. 1961. High temperature drying: Research, application, and experience in Germany. *Forest Products Journal* 11: 508-515.

Kovacs, M.I.P., B.X. Fu, S.M. Woods, G. Dahlke, C. Wang, A.K. Sarkar and K. Khan. 2003. A small scale laboratory noodle sheeting machine. *Journal of Texture Studies* 33: 559-569.

Kruger, J.E., M.H. Anderson and J.E. Dexter. 1994a. Effect of flour refinement on raw Cantonese noodle color and texture. *Cereal Chemistry* 71: 177-182.

Kruger, J.E., D.W. Hatcher, and R. DePauw. 1994b. A whole seed assay for polyphenol oxidase in Canadian prairie spring wheats and its usefulness as a measure of noodle darkening. *Cereal Chemistry* 71: 324-326.

Kruger, J.E., R.B. Matsuo and J.W. Dick (eds.). 1996. *Pasta and Noodle Technology.* St. Paul, MN: American Association of Cereal Chemists, Inc.

Kruger, J.E., D.W. Hatcher, and M.J. Anderson. 1998. The effect of incorporation of rye flour on the quality of oriental noodles. *Food Research International* 31(1): 27-35.

Kudra, T. and A.S. Mujumdar. 2002. *Advanced Drying Technologies*. New York, NY: Marcel Dekker, Inc.

Lane, A.M. and S. Stern. 1956. Application of superheated-vapor atmospheres to drying. *Mechanical Engineering* 78: 423-426.

Lavine, I., A.W. Gauger and C.A. Mann. 1930. Studies in the development of Dakota lignite. III – Drying of lignite without disintegration. *Industrial and Engineering Chemistry* 22(12): 1347-1360.

Lewis, W.K. 1921. The rate of drying of solid materials. *Industrial Engineering Chemistry* 13(5): 427-438.

Li, Y.B., J. Seyed-Yagoobi, R.G. Moreira and R. Yamsaengsung. 1999. Superheated steam impingement drying of tortilla chips. *Drying Technology* 17(1&2): 191-213.

Markowski, M., S. Cenkowski, D.W. Hatcher, J.E. Dexter and N.M. Edwards. 2003. The effect of superheated steam dehydration kinetics on textural properties of Asian noodles. *Transaction of the ASAE* 46: 389-395.

Martinello, M.A., M.A. Mattea and G. Crapiste. 2003. Superheated steam drying of parsley: A fixed bed model for predicting drying performance. *Latin America Applied Research* 33: 333-337.

McMillan, D. 2002. New white wheat bred for Asian noodles. Western Producer, August 15, 2002.

Meunier, J. and R.J. Munz. 1986. Flash drying with superheated steam – A mathematical model. In *Drying' 86*, ed. A.S. Mujumdar, vol. 2: 580-587. New York, NY: Hemisphere Publishing Corporation.

Miskelly, D.M. 1993. Noodles – a new look at an old food. *Food Australia* 45: 496-500.

Miskelly, D.M. 1996. The use of alkali for noodle processing. In *Pasta and Noodle Technology*, eds. J.E. Kruger, R.B. Matsuo and J.W. Dick, 227-273. St. Paul, MN: American Association of Cereal Chemists, Inc.

Mohamed, A.A., P. Rayas-Duarte, J. Xu, D.E. Palmquist, and G.E. Inglett. 2005. Hard red winter wheat/Nutrim-OB alkaline fresh noodles: Processing and texture analysis. *Journal of Food Science* 70(1): S1-S7.

Morris, C.F., H.C. Jeffers and D.A. Engle. 2000. Effect of processing, formula and measurement variables on alkaline noodle color – Toward an optimized laboratory system. *Cereal Chemistry* 77(1): 77-85.

Nagao, S. 1996. Processing technology of noodle products in Japan. In *Pasta and Noodle Technology*, eds. J.E. Kruger, R.B. Matsuo and J.W. Dick,169-194. St. Paul, MN: American Association of Cereal Chemists, Inc.

Oh, N.H., P.A. Seib, C.W. Deyoe and A.B. Ward. 1983. Noodles I. Measuring the textural characteristics of cooked noodles. *Cereal Chemistry* 60: 433-438.

Oh, N.H., P.A. Seib, C.W. Deyoe and A.B. Ward. 1985a. Noodles II. The surface firmness of cooked noodles from soft and hard wheat flours. *Cereal Chemistry* 62: 431-436.

Oh, N.H., P.A. Seib, A.B. Ward and C.W. Deyoe. 1985b. Noodles IV. Influence of flour protein, extraction rate, particle size, and starch damage on the quality characteristics of dry noodles. *Cereal Chemistry* 62: 441-446.

Pabis, S. and S.M. Henderson. 1961. Grain drying theory: II. A critical analysis of the drying curve for shelled maize. *Journal of Agricultural Engineering Research* 6(4): 272-277.

Pabis, S., D.S. Jayas and S. Cenkowski. 1998. *Grain Drying–Theory and Practice*. New York, NY: John Wiley and Sons.

Page, G. 1949. Factors influencing the maximum rates of air drying shelled corn in thin layers. Unpublished M.Sc. thesis. Purdue University. (Cited by Jayas et al. 1991)

Pakowski, Z., A. Druzdzel and J. Drwiega. 2004. Validation of a model of an expanding superheated steam flash dryer for cut tobacco based on processing data. *Drying Technology* 22(1&2): 45-57.

Park, C.S. and B.K. Baik. 2004a. Relationship between protein characteristics and instant noodle making quality of wheat flour. *Cereal Chemistry* 81(2): 159-164.

Park, C.S. and B.-K. Baik. 2004b. Significance of amylose content of wheat starch on processing and textural properties of instant noodles. *Cereal Chemistry* 81(4): 521-526.

Potter, O.E. and C. Beeby. 1994. Scale-up of steam drying. *Drying Technology* 12(1-2): 179-215.

Prachayawarakorn, S., S. Soponronnarit, S. Wetchacama and D. Jaisut. 2002. Desorption isotherms and drying characteristics of shrimp in superheated steam and hot air. *Drying Technology* 20:669-684.

Prachayawarakorn, S., P. Prachayawasin and S. Soponronnarit. 2004. Effective diffusivity and kinetics of urease inactivation and color change during processing of soybeans with superheated-steam fluidized bed. *Drying Technology* 22(9): 2095-2118.

Pronyk, C., S. Cenkowski and W.E. Muir. 2004. Drying foodstuffs with superheated steam. *Drying Technology* 22(5): 899-916.

Pronyk, C., S. Cenkowski, W.E. Muir. 2005. Current status of superheated steam drying and processing. Proceedings of the 3rd Inter-American Drying Conference: August 21-23, 2005, Montreal Canada.

Resmini, P. and L. Pelligrino. 1994. Occurrence of protein-bound lysylpyrrolaldehyde in dried pasta. *Cereal Chemistry* 71: 254-256.

Schwartze, J.P. and S. Bröcker. 2002. A theoretical explanation for the inversion temperature. *Chemical Engineering Journal* 86:61-67.

Shibata, H. and A.S. Mujumdar. 1994. Steam drying technologies: Japanese R&D. *Drying Technology* 12:1485-1524.

Stute, R. 1992. Hydrothermal modification of starches: The difference between annealing and heat/moisture-treatment. *Starch* 44(6): 205-214.

Svensson, C. 1980. Steam drying of pulp. In *Drying'80*, ed. A.S. Mujumdar, vol. 2, 301- 307. New York, NY: Hemisphere Publishing Corporation.

Systat. 2006. *SigmaStat User's Guide*. Point Richmond, CA: Systat Software Inc.

Szczesniak, A.S. 1963. Classification of textural characteristics. *Journal of Food Science* 28: 385-389.

Szczesniak, A.S. 1995. Texture profile analysis: Methodology interpretation clarified. *Journal of Food Science* 60(6): vii.

Szczesniak, A.S. 1998. Sensory texture profiling – Historical and scientific perspectives. *Food Technology* 52(8): 54-57.

Taechapairoj, C., I. Dhuchakallaya, S. Soponronnarit, S. Wetchacama and S. Prachayawarakorn. 2003. Superheated steam fluidised bed paddy drying. *Journal of Food Engineering* 58: 67-73.

Taechapairoj, C., S. Prachayawarakorn and S. Soponronnarit. 2004. Characteristics of rice dried in superheated-steam fluidized-bed. *Drying Technology* 22(4): 719-743.

Tang, C., F. Hsieh, H. Heymann and H.E. Huff. 1999. Analyzing and correlating instrumental and sensory data: a multivariate study of physical properties of cooked wheat noodles. *Journal of Food Quality* 22: 193-211.

Tang, Z. and S. Cenkowski. 2000. Dehydration dynamics of potatoes in superheated steam and hot air. *Canadian Agricultural Engineering* 42: 33-41.

Tang, Z. and S. Cenkowski. 2001. Equilibrium moisture content of spent grains in superheated steam under atmospheric pressure. *Transactions of the ASAE* 44(5): 1261-1264.

Tang, Z., S. Cenkowski and W.E. Muir. 2000. Dehydration of sugar-beet pulp in superheated steam and hot air. *Transactions of the ASAE* 43(3): 685-689.

Tang, Z., S. Cenkowski and M. Izydorczyk. 2005. Thin-layer drying of spent grains in superheated steam. *Journal of Food Engineering* 67: 457-465.

Tatemoto, Y., Y. Mawatari, K. Sakurai, K. Noda and N. Komatsu. 2003. Drying characteristics of porous material in a fluidized bed of fluidizing particles with superheated steam. *Journal of Chemical Engineering of Japan* 36(6): 655-662.

Toledo, R.T. 2007. *Fundamentals of Food Process Engineering.* 3rd Edition, New York, NY: Springer.

Urbaniec, K. and J. Malczewski. 1997. Experimental investigations of beet pulp drying in superheated steam under pressure. *Drying Technology* 15(6-8): 2005-2013.

van Deventer, H.C. and R. M. H. Heijmans. 2001. Drying with superheated steam. *Drying Technology* 19: 2033-2045.

van Deventer, H.C. 2004. Industrial superheated steam drying. TNO-report R 2004/239. Apeldoorn, The Netherlands; TNO Environment, Energy, and Process Innovation Institute.

Veeman, M.M., J.R. Unterschultz and R.B. Kim. 2002. *Canadian Wheat Export Prospects in the Asian Noodle Market: Analyzing Japanese and Korean Milling Industries*. AARI Project #99M444. Department of Rural Economy, Edmonton, AB.

Wenzel, L. and R.R. White. 1951. Drying granular solids in superheated steam. *Industrial and Engineering Chemistry* 43: 1829-1837.

Willett, W.C. and A. Ascherio. 1994. Trans fatty acids: Are the effects only marginal? *American Journal of Public Health* 84: 722-724.

Wills, R.B.H. and M. Wootton. 1997. Sensory perceptions by Koreans of dry-salted wheat noodles. *Journal of the Science of Food and Agriculture* 74: 81-88.

Wimmerstedt, R. 1995. Steam drying – History and future. *Drying Technology* 13(5-7): 1059-1076.

Wimmerstedt, R. and J. Hager. 1996. Steam drying – Modelling and applications. *Drying Technology* 14(5): 1099-1119.

Yang, H., N. Sakai and M. Watanabe. 2001. Drying model with non-isotropic shrinkage deformation undergoing simultaneous heat and mass transfer. *Drying Technology* 19(7): 1441-1460.

Yoshida, T. and T. Hyodo. 1963. Superheated vapour as a drying agent in spinning fiber. *I&EC Process Design and Development* 2(1): 52-56.

Yoshida, T. and T. Hyodo. 1966. Superheated vapor speeds drying of foods. *Food Engineering* 38(1): 86-87.

Yun, S.H., G. Rema and K. Quail. 1997. Instrumental assessments of Japanese white salted noodle quality. *Journal of the Science of Food and Agriculture* 74: 81-88.

A - APPENDICES FOR CHAPTER 4

Table A1.1. Mixograph results for CWHW Snowbird used in experiments

Mixograph					
MDT (min)	PHG (%)	ETP (%•min)	PBW (%)	TEG (%•min)	BWE (%•min)
5.14	37.02	151.05	18.47	348.74	166.44

MDT = mixograph development time, PHG = peak height, ETP = energy to peak, PBW = peak band width, TEG = total energy, BWE = band width energy

Table A1.2. Farinograph results for CWHW Snowbird used in experiments

Farinograph			
FAB (%)	DDT (min)	STA (min)	MTI (FU)
64.4	18.9	39.4	12

FAB = Farinograph absorption (14% mc), DDT = dough development time, STA = stability, MTI = mixing tolerance index, FU = Farinograph units

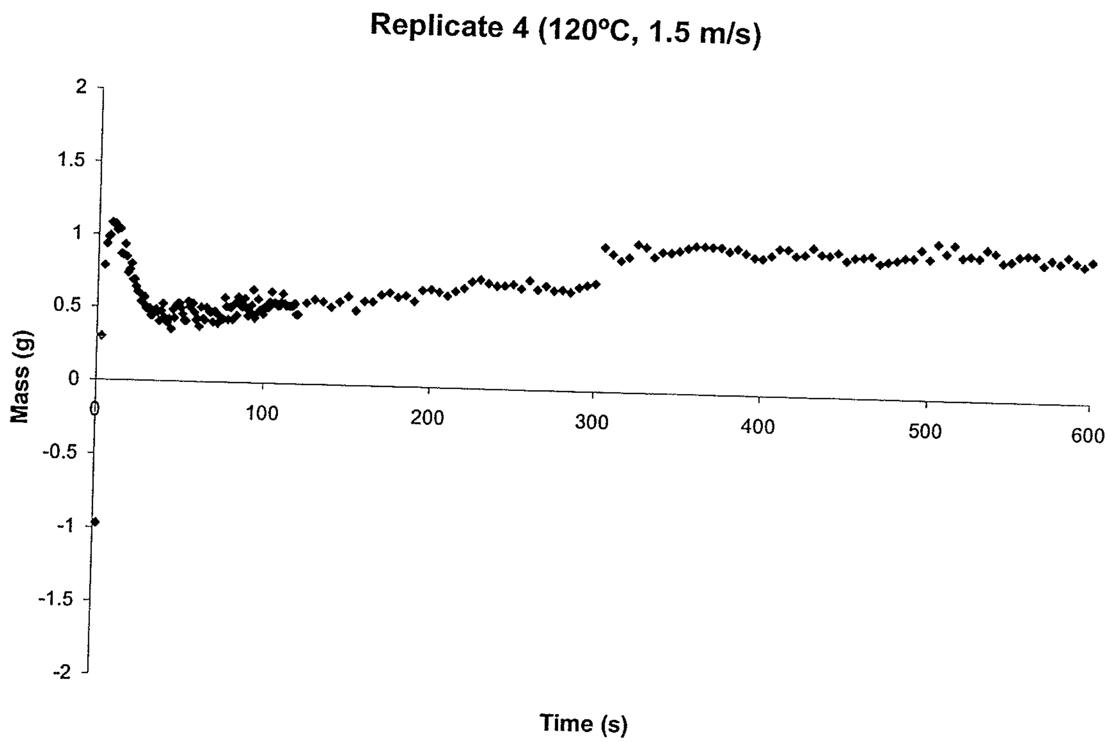


Fig. A1.1. Mass change experiment where noodle strands that were longer than 15 mm curled up resulting in a decrease in lifting force and an increased mass reading.

Table A1.3. Cooking times for superheated steam processed noodles

Temperature	Flow Rate	Processing Time (s)	Cooking Time (min)
110°C	0.5 m/s	467	7
		934	7.5
		1400	7.5
110°C	1.0 m/s	267	6.5
		533	7.5
		800	7.5
110°C	1.5 m/s	233	6.5
		466	7.5
		700	7.5
115°C	0.5 m/s	367	6.5
		733	6.5
		1100	7
115°C	1.0 m/s	233	6.5
		466	6
		700	6
115°C	1.5 m/s	133	5
		266	5
		400	6
120°C	0.5 m/s	267	5
		533	5
		800	5.5
120°C	1.0 m/s	200	4.5
		400	5
		600	5
120°C	1.5 m/s	117	4
		233	4
		350	4.5
125°C	0.5 m/s	217	4.5
		433	5
		650	5
125°C	1.0 m/s	167	4.5
		333	4.5
		500	5.5
125°C	1.5 m/s	100	4
		200	4.5
		300	5

Temperature	Flow Rate	Processing Time (s)	Cooking Time (min)
130°C	0.5 m/s	167	4
		333	4.5
		500	4.5
130°C	1.0 m/s	133	4
		266	4
		400	4.5
130°C	1.5 m/s	83	3.5
		167	3.5
		250	4
135°C	0.5 m/s	150	4.5
		300	4.5
		450	4.5
135°C	1.0 m/s	117	4.5
		233	4.5
		350	5
135°C	1.5 m/s	75	4
		150	4.5
		225	4.5
140°C	0.5 m/s	133	4.5
		266	5
		400	5
140°C	1.0 m/s	100	4.5
		200	5
		300	5
140°C	1.5 m/s	67	4
		133	4.5
		200	5
145°C	0.5 m/s	117	4.5
		233	5
		350	5.5
145°C	1.0 m/s	83	4
		167	4.5
		250	5
145°C	1.5 m/s	58	4
		117	4.5
		175	5
150°C	0.5 m/s	100	4.5
		200	5
		300	5
150°C	1.0 m/s	67	4
		133	5
		200	5
150°C	1.5 m/s	50	4
		100	5
		150	5

Table A1.4. Cooking times for control and commercial noodles

Noodle	Cooking Time (min)
Fresh Noodles	4
Fried Control	4
Air Dried Control	6
Rosan	3.5
Nong Shim	5
No Name	3
Noodle Time	3
Six Fortune	3
Farkay	3.5

Table A1.5. Comparison of colour measurement methods for noodles processed at 150°C, 1.5 m/s for 150s.

Replicate	Granular Attachment			Laying Flat		
	L*	a*	b*	L*	a*	b*
1	60.21	3.67	25.25	69.16	4.82	28.92
2	61.92	3.66	25.70	68.93	5.02	29.60
3	63.05	3.57	26.09	69.16	5.12	29.57
4	62.78	3.67	26.28	69.29	4.83	28.33
5	63.15	3.47	26.24	68.91	5.10	29.94
Avg	62.22	3.61	25.91	69.09	4.98	29.27
St Dev	1.224	0.088	0.435	0.164	0.145	0.643

B - APPENDICES FOR CHAPTER 5

Appendix B1. EMC data for noodles processed in superheated steam (Chapter 5.1.1)

Table B1. Final moisture content (EMC) of Asian noodles processed in superheated steam at various velocities and temperatures.

Temperature °C	Relative Pressure Pv/Psat	Flow Rate m/s	EMC (%db)	EMC (kg/kg db)	Average EMC (kg/kg db)
110	0.727	0.5	12.1	0.121	
		1.0	12.6	0.126	0.123
		1.5	12.1	0.121	
115	0.620	0.5	9.1	0.091	
		1.0	9.8	0.098	0.094
		1.5	9.3	0.093	
120	0.526	0.5	7.8	0.078	
		1.0	7.0	0.070	0.074
		1.5	7.4	0.074	
125	0.449	0.5	7.3	0.073	
		1.0	6.7	0.067	0.068
		1.5	6.4	0.064	
130	0.388	0.5	6.4	0.064	
		1.0	6.0	0.060	0.062
		1.5	6.2	0.062	
135	0.333	0.5	5.6	0.056	
		1.0	4.8	0.048	0.052
		1.5	5.2	0.052	
140	0.289	0.5	4.5	0.045	
		1.0	4.7	0.047	0.044
		1.5	4.1	0.041	
145	0.251	0.5	5.3	0.053	
		1.0	4.7	0.047	0.047
		1.5	4.0	0.040	
150	0.220	0.5	5.0	0.050	
		1.0	4.3	0.043	0.043
		1.5	3.5	0.035	

(db) dry basis

Appendix B2. Changes in moisture ratio with drying (Chapter 5.2.2)

Table B2.1. Change in moisture ratio of Asian noodles dried in superheated steam at 110°C and 0.5 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2	1.13	0.03	150	1.08	0.03	390	0.54	0.04	630	0.30	0.04
4	1.15	0.10	155	1.07	0.03	395	0.53	0.04	635	0.29	0.04
6	1.31	0.12	160	1.05	0.03	400	0.52	0.03	640	0.29	0.04
8	1.50	0.11	165	1.02	0.02	405	0.52	0.04	645	0.28	0.04
10	1.60	0.07	170	1.01	0.03	410	0.52	0.04	650	0.28	0.04
12	1.56	0.05	175	0.99	0.04	415	0.50	0.06	655	0.27	0.03
14	1.58	0.08	180	0.97	0.03	420	0.49	0.06	660	0.27	0.04
16	1.62	0.12	185	0.95	0.06	425	0.49	0.05	665	0.27	0.04
18	1.62	0.12	190	0.93	0.05	430	0.49	0.04	670	0.27	0.04
20	1.59	0.12	195	0.92	0.05	435	0.48	0.04	675	0.26	0.04
22	1.57	0.09	200	0.90	0.05	440	0.47	0.04	680	0.26	0.04
24	1.55	0.12	205	0.88	0.04	445	0.47	0.04	685	0.25	0.04
26	1.52	0.12	210	0.87	0.04	450	0.47	0.04	690	0.25	0.04
28	1.50	0.11	215	0.85	0.04	455	0.46	0.03	695	0.25	0.04
30	1.50	0.12	220	0.85	0.04	460	0.46	0.04	700	0.25	0.04
32	1.49	0.11	225	0.83	0.03	465	0.45	0.04	705	0.24	0.04
34	1.48	0.11	230	0.81	0.04	470	0.45	0.04	710	0.24	0.04
36	1.45	0.13	235	0.80	0.03	475	0.44	0.04	715	0.23	0.04
38	1.44	0.13	240	0.79	0.04	480	0.44	0.05	720	0.23	0.04
40	1.44	0.11	245	0.77	0.03	485	0.43	0.04	725	0.22	0.04
42	1.43	0.12	250	0.76	0.03	490	0.43	0.04	730	0.22	0.04
44	1.42	0.12	255	0.74	0.03	495	0.42	0.04	735	0.22	0.03
46	1.42	0.11	260	0.74	0.04	500	0.42	0.04	740	0.22	0.03
48	1.40	0.12	265	0.72	0.03	505	0.41	0.04	745	0.21	0.03
50	1.38	0.13	270	0.71	0.03	510	0.40	0.04	750	0.21	0.04
52	1.37	0.13	275	0.71	0.03	515	0.39	0.04	755	0.21	0.04
54	1.36	0.13	280	0.70	0.03	520	0.39	0.04	760	0.21	0.04
56	1.37	0.13	285	0.69	0.03	525	0.39	0.04	765	0.20	0.04
58	1.36	0.13	290	0.68	0.03	530	0.38	0.04	770	0.19	0.03
60	1.38	0.12	295	0.67	0.03	535	0.38	0.04	775	0.19	0.03
60	1.36	0.13	300	0.67	0.03	540	0.38	0.04	780	0.19	0.03
65	1.35	0.12	305	0.66	0.03	545	0.37	0.04	785	0.19	0.03
70	1.35	0.11	310	0.66	0.04	550	0.37	0.04	790	0.18	0.04
75	1.34	0.10	315	0.65	0.04	555	0.36	0.04	795	0.19	0.03
80	1.32	0.08	320	0.63	0.04	560	0.35	0.05	800	0.18	0.03
85	1.29	0.10	325	0.63	0.04	565	0.35	0.05	805	0.18	0.03
90	1.28	0.10	330	0.63	0.04	570	0.34	0.04	810	0.18	0.03
95	1.26	0.09	335	0.62	0.04	575	0.33	0.04	815	0.17	0.03
100	1.24	0.08	340	0.61	0.04	580	0.33	0.03	820	0.17	0.03
105	1.22	0.09	345	0.60	0.03	585	0.33	0.04	825	0.17	0.03
110	1.19	0.09	350	0.59	0.03	590	0.33	0.04	830	0.16	0.03
115	1.19	0.09	355	0.59	0.04	595	0.32	0.04	835	0.16	0.03
120	1.17	0.07	360	0.58	0.04	600	0.31	0.04	840	0.16	0.03
125	1.15	0.06	365	0.57	0.04	605	0.31	0.04	845	0.15	0.04
130	1.14	0.06	370	0.57	0.03	610	0.31	0.04	850	0.15	0.03
135	1.13	0.05	375	0.56	0.03	615	0.31	0.04	855	0.15	0.03
140	1.11	0.03	380	0.55	0.04	620	0.31	0.04	860	0.15	0.03
145	1.10	0.03	385	0.55	0.04	625	0.30	0.03	865	0.15	0.03

[(a)] MR = Moisture Ratio (average n=6)

Table B2.1 (cont'd). Change in moisture ratio of Asian noodles dried in superheated steam at 110°C and 0.5 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
870	0.14	0.03	1110	0.06	0.02	1350	0.02	0.02
875	0.14	0.03	1115	0.06	0.02	1355	0.02	0.02
880	0.14	0.03	1120	0.06	0.02	1360	0.02	0.02
885	0.13	0.03	1125	0.06	0.02	1365	0.02	0.02
890	0.13	0.03	1130	0.06	0.03	1370	0.02	0.02
895	0.12	0.03	1135	0.06	0.03	1375	0.02	0.02
900	0.12	0.02	1140	0.06	0.03	1380	0.02	0.02
905	0.13	0.03	1145	0.06	0.03	1385	0.02	0.03
910	0.13	0.03	1150	0.06	0.03	1390	0.02	0.02
915	0.13	0.03	1155	0.06	0.03	1395	0.02	0.02
920	0.12	0.03	1160	0.05	0.03	1400	0.02	0.02
925	0.12	0.03	1165	0.05	0.03	1405	0.01	0.03
930	0.12	0.03	1170	0.05	0.03	1410	0.01	0.03
935	0.11	0.03	1175	0.04	0.05	1415	0.01	0.02
940	0.11	0.03	1180	0.04	0.04	1420	0.01	0.02
945	0.11	0.03	1185	0.04	0.03	1425	0.01	0.03
950	0.11	0.03	1190	0.04	0.03	1430	0.01	0.03
955	0.10	0.02	1195	0.05	0.03	1435	0.01	0.02
960	0.10	0.02	1200	0.04	0.03	1440	0.02	0.02
965	0.10	0.03	1205	0.04	0.03	1445	0.01	0.02
970	0.10	0.03	1210	0.04	0.03	1450	0.01	0.02
975	0.10	0.03	1215	0.04	0.03	1455	0.01	0.03
980	0.10	0.03	1220	0.04	0.03	1460	0.01	0.02
985	0.09	0.03	1225	0.04	0.03	1465	0.01	0.02
990	0.09	0.03	1230	0.04	0.03	1470	0.01	0.02
995	0.10	0.02	1235	0.04	0.03	1475	0.01	0.02
1000	0.09	0.02	1240	0.03	0.03	1480	0.01	0.02
1005	0.09	0.03	1245	0.03	0.03	1485	0.01	0.02
1010	0.09	0.03	1250	0.04	0.03	1490	0.01	0.02
1015	0.09	0.03	1255	0.04	0.03	1495	0.01	0.03
1020	0.09	0.03	1260	0.03	0.03	1500	0.01	0.02
1025	0.08	0.03	1265	0.03	0.03	1505	0.01	0.03
1030	0.08	0.03	1270	0.04	0.03	1510	0.00	0.03
1035	0.08	0.03	1275	0.03	0.03	1515	0.01	0.02
1040	0.08	0.02	1280	0.03	0.03	1520	0.01	0.02
1045	0.08	0.02	1285	0.03	0.02	1525	0.01	0.03
1050	0.08	0.02	1290	0.03	0.02	1530	0.01	0.03
1055	0.07	0.02	1295	0.03	0.03	1535	0.01	0.03
1060	0.07	0.02	1300	0.03	0.03	1540	0.01	0.03
1065	0.07	0.03	1305	0.02	0.03	1545	0.01	0.03
1070	0.07	0.03	1310	0.03	0.03	1550	0.00	0.03
1075	0.07	0.03	1315	0.02	0.03	1555	0.00	0.03
1080	0.07	0.03	1320	0.03	0.03			
1085	0.07	0.03	1325	0.02	0.03			
1090	0.07	0.03	1330	0.03	0.03			
1095	0.07	0.03	1335	0.03	0.02			
1100	0.06	0.02	1340	0.02	0.02			
1105	0.06	0.02	1345	0.02	0.02			

[(a)] MR = Moisture Ratio (average n=6)

Table B2.2. Change in moisture ratio of Asian noodles dried in superheated steam at 110°C and 1.0 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2			150	0.59	0.06	390	0.26	0.05	630	0.10	0.04
4			155	0.57	0.06	395	0.25	0.06	635	0.12	0.02
6			160	0.58	0.08	400	0.25	0.04	640	0.11	0.04
8			165	0.55	0.07	405	0.25	0.05	645	0.08	0.05
10			170	0.56	0.06	410	0.24	0.03	650	0.07	0.02
12			175	0.54	0.07	415	0.24	0.05	655	0.09	0.02
14			180	0.52	0.07	420	0.24	0.06	660	0.08	0.04
16			185	0.51	0.07	425	0.25	0.04	665	0.09	0.02
18			190	0.49	0.08	430	0.24	0.03	670	0.09	0.04
20			195	0.49	0.07	435	0.23	0.03	675	0.07	0.04
22			200	0.46	0.07	440	0.21	0.02	680	0.07	0.05
24	0.88	0.06	205	0.44	0.06	445	0.22	0.01	685	0.06	0.03
26	0.89	0.06	210	0.46	0.06	450	0.19	0.04	690	0.08	0.04
28	0.91	0.05	215	0.46	0.08	455	0.21	0.03	695	0.07	0.04
30	0.91	0.06	220	0.47	0.07	460	0.21	0.05	700	0.08	0.04
32	0.91	0.07	225	0.43	0.07	465	0.19	0.04	705	0.08	0.04
34	0.94	0.04	230	0.42	0.07	470	0.18	0.04	710	0.08	0.04
36	0.92	0.05	235	0.42	0.06	475	0.18	0.05	715	0.08	0.03
38	0.91	0.07	240	0.41	0.06	480	0.17	0.04	720	0.06	0.07
40	0.93	0.04	245	0.40	0.06	485	0.18	0.05	725	0.06	0.04
42	0.92	0.04	250	0.38	0.05	490	0.17	0.04	730	0.07	0.05
44	0.92	0.03	255	0.38	0.07	495	0.18	0.06	735	0.06	0.04
46	0.92	0.03	260	0.37	0.07	500	0.16	0.06	740	0.05	0.02
48	0.91	0.05	265	0.38	0.06	505	0.16	0.04	745	0.03	0.04
50	0.91	0.04	270	0.37	0.08	510	0.16	0.04	750	0.05	0.04
52	0.91	0.04	275	0.36	0.06	515	0.17	0.04	755	0.05	0.03
54	0.92	0.04	280	0.35	0.05	520	0.16	0.04	760	0.05	0.02
56	0.89	0.02	285	0.36	0.06	525	0.17	0.06	765	0.05	0.02
58	0.89	0.03	290	0.36	0.06	530	0.16	0.04	770	0.06	0.02
60	0.88	0.03	295	0.32	0.04	535	0.14	0.04	775	0.05	0.02
60	0.88	0.04	300	0.33	0.06	540	0.15	0.04	780	0.05	0.02
65	0.85	0.03	305	0.33	0.05	545	0.13	0.05	785	0.06	0.03
70	0.83	0.02	310	0.34	0.05	550	0.14	0.03	790	0.04	0.05
75	0.82	0.05	315	0.32	0.03	555	0.13	0.03	795	0.07	0.03
80	0.81	0.03	320	0.31	0.05	560	0.11	0.03	800	0.05	0.05
85	0.81	0.03	325	0.32	0.04	565	0.12	0.05	805	0.04	0.03
90	0.77	0.05	330	0.30	0.04	570	0.11	0.02	810	0.06	0.05
95	0.77	0.03	335	0.30	0.05	575	0.13	0.01	815	0.06	0.03
100	0.74	0.04	340	0.31	0.03	580	0.12	0.02	820	0.05	0.05
105	0.71	0.05	345	0.30	0.05	585	0.12	0.03	825	0.06	0.05
110	0.70	0.06	350	0.26	0.04	590	0.12	0.02	830	0.06	0.05
115	0.68	0.04	355	0.27	0.05	595	0.15	0.03	835	0.07	0.06
120	0.67	0.06	360	0.28	0.03	600	0.13	0.04	840	0.06	0.05
125	0.66	0.05	365	0.27	0.04	605	0.14	0.04	845	0.05	0.04
130	0.65	0.06	370	0.27	0.03	610	0.13	0.05	850	0.05	0.04
135	0.63	0.05	375	0.26	0.03	615	0.12	0.05	855	0.05	0.03
140	0.62	0.05	380	0.28	0.05	620	0.12	0.03	860	0.07	0.03
145	0.60	0.05	385	0.28	0.07	625	0.12	0.05	865	0.05	0.03

[a] MR = Moisture Ratio (average, n=6)

Table B2.3. Change in moisture ratio of Asian noodles dried in superheated steam at 110°C and 1.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.40	0.25	150	0.44	0.09	390	0.15	0.06	630	0.04	0.06
4	1.10	0.13	155	0.42	0.08	395	0.12	0.09	635	0.06	0.07
6	1.13	0.11	160	0.37	0.15	400	0.13	0.09	640	0.06	0.05
8	1.07	0.15	165	0.42	0.10	405	0.12	0.07	645	0.07	0.07
10	1.03	0.16	170	0.41	0.17	410	0.13	0.05	650	0.06	0.08
12	0.93	0.17	175	0.39	0.08	415	0.13	0.05	655	0.05	0.04
14	0.93	0.16	180	0.39	0.08	420	0.10	0.09	660	0.06	0.04
16	0.90	0.21	185	0.38	0.07	425	0.13	0.05	665	0.05	0.05
18	0.88	0.21	190	0.35	0.12	430	0.11	0.06	670	0.04	0.05
20	0.89	0.20	195	0.36	0.07	435	0.10	0.09	675	0.05	0.05
22	0.88	0.22	200	0.36	0.07	440	0.10	0.10	680	0.06	0.04
24	0.88	0.22	205	0.33	0.09	445	0.11	0.07	685	0.06	0.05
26	0.89	0.22	210	0.31	0.11	450	0.13	0.06	690	0.05	0.06
28	0.90	0.23	215	0.32	0.14	455	0.10	0.08	695	0.03	0.07
30	0.87	0.23	220	0.32	0.07	460	0.13	0.06	700	0.04	0.04
32	0.87	0.23	225	0.29	0.11	465	0.11	0.10	705	0.04	0.06
34	0.81	0.23	230	0.28	0.10	470	0.11	0.09	710	0.05	0.05
36	0.82	0.23	235	0.28	0.07	475	0.11	0.09	715	0.04	0.08
38	0.79	0.25	240	0.31	0.09	480	0.11	0.06	720	0.06	0.04
40	0.76	0.19	245	0.25	0.08	485	0.09	0.10	725	0.03	0.08
42	0.72	0.21	250	0.26	0.07	490	0.10	0.09	730	0.03	0.07
44	0.73	0.18	255	0.28	0.08	495	0.08	0.07	735	0.03	0.08
46	0.70	0.17	260	0.25	0.08	500	0.09	0.05	740	0.01	0.08
48	0.67	0.16	265	0.26	0.09	505	0.09	0.07	745	0.01	0.06
50	0.66	0.16	270	0.23	0.09	510	0.09	0.06	750	0.03	0.03
52	0.64	0.16	275	0.29	0.07	515	0.09	0.06	755	0.03	0.06
54	0.65	0.17	280	0.27	0.07	520	0.09	0.07	760	0.02	0.07
56	0.65	0.15	285	0.24	0.08	525	0.09	0.08	765	0.01	0.06
58	0.66	0.16	290	0.24	0.07	530	0.07	0.07	770	0.03	0.07
60	0.65	0.14	295	0.23	0.07	535	0.07	0.07			
60	0.65	0.14	300	0.21	0.08	540	0.08	0.05			
65	0.65	0.16	305	0.23	0.08	545	0.07	0.05			
70	0.68	0.19	310	0.21	0.09	550	0.08	0.06			
75	0.68	0.18	315	0.20	0.07	555	0.07	0.06			
80	0.65	0.17	320	0.19	0.09	560	0.08	0.05			
85	0.65	0.11	325	0.19	0.06	565	0.06	0.08			
90	0.59	0.18	330	0.19	0.06	570	0.08	0.07			
95	0.59	0.20	335	0.17	0.06	575	0.05	0.05			
100	0.52	0.22	340	0.21	0.04	580	0.06	0.05			
105	0.50	0.22	345	0.18	0.08	585	0.07	0.06			
110	0.50	0.22	350	0.17	0.08	590	0.07	0.06			
115	0.51	0.22	355	0.17	0.07	595	0.04	0.07			
120	0.49	0.22	360	0.17	0.07	600	0.05	0.08			
125	0.48	0.22	365	0.17	0.07	605	0.05	0.10			
130	0.43	0.20	370	0.15	0.08	610	0.05	0.09			
135	0.40	0.20	375	0.13	0.07	615	0.04	0.08			
140	0.41	0.20	380	0.17	0.09	620	0.06	0.10			
145	0.42	0.16	385	0.14	0.09	625	0.04	0.08			

[a] MR = Moisture Ratio (average, n=6)

Table B2.4. Change in moisture ratio of Asian noodles dried in superheated steam at 115°C and 0.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.09	0.03	255	0.52	0.04	600	0.13	0.02	945	0.02	0.01
4	1.30	0.04	260	0.51	0.04	605	0.13	0.02	950	0.02	0.02
6	1.38	0.05	265	0.51	0.04	610	0.13	0.02	955	0.02	0.01
8	1.39	0.07	270	0.49	0.04	615	0.12	0.02	960	0.01	0.03
10	1.37	0.07	275	0.49	0.04	620	0.12	0.02	965	0.01	0.02
12	1.37	0.06	280	0.48	0.04	625	0.12	0.02	970	0.01	0.02
14	1.36	0.06	285	0.47	0.04	630	0.11	0.02	975	0.01	0.02
16	1.36	0.06	290	0.46	0.04	635	0.11	0.02	980	0.01	0.02
18	1.36	0.06	295	0.46	0.04	640	0.11	0.02	985	0.01	0.02
20	1.35	0.06	300	0.44	0.04	645	0.11	0.02	990	0.01	0.02
22	1.34	0.06	305	0.44	0.04	650	0.10	0.02	995	0.01	0.02
24	1.33	0.05	310	0.43	0.04	655	0.10	0.02	1000	0.01	0.02
26	1.32	0.05	315	0.42	0.03	660	0.10	0.02	1005	0.01	0.02
28	1.31	0.05	320	0.41	0.03	665	0.10	0.02	1010	0.01	0.02
30	1.30	0.05	325	0.40	0.03	670	0.09	0.02	1015	0.01	0.02
32	1.28	0.05	330	0.40	0.03	675	0.09	0.02	1020	0.01	0.02
34	1.28	0.05	335	0.39	0.03	680	0.09	0.02	1025	0.01	0.02
36	1.27	0.05	340	0.38	0.04	685	0.09	0.02	1030	0.01	0.02
38	1.26	0.04	345	0.38	0.03	690	0.09	0.02	1035	0.01	0.02
40	1.25	0.05	350	0.37	0.03	695	0.08	0.01	1040	0.00	0.02
42	1.22	0.02	355	0.36	0.03	700	0.08	0.01	1045	0.01	0.02
44	1.19	0.02	360	0.36	0.03	705	0.08	0.01	1050	0.01	0.02
46	1.18	0.02	365	0.35	0.03	710	0.07	0.02	1055	0.00	0.03
48	1.17	0.03	370	0.35	0.03	715	0.07	0.02	1060	0.00	0.02
50	1.16	0.02	375	0.34	0.03	720	0.07	0.02	1065	0.00	0.02
52	1.15	0.03	380	0.33	0.03	725	0.07	0.02	1070	0.00	0.02
54	1.14	0.03	385	0.33	0.03	730	0.07	0.02	1075	0.00	0.02
56	1.14	0.03	390	0.32	0.03	735	0.06	0.01	1080	0.00	0.02
58	1.14	0.02	395	0.32	0.03	740	0.06	0.02	1085	0.00	0.02
60	1.13	0.01	400	0.31	0.03	745	0.06	0.02	1090	0.00	0.02
60	1.12	0.02	405	0.31	0.03	750	0.06	0.02	1095	0.00	0.02
65	1.10	0.02	410	0.30	0.03	755	0.06	0.02	1100	0.00	0.02
70	1.09	0.04	415	0.29	0.03	760	0.06	0.02	1105	0.00	0.02
75	1.07	0.02	420	0.29	0.03	765	0.05	0.02			
80	1.07	0.04	425	0.28	0.03	770	0.05	0.02			
85	1.04	0.05	430	0.28	0.03	775	0.05	0.02			
90	1.02	0.05	435	0.27	0.03	780	0.05	0.02			
95	0.99	0.05	440	0.26	0.03	785	0.05	0.02			
100	0.97	0.05	445	0.26	0.03	790	0.05	0.02			
105	0.95	0.05	450	0.26	0.02	795	0.05	0.02			
110	0.93	0.06	455	0.25	0.03	800	0.04	0.02			
115	0.91	0.06	460	0.25	0.02	805	0.04	0.02			
120	0.89	0.06	465	0.24	0.02	810	0.04	0.02			
125	0.86	0.06	470	0.24	0.03	815	0.04	0.02			
130	0.85	0.06	475	0.23	0.02	820	0.04	0.02			
135	0.83	0.06	480	0.23	0.03	825	0.04	0.02			
140	0.81	0.06	485	0.22	0.02	830	0.04	0.02			
145	0.79	0.06	490	0.22	0.02	835	0.03	0.02			
150	0.77	0.06	495	0.21	0.02	840	0.03	0.01			
155	0.75	0.06	500	0.21	0.02	845	0.03	0.01			
160	0.74	0.06	505	0.20	0.02	850	0.03	0.02			
165	0.72	0.06	510	0.20	0.02	855	0.03	0.02			
170	0.70	0.06	515	0.20	0.02	860	0.02	0.03			
175	0.70	0.05	520	0.19	0.02	865	0.02	0.02			
180	0.68	0.05	525	0.19	0.02	870	0.03	0.02			
185	0.66	0.06	530	0.18	0.02	875	0.03	0.02			
190	0.65	0.05	535	0.18	0.02	880	0.03	0.02			
195	0.64	0.05	540	0.18	0.02	885	0.02	0.02			
200	0.63	0.05	545	0.17	0.02	890	0.02	0.02			
205	0.62	0.05	550	0.17	0.02	895	0.02	0.02			
210	0.61	0.05	555	0.16	0.02	900	0.02	0.02			
215	0.60	0.05	560	0.16	0.02	905	0.02	0.02			
220	0.59	0.04	565	0.16	0.02	910	0.02	0.02			
225	0.58	0.04	570	0.16	0.02	915	0.02	0.02			
230	0.57	0.04	575	0.15	0.02	920	0.02	0.02			
235	0.56	0.04	580	0.15	0.02	925	0.02	0.01			
240	0.55	0.04	585	0.14	0.02	930	0.02	0.02			
245	0.54	0.04	590	0.14	0.02	935	0.02	0.02			
250	0.53	0.04	595	0.14	0.02	940	0.02	0.02			

[a] MR = Moisture Ratio (average, n=6)

Table B2.5. Change in moisture ratio of Asian noodles dried in superheated steam at 115°C and 1.0 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.27	0.08	150	0.47	0.03	390	0.15	0.02	630	0.05	0.02
4	1.22	0.04	155	0.45	0.03	395	0.15	0.02	635	0.06	0.02
6	1.18	0.08	160	0.44	0.03	400	0.14	0.03	640	0.06	0.02
8	1.09	0.06	165	0.44	0.04	405	0.14	0.02	645	0.06	0.03
10	1.09	0.07	170	0.42	0.04	410	0.14	0.03	650	0.05	0.02
12	1.08	0.07	175	0.41	0.03	415	0.14	0.03	655	0.05	0.02
14	1.08	0.06	180	0.41	0.03	420	0.14	0.02	660	0.05	0.02
16	1.06	0.08	185	0.40	0.03	425	0.13	0.02	665	0.05	0.03
18	1.05	0.04	190	0.39	0.03	430	0.13	0.02	670	0.05	0.02
20	1.04	0.06	195	0.38	0.03	435	0.13	0.02	675	0.05	0.02
22	1.02	0.05	200	0.36	0.02	440	0.13	0.02	680	0.05	0.03
24	1.00	0.05	205	0.36	0.03	445	0.12	0.02	685	0.05	0.02
26	0.98	0.05	210	0.35	0.03	450	0.12	0.02	690	0.05	0.02
28	0.97	0.05	215	0.34	0.02	455	0.12	0.02	695	0.04	0.02
30	0.95	0.07	220	0.33	0.03	460	0.12	0.03	700	0.04	0.03
32	0.94	0.08	225	0.33	0.03	465	0.11	0.03	705	0.04	0.03
34	0.91	0.05	230	0.32	0.03	470	0.11	0.03	710	0.04	0.03
36	0.91	0.05	235	0.31	0.04	475	0.11	0.03	715	0.05	0.02
38	0.91	0.05	240	0.30	0.04	480	0.11	0.03	720	0.04	0.03
40	0.90	0.05	245	0.30	0.04	485	0.11	0.03	725	0.04	0.03
42	0.90	0.04	250	0.29	0.03	490	0.10	0.03	730	0.04	0.03
44	0.90	0.06	255	0.29	0.04	495	0.11	0.03	735	0.04	0.03
46	0.89	0.05	260	0.27	0.04	500	0.10	0.03	740	0.04	0.03
48	0.87	0.04	265	0.27	0.03	505	0.10	0.03	745	0.04	0.03
50	0.86	0.05	270	0.27	0.03	510	0.10	0.02	750	0.03	0.03
52	0.85	0.05	275	0.26	0.03	515	0.10	0.02	755	0.03	0.03
54	0.84	0.06	280	0.25	0.03	520	0.10	0.02	760	0.03	0.03
56	0.83	0.05	285	0.25	0.02	525	0.09	0.01	765	0.03	0.03
58	0.82	0.04	290	0.24	0.02	530	0.09	0.02	770	0.04	0.03
60	0.82	0.05	295	0.23	0.02	535	0.09	0.01	775	0.04	0.03
60	0.81	0.06	300	0.23	0.02	540	0.08	0.02	780	0.03	0.03
65	0.79	0.05	305	0.22	0.02	545	0.08	0.02	785	0.03	0.03
70	0.76	0.04	310	0.20	0.04	550	0.08	0.02			
75	0.73	0.05	315	0.21	0.03	555	0.08	0.02			
80	0.70	0.04	320	0.21	0.03	560	0.08	0.02			
85	0.68	0.04	325	0.20	0.03	565	0.08	0.03			
90	0.65	0.05	330	0.18	0.05	570	0.07	0.03			
95	0.65	0.04	335	0.18	0.04	575	0.08	0.02			
100	0.62	0.03	340	0.19	0.03	580	0.07	0.02			
105	0.60	0.04	345	0.18	0.03	585	0.07	0.02			
110	0.58	0.03	350	0.18	0.03	590	0.07	0.02			
115	0.57	0.04	355	0.16	0.04	595	0.07	0.02			
120	0.55	0.04	360	0.17	0.03	600	0.06	0.02			
125	0.53	0.04	365	0.17	0.03	605	0.06	0.02			
130	0.52	0.03	370	0.15	0.02	610	0.06	0.03			
135	0.51	0.03	375	0.16	0.02	615	0.06	0.02			
140	0.48	0.03	380	0.15	0.02	620	0.06	0.02			
145	0.48	0.03	385	0.16	0.02	625	0.06	0.03			

[a] MR = Moisture Ratio (average, n=6)

Table B2.6. Change in moisture ratio of Asian noodles dried in superheated steam at 115°C and 1.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.23	0.42	150	0.27	0.09	390	0.03	0.07
4	0.86	0.20	155	0.25	0.09	395	0.04	0.08
6	0.89	0.08	160	0.24	0.09	400	0.05	0.06
8	0.94	0.15	165	0.25	0.09	405	0.04	0.06
10	0.88	0.05	170	0.23	0.09	410	0.02	0.07
12	0.87	0.13	175	0.21	0.11	415	0.04	0.08
14	0.86	0.13	180	0.20	0.09	420	0.02	0.07
16	0.89	0.14	185	0.22	0.09	425	0.04	0.06
18	0.85	0.15	190	0.21	0.09	430	0.02	0.07
20	0.80	0.16	195	0.21	0.08	435	0.02	0.07
22	0.78	0.16	200	0.18	0.08	440	0.03	0.07
24	0.76	0.15	205	0.17	0.08	445	0.03	0.06
26	0.76	0.15	210	0.18	0.08	450	0.02	0.07
28	0.70	0.07	215	0.16	0.08	455	0.02	0.08
30	0.77	0.19	220	0.14	0.09	460	0.02	0.06
32	0.74	0.14	225	0.15	0.08	465	0.02	0.06
34	0.74	0.15	230	0.14	0.08	470	0.01	0.06
36	0.74	0.15	235	0.15	0.08	475	0.02	0.07
38	0.73	0.17	240	0.12	0.09	480	0.02	0.06
40	0.72	0.17	245	0.13	0.08	485	0.01	0.06
42	0.70	0.17	250	0.12	0.08	490	0.01	0.06
44	0.68	0.16	255	0.12	0.08	495	0.01	0.07
46	0.68	0.16	260	0.10	0.08	500	0.01	0.07
48	0.67	0.18	265	0.12	0.09	505	0.00	0.06
50	0.68	0.17	270	0.12	0.09	510	0.00	0.06
52	0.65	0.17	275	0.09	0.07	515	0.02	0.07
54	0.62	0.18	280	0.10	0.07	520	0.01	0.07
56	0.60	0.19	285	0.09	0.08	525	0.01	0.06
58	0.61	0.14	290	0.08	0.08	530	0.02	0.07
60	0.53	0.15	295	0.09	0.07	535	0.03	0.07
60	0.52	0.15	300	0.10	0.08	540	0.03	0.07
65	0.52	0.15	305	0.07	0.06	545	0.00	0.06
70	0.53	0.11	310	0.07	0.08	550	0.00	0.06
75	0.52	0.11	315	0.08	0.07	555	0.01	0.06
80	0.49	0.10	320	0.08	0.07			
85	0.47	0.10	325	0.09	0.06			
90	0.44	0.11	330	0.07	0.07			
95	0.43	0.11	335	0.05	0.07			
100	0.42	0.11	340	0.05	0.07			
105	0.37	0.11	345	0.06	0.07			
110	0.34	0.10	350	0.05	0.07			
115	0.37	0.10	355	0.05	0.06			
120	0.33	0.10	360	0.06	0.07			
125	0.32	0.11	365	0.05	0.06			
130	0.30	0.09	370	0.05	0.07			
135	0.29	0.11	375	0.06	0.05			
140	0.27	0.11	380	0.03	0.07			
145	0.27	0.09	385	0.03	0.07			

[a] MR = Moisture Ratio (average, n=6)

Table B2.7. Change in moisture ratio of Asian noodles dried in superheated steam at 120°C and 0.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.08	0.03	150	0.64	0.03	390	0.16	0.02	630	0.03	0.02
4	1.28	0.03	155	0.62	0.03	395	0.16	0.02	635	0.03	0.02
6	1.34	0.03	160	0.61	0.03	400	0.15	0.02	640	0.03	0.02
8	1.34	0.04	165	0.59	0.03	405	0.15	0.02	645	0.03	0.02
10	1.34	0.06	170	0.58	0.03	410	0.14	0.02	650	0.03	0.02
12	1.34	0.04	175	0.57	0.03	415	0.14	0.02	655	0.03	0.02
14	1.35	0.03	180	0.55	0.03	420	0.14	0.02	660	0.03	0.02
16	1.34	0.03	185	0.54	0.03	425	0.13	0.02	665	0.03	0.02
18	1.34	0.03	190	0.53	0.03	430	0.13	0.02	670	0.02	0.02
20	1.33	0.04	195	0.52	0.03	435	0.12	0.02	675	0.02	0.02
22	1.32	0.03	200	0.50	0.03	440	0.12	0.02	680	0.02	0.02
24	1.31	0.04	205	0.49	0.04	445	0.12	0.02	685	0.02	0.02
26	1.30	0.04	210	0.47	0.03	450	0.11	0.02	690	0.02	0.02
28	1.28	0.05	215	0.46	0.03	455	0.11	0.02	695	0.02	0.02
30	1.27	0.04	220	0.45	0.03	460	0.11	0.02	700	0.02	0.02
32	1.26	0.05	225	0.44	0.03	465	0.10	0.02	705	0.02	0.02
34	1.25	0.05	230	0.43	0.03	470	0.10	0.02	710	0.02	0.02
36	1.23	0.04	235	0.41	0.03	475	0.10	0.02	715	0.02	0.02
38	1.22	0.04	240	0.41	0.03	480	0.09	0.02	720	0.02	0.02
40	1.20	0.05	245	0.39	0.04	485	0.09	0.02	725	0.02	0.02
42	1.19	0.05	250	0.38	0.03	490	0.09	0.02	730	0.02	0.02
44	1.17	0.06	255	0.37	0.03	495	0.08	0.02	735	0.02	0.02
46	1.16	0.05	260	0.36	0.03	500	0.08	0.02	740	0.02	0.02
48	1.15	0.05	265	0.35	0.03	505	0.07	0.02	745	0.01	0.02
50	1.13	0.05	270	0.34	0.03	510	0.08	0.02	750	0.02	0.02
52	1.12	0.06	275	0.33	0.03	515	0.07	0.02	755	0.01	0.02
54	1.10	0.06	280	0.32	0.03	520	0.07	0.02	760	0.01	0.02
56	1.08	0.05	285	0.31	0.03	525	0.07	0.02	765	0.01	0.02
58	1.07	0.06	290	0.30	0.03	530	0.07	0.02	770	0.01	0.02
60	1.06	0.05	295	0.29	0.03	535	0.06	0.02	775	0.01	0.02
60	1.05	0.06	300	0.29	0.03	540	0.06	0.02	780	0.01	0.02
65	1.03	0.06	305	0.28	0.03	545	0.06	0.02	785	0.01	0.02
70	1.00	0.05	310	0.27	0.03	550	0.06	0.02	790	0.01	0.02
75	0.97	0.06	315	0.26	0.03	555	0.06	0.02	795	0.01	0.02
80	0.93	0.05	320	0.25	0.03	560	0.05	0.02	800	0.01	0.02
85	0.90	0.05	325	0.25	0.03	565	0.05	0.02	805	0.01	0.02
90	0.88	0.04	330	0.24	0.03	570	0.05	0.02	810	0.01	0.02
95	0.85	0.05	335	0.23	0.03	575	0.05	0.02	815	0.01	0.02
100	0.82	0.05	340	0.22	0.03	580	0.05	0.02	820	0.01	0.02
105	0.80	0.04	345	0.22	0.03	585	0.04	0.02	825	0.01	0.02
110	0.78	0.04	350	0.21	0.03	590	0.04	0.03	830	0.01	0.02
115	0.76	0.03	355	0.20	0.03	595	0.04	0.02	835	0.01	0.02
120	0.74	0.03	360	0.19	0.02	600	0.04	0.02	840	0.01	0.02
125	0.71	0.03	365	0.19	0.02	605	0.04	0.02	845	0.01	0.02
130	0.70	0.03	370	0.18	0.02	610	0.04	0.02	850	0.01	0.02
135	0.69	0.03	375	0.18	0.02	615	0.04	0.02	855	0.01	0.02
140	0.67	0.03	380	0.17	0.02	620	0.03	0.02	860	0.01	0.02
145	0.65	0.03	385	0.17	0.02	625	0.03	0.02	865	0.01	0.02

[a] MR = Moisture Ratio (average, n=6)

Table B2.8. Change in moisture ratio of Asian noodles dried in superheated steam at 120°C and 1.0 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2			150	0.35	0.09	390	0.07	0.08
4			155	0.35	0.09	395	0.08	0.08
6			160	0.34	0.08	400	0.08	0.07
8			165	0.32	0.09	405	0.07	0.07
10			170	0.32	0.09	410	0.06	0.07
12			175	0.32	0.09	415	0.05	0.06
14			180	0.31	0.08	420	0.04	0.06
16			185	0.30	0.09	425	0.04	0.06
18			190	0.30	0.08	430	0.04	0.07
20			195	0.28	0.09	435	0.04	0.07
22	0.82	0.11	200	0.26	0.10	440	0.04	0.07
24	0.81	0.11	205	0.27	0.10	445	0.04	0.07
26	0.81	0.11	210	0.26	0.08	450	0.03	0.08
28	0.80	0.11	215	0.25	0.09	455	0.03	0.07
30	0.80	0.10	220	0.25	0.08	460	0.04	0.07
32	0.77	0.12	225	0.24	0.09	465	0.03	0.06
34	0.75	0.13	230	0.24	0.08	470	0.02	0.07
36	0.74	0.12	235	0.20	0.08	475	0.01	0.08
38	0.73	0.12	240	0.20	0.08	480	0.00	0.06
40	0.72	0.11	245	0.21	0.08	485	0.01	0.06
42	0.71	0.10	250	0.19	0.08	490	0.01	0.08
44	0.69	0.11	255	0.19	0.09	495	0.02	0.07
46	0.69	0.10	260	0.19	0.08	500	0.02	0.07
48	0.68	0.10	265	0.18	0.09	505	0.02	0.07
50	0.67	0.10	270	0.18	0.09	510	0.01	0.08
52	0.66	0.10	275	0.18	0.09	515	0.02	0.07
54	0.65	0.09	280	0.18	0.08	520	0.02	0.06
56	0.63	0.09	285	0.16	0.07	525	0.01	0.06
58	0.63	0.09	290	0.16	0.07	530	0.01	0.07
60	0.62	0.09	295	0.15	0.07	535	0.02	0.07
60	0.60	0.09	300	0.15	0.07	540	0.01	0.06
65	0.58	0.08	305	0.14	0.06	545	0.01	0.07
70	0.56	0.09	310	0.14	0.07	550	0.00	0.07
75	0.55	0.10	315	0.13	0.07	555	0.01	0.06
80	0.54	0.10	320	0.12	0.07	560	0.01	0.05
85	0.52	0.10	325	0.13	0.07	565	0.02	0.05
90	0.50	0.09	330	0.11	0.07	570	0.01	0.06
95	0.48	0.10	335	0.11	0.08	575	0.01	0.07
100	0.47	0.10	340	0.11	0.07	580	0.01	0.07
105	0.45	0.10	345	0.10	0.08	585	0.00	0.07
110	0.44	0.10	350	0.10	0.09	590	0.00	0.07
115	0.44	0.10	355	0.09	0.08	595	0.00	0.06
120	0.43	0.10	360	0.11	0.09	600	-0.01	0.07
125	0.42	0.10	365	0.09	0.07	605	0.00	0.06
130	0.40	0.09	370	0.09	0.08	610	-0.02	0.09
135	0.39	0.07	375	0.08	0.09	615	-0.01	0.07
140	0.38	0.08	380	0.07	0.09	620	0.03	0.06
145	0.37	0.08	385	0.07	0.08			

[(a)] MR = Moisture Ratio (average, n=6)

Table B2.9. Change in moisture ratio of Asian noodles dried in superheated steam at 120°C and 1.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.27	0.28	52	0.55	0.15	160	0.19	0.11	285	0.08	0.11	410	0.06	0.11
4	0.89	0.14	54	0.52	0.16	165	0.19	0.12	290	0.06	0.13	415	0.05	0.11
6	0.93	0.15	56	0.51	0.14	170	0.18	0.12	295	0.07	0.11	420	0.04	0.13
8	0.89	0.13	58	0.51	0.13	175	0.17	0.11	300	0.06	0.11	425	0.04	0.13
10	0.85	0.14	60	0.47	0.11	180	0.15	0.12	305	0.06	0.10	430	0.04	0.13
12	0.81	0.12	60	0.46	0.11	185	0.15	0.12	310	0.07	0.13	435	0.04	0.12
14	0.75	0.15	65	0.48	0.12	190	0.15	0.11	315	0.07	0.10	440	0.04	0.11
16	0.72	0.17	70	0.43	0.14	195	0.15	0.11	320	0.06	0.12	445	0.04	0.11
18	0.71	0.15	75	0.44	0.14	200	0.14	0.13	325	0.05	0.12	450	0.03	0.11
20	0.67	0.13	80	0.36	0.16	205	0.14	0.14	330	0.05	0.11	455	0.03	0.10
22	0.68	0.10	85	0.34	0.15	210	0.13	0.11	335	0.05	0.11	460	0.04	0.10
24	0.65	0.11	90	0.37	0.14	215	0.12	0.12	340	0.04	0.11	465	0.03	0.14
26	0.64	0.14	95	0.34	0.14	220	0.11	0.13	345	0.04	0.12	470	0.02	0.11
28	0.69	0.13	100	0.33	0.12	225	0.10	0.14	350	0.04	0.10	475	0.01	0.10
30	0.66	0.14	105	0.32	0.15	230	0.10	0.13	355	0.02	0.11	480	0.00	0.08
32	0.64	0.15	110	0.29	0.13	235	0.11	0.12	360	0.02	0.11	485	0.01	0.09
34	0.65	0.17	115	0.29	0.14	240	0.10	0.11	365	0.04	0.10	490	0.01	0.09
36	0.62	0.14	120	0.28	0.11	245	0.09	0.13	370	0.03	0.10			
38	0.60	0.14	125	0.25	0.13	250	0.09	0.14	375	0.03	0.13			
40	0.59	0.13	130	0.26	0.10	255	0.08	0.13	380	0.04	0.12			
42	0.61	0.12	135	0.23	0.13	260	0.10	0.12	385	0.02	0.10			
44	0.58	0.15	140	0.23	0.13	265	0.08	0.14	390	0.04	0.12			
46	0.58	0.15	145	0.21	0.12	270	0.06	0.12	395	0.04	0.10			
48	0.55	0.15	150	0.22	0.11	275	0.07	0.11	400	0.03	0.12			
50	0.53	0.15	155	0.19	0.10	280	0.07	0.11	405	0.02	0.11			

[a] MR = Moisture Ratio (average, n=6)

Table B2.10. Change in moisture ratio of Asian noodles dried in superheated steam at 125°C and 0.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.02	0.04	150	0.52	0.03	390	0.12	0.01	630	0.03	0.02
4	1.12	0.04	155	0.51	0.03	395	0.12	0.01	635	0.03	0.02
6	1.15	0.04	160	0.49	0.03	400	0.11	0.01	640	0.03	0.02
8	1.16	0.03	165	0.48	0.03	405	0.11	0.01	645	0.03	0.01
10	1.11	0.09	170	0.47	0.03	410	0.11	0.01	650	0.03	0.02
12	1.10	0.08	175	0.46	0.02	415	0.10	0.01	655	0.03	0.02
14	1.11	0.07	180	0.44	0.02	420	0.10	0.01	660	0.03	0.02
16	1.11	0.03	185	0.43	0.03	425	0.10	0.01	665	0.03	0.02
18	1.10	0.03	190	0.42	0.03	430	0.09	0.01	670	0.02	0.02
20	1.10	0.03	195	0.41	0.03	435	0.09	0.01	675	0.02	0.02
22	1.09	0.04	200	0.39	0.03	440	0.08	0.02	680	0.02	0.02
24	1.07	0.02	205	0.38	0.02	445	0.08	0.01	685	0.02	0.02
26	1.06	0.02	210	0.37	0.02	450	0.08	0.01	690	0.02	0.02
28	1.05	0.02	215	0.36	0.03	455	0.08	0.01	695	0.02	0.02
30	1.04	0.01	220	0.35	0.02	460	0.08	0.01	700	0.02	0.02
32	1.03	0.02	225	0.34	0.02	465	0.08	0.01	705	0.03	0.02
34	1.01	0.02	230	0.33	0.03	470	0.07	0.01			
36	1.00	0.01	235	0.32	0.03	475	0.07	0.01			
38	0.98	0.01	240	0.31	0.03	480	0.07	0.01			
40	0.97	0.02	245	0.30	0.02	485	0.07	0.01			
42	0.96	0.02	250	0.30	0.02	490	0.07	0.01			
44	0.95	0.02	255	0.29	0.02	495	0.06	0.01			
46	0.93	0.02	260	0.27	0.02	500	0.06	0.01			
48	0.92	0.02	265	0.27	0.02	505	0.06	0.01			
50	0.90	0.02	270	0.26	0.02	510	0.06	0.01			
52	0.89	0.02	275	0.25	0.02	515	0.06	0.01			
54	0.88	0.02	280	0.24	0.02	520	0.05	0.01			
56	0.86	0.02	285	0.24	0.02	525	0.05	0.01			
58	0.85	0.02	290	0.23	0.02	530	0.05	0.01			
60	0.84	0.02	295	0.22	0.02	535	0.05	0.01			
60	0.82	0.02	300	0.21	0.02	540	0.05	0.01			
65	0.82	0.02	305	0.20	0.02	545	0.05	0.01			
70	0.79	0.02	310	0.20	0.02	550	0.05	0.01			
75	0.77	0.02	315	0.19	0.02	555	0.05	0.01			
80	0.75	0.02	320	0.18	0.01	560	0.04	0.01			
85	0.73	0.02	325	0.18	0.01	565	0.04	0.01			
90	0.71	0.02	330	0.17	0.01	570	0.04	0.01			
95	0.68	0.02	335	0.17	0.01	575	0.04	0.01			
100	0.67	0.02	340	0.16	0.01	580	0.04	0.02			
105	0.65	0.02	345	0.16	0.01	585	0.04	0.02			
110	0.64	0.02	350	0.15	0.01	590	0.04	0.02			
115	0.62	0.02	355	0.15	0.01	595	0.03	0.01			
120	0.61	0.02	360	0.14	0.01	600	0.03	0.02			
125	0.59	0.02	365	0.14	0.01	605	0.03	0.02			
130	0.58	0.03	370	0.13	0.01	610	0.03	0.02			
135	0.56	0.02	375	0.13	0.01	615	0.03	0.02			
140	0.55	0.02	380	0.13	0.01	620	0.03	0.02			
145	0.53	0.02	385	0.12	0.01	625	0.03	0.02			

[a] MR = Moisture Ratio (average, n=6)

Table B2.11. Change in moisture ratio of Asian noodles dried in superheated steam at 125°C and 1.0 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2	1.17	0.29	60	0.46	0.07	210	0.18	0.02	360	0.04	0.02	510	0.01	0.02
4	0.98	0.06	65	0.45	0.07	215	0.17	0.02	365	0.04	0.02	515	0.01	0.02
6	0.88	0.08	70	0.44	0.06	220	0.16	0.01	370	0.04	0.02	520	0.01	0.02
8	0.81	0.06	75	0.44	0.05	225	0.15	0.01	375	0.04	0.02	525	0.01	0.02
10	0.80	0.09	80	0.41	0.05	230	0.15	0.01	380	0.03	0.02	530	0.01	0.02
12	0.75	0.10	85	0.40	0.04	235	0.14	0.01	385	0.03	0.02	535	0.01	0.02
14	0.73	0.12	90	0.38	0.05	240	0.13	0.01	390	0.03	0.02	540	0.01	0.02
16	0.71	0.11	95	0.38	0.04	245	0.13	0.01	395	0.03	0.02	545	0.01	0.02
18	0.68	0.12	100	0.37	0.04	250	0.13	0.01	400	0.03	0.02			
20	0.67	0.12	105	0.36	0.04	255	0.12	0.02	405	0.03	0.02			
22	0.68	0.11	110	0.35	0.03	260	0.11	0.02	410	0.03	0.02			
24	0.64	0.10	115	0.33	0.04	265	0.11	0.02	415	0.03	0.02			
26	0.63	0.10	120	0.32	0.04	270	0.11	0.02	420	0.03	0.02			
28	0.61	0.09	125	0.31	0.03	275	0.10	0.02	425	0.03	0.02			
30	0.59	0.11	130	0.30	0.04	280	0.09	0.02	430	0.02	0.02			
32	0.59	0.10	135	0.28	0.03	285	0.09	0.02	435	0.02	0.01			
34	0.58	0.10	140	0.27	0.04	290	0.09	0.02	440	0.02	0.02			
36	0.55	0.11	145	0.25	0.03	295	0.08	0.01	445	0.02	0.02			
38	0.55	0.10	150	0.25	0.02	300	0.08	0.02	450	0.02	0.02			
40	0.53	0.09	155	0.24	0.03	305	0.08	0.02	455	0.03	0.02			
42	0.53	0.10	160	0.23	0.03	310	0.08	0.02	460	0.02	0.02			
44	0.53	0.10	165	0.23	0.03	315	0.07	0.02	465	0.02	0.02			
46	0.52	0.07	170	0.22	0.02	320	0.07	0.02	470	0.02	0.02			
48	0.51	0.06	175	0.21	0.02	325	0.06	0.02	475	0.02	0.02			
50	0.50	0.08	180	0.20	0.02	330	0.05	0.01	480	0.02	0.02			
52	0.50	0.06	185	0.20	0.02	335	0.05	0.01	485	0.02	0.02			
54	0.48	0.06	190	0.19	0.02	340	0.05	0.02	490	0.02	0.02			
56	0.49	0.07	195	0.18	0.03	345	0.04	0.03	495	0.02	0.02			
58	0.47	0.07	200	0.18	0.02	350	0.04	0.02	500	0.02	0.02			
60	0.47	0.07	205	0.18	0.02	355	0.04	0.02	505	0.01	0.02			

[(a)] MR = Moisture Ratio (average, n=6)

Table B2.12. Change in moisture ratio of Asian noodles dried in superheated steam at 125°C and 1.5 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2	2.00	0.44	52	0.40	0.16	160	0.15	0.13	285	0.04	0.12
4	1.20	0.13	54	0.37	0.17	165	0.14	0.13	290	0.05	0.10
6	0.94	0.16	56	0.36	0.16	170	0.15	0.11	295	0.04	0.11
8	0.81	0.13	58	0.38	0.15	175	0.12	0.12	300	0.04	0.12
10	0.79	0.15	60	0.37	0.18	180	0.12	0.11	305	0.04	0.12
12	0.75	0.14	60	0.37	0.13	185	0.12	0.12	310	0.02	0.12
14	0.72	0.15	65	0.35	0.13	190	0.13	0.12	315	0.03	0.12
16	0.75	0.18	70	0.33	0.14	195	0.13	0.12	320	0.01	0.12
18	0.70	0.18	75	0.32	0.12	200	0.10	0.11	325	0.01	0.11
20	0.67	0.14	80	0.32	0.15	205	0.10	0.10	330	0.01	0.13
22	0.66	0.13	85	0.29	0.12	210	0.07	0.10	335	0.02	0.13
24	0.62	0.17	90	0.27	0.14	215	0.11	0.12	340	0.02	0.11
26	0.59	0.15	95	0.27	0.12	220	0.11	0.11	345	0.02	0.11
28	0.61	0.16	100	0.29	0.12	225	0.09	0.12	350	0.02	0.10
30	0.61	0.18	105	0.26	0.11	230	0.09	0.10			
32	0.56	0.18	110	0.24	0.13	235	0.09	0.11			
34	0.53	0.16	115	0.24	0.13	240	0.07	0.11			
36	0.55	0.18	120	0.22	0.13	245	0.07	0.10			
38	0.53	0.18	125	0.20	0.10	250	0.05	0.12			
40	0.52	0.16	130	0.18	0.16	255	0.06	0.12			
42	0.50	0.17	135	0.22	0.12	260	0.05	0.12			
44	0.46	0.18	140	0.19	0.09	265	0.05	0.10			
46	0.48	0.14	145	0.16	0.12	270	0.06	0.11			
48	0.46	0.17	150	0.16	0.15	275	0.05	0.11			
50	0.40	0.17	155	0.14	0.13	280	0.04	0.11			

[(a)] MR = Moisture Ratio (average, n=6)

Table B2.13. Change in moisture ratio of Asian noodles dried in superheated steam at 130°C and 0.5 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2	1.00	0.09	60	0.76	0.02	210	0.23	0.03	360	0.04	0.02	510	0.01	0.02
4	1.13	0.06	65	0.76	0.02	215	0.21	0.03	365	0.03	0.02	515	0.01	0.02
6	1.26	0.04	70	0.74	0.02	220	0.20	0.03	370	0.03	0.02	520	0.01	0.02
8	1.27	0.05	75	0.71	0.02	225	0.19	0.03	375	0.03	0.02	525	0.01	0.02
10	1.25	0.04	80	0.69	0.02	230	0.18	0.03	380	0.03	0.02	530	0.01	0.02
12	1.24	0.04	85	0.67	0.02	235	0.17	0.02	385	0.03	0.02	535	0.01	0.02
14	1.24	0.04	90	0.64	0.02	240	0.16	0.03	390	0.02	0.02	540	0.01	0.02
16	1.22	0.03	95	0.63	0.02	245	0.15	0.02	395	0.02	0.02	545	0.01	0.02
18	1.20	0.03	100	0.60	0.02	250	0.14	0.02	400	0.02	0.02			
20	1.18	0.03	105	0.58	0.02	255	0.13	0.02	405	0.02	0.02			
22	1.15	0.03	110	0.56	0.03	260	0.13	0.02	410	0.02	0.02			
24	1.13	0.02	115	0.54	0.02	265	0.12	0.02	415	0.02	0.02			
26	1.11	0.02	120	0.52	0.02	270	0.11	0.02	420	0.02	0.02			
28	1.08	0.02	125	0.50	0.02	275	0.11	0.02	425	0.02	0.02			
30	1.06	0.02	130	0.48	0.02	280	0.10	0.02	430	0.01	0.02			
32	1.04	0.02	135	0.46	0.03	285	0.09	0.02	435	0.01	0.02			
34	1.01	0.02	140	0.45	0.02	290	0.09	0.02	440	0.01	0.02			
36	0.98	0.02	145	0.42	0.02	295	0.08	0.02	445	0.01	0.02			
38	0.96	0.01	150	0.41	0.03	300	0.07	0.02	450	0.01	0.02			
40	0.94	0.02	155	0.39	0.03	305	0.07	0.02	455	0.01	0.02			
42	0.92	0.02	160	0.37	0.03	310	0.07	0.02	460	0.01	0.02			
44	0.90	0.02	165	0.35	0.03	315	0.06	0.02	465	0.01	0.02			
46	0.88	0.02	170	0.34	0.03	320	0.06	0.02	470	0.01	0.02			
48	0.86	0.02	175	0.32	0.03	325	0.06	0.02	475	0.01	0.02			
50	0.84	0.02	180	0.31	0.03	330	0.05	0.02	480	0.01	0.02			
52	0.83	0.02	185	0.30	0.03	335	0.05	0.02	485	0.01	0.02			
54	0.82	0.01	190	0.28	0.03	340	0.05	0.02	490	0.01	0.02			
56	0.80	0.01	195	0.26	0.03	345	0.04	0.02	495	0.01	0.02			
58	0.79	0.02	200	0.25	0.03	350	0.04	0.02	500	0.01	0.02			
60	0.77	0.02	205	0.24	0.03	355	0.04	0.02	505	0.01	0.02			

[(a)] MR = Moisture Ratio (average, n=6)

Table B2.14. Change in moisture ratio of Asian noodles dried in superheated steam at 130°C and 1.0 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2			52	0.56	0.12	160	0.21	0.08	285	0.06	0.08	410	0.02	0.11
4			54	0.55	0.12	165	0.20	0.08	290	0.04	0.09	415	0.02	0.11
6			56	0.54	0.11	170	0.19	0.07	295	0.03	0.08	420	0.01	0.09
8			58	0.54	0.11	175	0.19	0.10	300	0.04	0.08	425	0.02	0.10
10			60	0.54	0.11	180	0.18	0.09	305	0.04	0.08	430	0.00	0.10
12			60	0.52	0.11	185	0.16	0.08	310	0.04	0.09	435	0.01	0.09
14			65	0.48	0.10	190	0.14	0.06	315	0.04	0.09			
16			70	0.48	0.11	195	0.15	0.07	320	0.03	0.09			
18			75	0.45	0.10	200	0.14	0.07	325	0.02	0.08			
20			80	0.45	0.09	205	0.13	0.07	330	0.02	0.09			
22	0.83	0.13	85	0.43	0.08	210	0.13	0.07	335	0.02	0.08			
24	0.82	0.13	90	0.41	0.09	215	0.13	0.10	340	0.02	0.08			
26	0.80	0.13	95	0.38	0.09	220	0.13	0.08	345	0.02	0.08			
28	0.77	0.14	100	0.37	0.09	225	0.11	0.08	350	0.01	0.09			
30	0.76	0.13	105	0.36	0.10	230	0.11	0.08	355	0.01	0.10			
32	0.73	0.14	110	0.35	0.11	235	0.10	0.08	360	0.02	0.08			
34	0.70	0.15	115	0.34	0.10	240	0.10	0.09	365	0.01	0.10			
36	0.67	0.13	120	0.34	0.10	245	0.09	0.09	370	0.02	0.10			
38	0.66	0.13	125	0.31	0.09	250	0.10	0.09	375	0.01	0.11			
40	0.65	0.12	130	0.30	0.09	255	0.08	0.08	380	0.01	0.09			
42	0.64	0.14	135	0.28	0.09	260	0.07	0.09	385	-0.01	0.10			
44	0.63	0.12	140	0.26	0.09	265	0.06	0.09	390	0.00	0.12			
46	0.60	0.11	145	0.25	0.09	270	0.06	0.09	395	0.00	0.09			
48	0.59	0.12	150	0.24	0.09	275	0.06	0.08	400	0.02	0.10			
50	0.58	0.13	155	0.21	0.09	280	0.05	0.09	405	0.02	0.10			

[a] MR = Moisture Ratio (average, n=6)

Table B2.15. Change in moisture ratio of Asian noodles dried in superheated steam at 130°C and 1.5 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2	1.59	0.34	42	0.59	0.04	110	0.24	0.03	210	0.05	0.02
4	1.16	0.13	44	0.58	0.04	115	0.25	0.04	215	0.07	0.03
6	1.10	0.07	46	0.55	0.03	120	0.23	0.04	220	0.07	0.01
8	1.05	0.07	48	0.54	0.08	125	0.24	0.04	225	0.06	0.01
10	0.98	0.05	50	0.52	0.02	130	0.22	0.05	230	0.05	0.02
12	0.91	0.06	52	0.51	0.03	135	0.21	0.04	235	0.06	0.02
14	0.89	0.07	54	0.49	0.02	140	0.20	0.04	240	0.06	0.04
16	0.86	0.05	56	0.49	0.03	145	0.17	0.05	245	0.05	0.04
18	0.87	0.05	58	0.47	0.07	150	0.17	0.05	250	0.07	0.02
20	0.83	0.04	60	0.44	0.02	155	0.16	0.05	255	0.04	0.05
22	0.80	0.05	60	0.43	0.03	160	0.16	0.03	260	0.05	0.03
24	0.75	0.06	65	0.44	0.05	165	0.13	0.03	265	0.04	0.04
26	0.77	0.05	70	0.39	0.03	170	0.14	0.04	270	0.03	0.02
28	0.75	0.06	75	0.37	0.05	175	0.12	0.03	275	0.05	0.03
30	0.74	0.07	80	0.37	0.02	180	0.11	0.04	280	0.04	0.04
32	0.73	0.03	85	0.34	0.03	185	0.10	0.04	285	0.04	0.04
34	0.69	0.07	90	0.32	0.04	190	0.11	0.02	290	0.04	0.03
36	0.68	0.05	95	0.31	0.05	195	0.08	0.03	295	0.00	0.01
38	0.64	0.07	100	0.28	0.02	200	0.09	0.03	300	0.03	0.02
40	0.62	0.05	105	0.27	0.04	205	0.06	0.02	305	0.03	0.02

[(a)] MR = Moisture Ratio (average, n=6)

Table B2.16. Change in moisture ratio of Asian noodles dried in superheated steam at 135°C and 0.5 m/s.

Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2	1.04	0.04	60	0.70	0.05	210	0.22	0.04	360	0.05	0.04
4	1.12	0.08	65	0.68	0.05	215	0.20	0.04	365	0.04	0.04
6	1.10	0.10	70	0.66	0.05	220	0.20	0.04	370	0.04	0.04
8	1.09	0.07	75	0.64	0.04	225	0.18	0.04	375	0.04	0.04
10	1.10	0.04	80	0.62	0.05	230	0.18	0.04	380	0.04	0.04
12	1.08	0.06	85	0.60	0.05	235	0.17	0.04	385	0.04	0.04
14	1.07	0.05	90	0.58	0.05	240	0.16	0.04	390	0.03	0.04
16	1.05	0.05	95	0.56	0.05	245	0.15	0.04	395	0.03	0.04
18	1.03	0.05	100	0.54	0.04	250	0.15	0.04	400	0.03	0.04
20	1.00	0.05	105	0.52	0.04	255	0.14	0.04	405	0.03	0.04
22	0.98	0.06	110	0.50	0.05	260	0.13	0.04	410	0.03	0.04
24	0.96	0.06	115	0.48	0.05	265	0.13	0.04	415	0.03	0.04
26	0.94	0.06	120	0.47	0.04	270	0.12	0.04	420	0.03	0.04
28	0.92	0.05	125	0.45	0.05	275	0.11	0.04	425	0.03	0.04
30	0.90	0.05	130	0.43	0.04	280	0.11	0.04	430	0.03	0.04
32	0.88	0.05	135	0.41	0.04	285	0.10	0.04	435	0.03	0.04
34	0.86	0.05	140	0.40	0.05	290	0.10	0.04	440	0.03	0.04
36	0.85	0.05	145	0.38	0.04	295	0.09	0.04	445	0.02	0.04
38	0.83	0.05	150	0.37	0.04	300	0.09	0.04	450	0.02	0.04
40	0.82	0.05	155	0.35	0.04	305	0.08	0.04	455	0.02	0.04
42	0.81	0.05	160	0.33	0.05	310	0.08	0.04	460	0.02	0.04
44	0.79	0.04	165	0.33	0.05	315	0.08	0.04	465	0.02	0.04
46	0.78	0.05	170	0.31	0.05	320	0.07	0.04	470	0.02	0.04
48	0.77	0.05	175	0.30	0.04	325	0.07	0.04	475	0.02	0.04
50	0.76	0.05	180	0.28	0.04	330	0.07	0.04	480	0.02	0.04
52	0.75	0.05	185	0.27	0.04	335	0.06	0.04	485	0.02	0.04
54	0.74	0.05	190	0.26	0.04	340	0.06	0.04	490	0.02	0.04
56	0.73	0.05	195	0.25	0.04	345	0.06	0.04	495	0.02	0.04
58	0.72	0.05	200	0.24	0.04	350	0.05	0.04	500	0.02	0.04
60	0.70	0.05	205	0.23	0.04	355	0.05	0.04	505	0.02	0.04

[(a)] MR = Moisture Ratio (average, n=6)

Table B2.17. Change in moisture ratio of Asian noodles dried in superheated steam at 135°C and 1.0 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.02	0.19	52	0.36	0.07	160	0.15	0.03	285	0.04	0.03	410	0.01	0.02
4	0.91	0.12	54	0.36	0.07	165	0.15	0.04	290	0.03	0.03	415	0.01	0.02
6	0.76	0.09	56	0.36	0.07	170	0.14	0.04	295	0.04	0.02	420	0.01	0.03
8	0.69	0.09	58	0.34	0.06	175	0.14	0.03	300	0.03	0.02	425	0.01	0.02
10	0.64	0.08	60	0.33	0.06	180	0.13	0.04	305	0.03	0.02	430	0.01	0.03
12	0.61	0.10	60	0.33	0.06	185	0.12	0.03	310	0.03	0.02	435	0.01	0.03
14	0.57	0.11	65	0.31	0.04	190	0.11	0.03	315	0.03	0.02			
16	0.57	0.09	70	0.30	0.06	195	0.11	0.03	320	0.03	0.03			
18	0.54	0.10	75	0.30	0.06	200	0.11	0.03	325	0.02	0.03			
20	0.55	0.07	80	0.28	0.05	205	0.09	0.02	330	0.02	0.03			
22	0.51	0.09	85	0.27	0.05	210	0.10	0.03	335	0.02	0.03			
24	0.51	0.07	90	0.27	0.04	215	0.09	0.03	340	0.01	0.02			
26	0.47	0.09	95	0.26	0.03	220	0.09	0.03	345	0.01	0.02			
28	0.48	0.08	100	0.25	0.04	225	0.08	0.03	350	0.01	0.03			
30	0.46	0.09	105	0.24	0.05	230	0.07	0.03	355	0.02	0.03			
32	0.45	0.10	110	0.23	0.04	235	0.06	0.02	360	0.02	0.03			
34	0.45	0.08	115	0.23	0.03	240	0.05	0.02	365	0.02	0.03			
36	0.42	0.10	120	0.23	0.04	245	0.05	0.02	370	0.01	0.03			
38	0.41	0.08	125	0.21	0.05	250	0.05	0.03	375	0.01	0.02			
40	0.41	0.08	130	0.19	0.05	255	0.05	0.03	380	0.01	0.03			
42	0.40	0.07	135	0.19	0.05	260	0.04	0.02	385	0.01	0.03			
44	0.39	0.08	140	0.18	0.05	265	0.04	0.02	390	0.01	0.03			
46	0.38	0.08	145	0.18	0.04	270	0.04	0.03	395	0.00	0.03			
48	0.38	0.08	150	0.17	0.05	275	0.04	0.03	400	0.00	0.03			
50	0.36	0.08	155	0.16	0.04	280	0.04	0.02	405	0.01	0.03			

[a] MR = Moisture Ratio (average, n=6)

Table B2.18. Change in moisture ratio of Asian noodles dried in superheated steam at 135°C and 1.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.39	0.19	42	0.41	0.10	110	0.23	0.10	210	0.06	0.06
4	0.93	0.13	44	0.39	0.08	115	0.21	0.10	215	0.05	0.08
6	0.81	0.18	46	0.36	0.12	120	0.20	0.08	220	0.06	0.08
8	0.78	0.22	48	0.36	0.08	125	0.17	0.10	225	0.05	0.08
10	0.76	0.17	50	0.37	0.09	130	0.16	0.09	230	0.03	0.07
12	0.71	0.15	52	0.35	0.08	135	0.15	0.08	235	0.06	0.07
14	0.70	0.14	54	0.37	0.09	140	0.14	0.09	240	0.03	0.10
16	0.68	0.15	56	0.36	0.09	145	0.15	0.08	245	0.03	0.08
18	0.62	0.17	58	0.31	0.10	150	0.12	0.09	250	0.04	0.07
20	0.63	0.13	60	0.31	0.08	155	0.12	0.09	255	0.04	0.08
22	0.58	0.13	60	0.32	0.07	160	0.12	0.08	260	0.02	0.07
24	0.56	0.12	65	0.32	0.08	165	0.11	0.07	265	0.02	0.08
26	0.55	0.12	70	0.30	0.11	170	0.12	0.08	270	0.02	0.08
28	0.53	0.15	75	0.30	0.10	175	0.09	0.08	275	0.01	0.07
30	0.46	0.12	80	0.26	0.09	180	0.10	0.08	280	0.02	0.07
32	0.47	0.10	85	0.24	0.11	185	0.09	0.06	285	0.02	0.07
34	0.48	0.11	90	0.25	0.09	190	0.07	0.06	290	0.02	0.07
36	0.41	0.11	95	0.23	0.07	195	0.07	0.05	295	0.02	0.06
38	0.42	0.09	100	0.24	0.10	200	0.06	0.06	300	0.02	0.05
40	0.41	0.11	105	0.20	0.08	205	0.07	0.05	305	0.01	0.06

[a] MR = Moisture Ratio (average, n=6)

Table B2.19. Change in moisture ratio of Asian noodles dried in superheated steam at 140°C and 0.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.18	0.04	52	0.79	0.04	160	0.30	0.04	285	0.05	0.02	410	0.01	0.01
4	1.14	0.06	54	0.77	0.03	165	0.28	0.03	290	0.05	0.02	415	0.00	0.01
6	1.20	0.06	56	0.76	0.03	170	0.27	0.03	295	0.05	0.02	420	0.00	0.02
8	1.19	0.06	58	0.75	0.03	175	0.25	0.03	300	0.04	0.02	425	0.00	0.02
10	1.17	0.06	60	0.74	0.03	180	0.24	0.03	305	0.04	0.02	430	0.01	0.02
12	1.15	0.06	60	0.73	0.03	185	0.22	0.03	310	0.03	0.01	435	0.00	0.02
14	1.13	0.06	65	0.70	0.03	190	0.21	0.03	315	0.03	0.01	440	0.00	0.02
16	1.11	0.05	70	0.68	0.03	195	0.20	0.03	320	0.03	0.01	445	0.00	0.02
18	1.09	0.05	75	0.65	0.03	200	0.18	0.03	325	0.03	0.01	450	0.00	0.02
20	1.06	0.05	80	0.63	0.03	205	0.17	0.03	330	0.03	0.01	455	0.00	0.02
22	1.05	0.06	85	0.61	0.02	210	0.16	0.03	335	0.03	0.01	460	0.00	0.02
24	1.02	0.05	90	0.58	0.03	215	0.15	0.03	340	0.02	0.01	465	0.00	0.02
26	0.99	0.05	95	0.56	0.03	220	0.14	0.03	345	0.02	0.01			
28	0.97	0.06	100	0.54	0.03	225	0.13	0.03	350	0.02	0.01			
30	0.95	0.05	105	0.51	0.03	230	0.12	0.03	355	0.02	0.01			
32	0.93	0.05	110	0.49	0.03	235	0.11	0.03	360	0.02	0.01			
34	0.91	0.04	115	0.47	0.03	240	0.10	0.02	365	0.02	0.01			
36	0.90	0.05	120	0.45	0.03	245	0.10	0.02	370	0.02	0.01			
38	0.88	0.04	125	0.42	0.03	250	0.09	0.02	375	0.01	0.02			
40	0.86	0.04	130	0.40	0.03	255	0.08	0.02	380	0.01	0.02			
42	0.85	0.04	135	0.39	0.03	260	0.08	0.02	385	0.01	0.02			
44	0.84	0.04	140	0.37	0.04	265	0.07	0.02	390	0.01	0.02			
46	0.82	0.04	145	0.35	0.03	270	0.07	0.02	395	0.01	0.02			
48	0.81	0.04	150	0.34	0.04	275	0.06	0.02	400	0.01	0.02			
50	0.80	0.04	155	0.32	0.04	280	0.06	0.02	405	0.01	0.02			

[a] MR = Moisture Ratio (average, n=6)

Table B2.20. Change in moisture ratio of Asian noodles dried in superheated steam at 140°C and 1.0 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2			52	0.49	0.06	160	0.15	0.07	285	0.03	0.06
4			54	0.49	0.06	165	0.14	0.08	290	0.02	0.06
6			56	0.47	0.07	170	0.14	0.07	295	0.03	0.06
8			58	0.46	0.08	175	0.12	0.07	300	0.02	0.07
10			60	0.46	0.08	180	0.13	0.05	305	0.02	0.07
12			60	0.45	0.07	185	0.11	0.07	310	0.01	0.06
14			65	0.44	0.08	190	0.10	0.04	315	0.02	0.06
16			70	0.41	0.07	195	0.09	0.07	320	0.03	0.07
18			75	0.40	0.06	200	0.08	0.06	325	0.03	0.04
20			80	0.39	0.08	205	0.08	0.06	330	0.02	0.06
22	0.64	0.06	85	0.34	0.07	210	0.11	0.04	335	0.01	0.06
24	0.63	0.06	90	0.34	0.07	215	0.09	0.04	340	0.02	0.07
26	0.63	0.07	95	0.33	0.06	220	0.06	0.07	345	0.01	0.06
28	0.62	0.07	100	0.31	0.07	225	0.07	0.07	350	0.02	0.06
30	0.60	0.06	105	0.30	0.07	230	0.07	0.07	355	0.02	0.06
32	0.59	0.05	110	0.27	0.08	235	0.07	0.06	360	0.02	0.06
34	0.59	0.07	115	0.26	0.07	240	0.06	0.06	365	0.02	0.06
36	0.56	0.06	120	0.25	0.07	245	0.05	0.07	370	0.00	0.07
38	0.54	0.06	125	0.23	0.07	250	0.04	0.07	375	0.02	0.08
40	0.54	0.06	130	0.23	0.07	255	0.06	0.08	380	0.00	0.07
42	0.53	0.07	135	0.21	0.08	260	0.05	0.06	385	0.01	0.07
44	0.52	0.06	140	0.20	0.08	265	0.04	0.06			
46	0.52	0.06	145	0.19	0.08	270	0.03	0.07			
48	0.50	0.06	150	0.17	0.07	275	0.04	0.06			
50	0.50	0.06	155	0.16	0.07	280	0.02	0.05			

[a] MR = Moisture Ratio (average, n=6)

Table B2.21. Change in moisture ratio of Asian noodles dried in superheated steam at 140°C and 1.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.48	0.41	36	0.37	0.13	80	0.26	0.09	165	0.08	0.06
4	0.95	0.27	38	0.34	0.16	85	0.24	0.05	170	0.07	0.07
6	0.75	0.19	40	0.36	0.14	90	0.21	0.08	175	0.06	0.06
8	0.71	0.20	42	0.36	0.14	95	0.19	0.08	180	0.06	0.07
10	0.64	0.20	44	0.36	0.12	100	0.19	0.10	185	0.06	0.05
12	0.61	0.20	46	0.33	0.09	105	0.18	0.08	190	0.03	0.06
14	0.60	0.18	48	0.31	0.10	110	0.17	0.09	195	0.04	0.07
16	0.55	0.21	50	0.31	0.10	115	0.16	0.08	200	0.03	0.05
18	0.54	0.16	52	0.31	0.10	120	0.15	0.08	205	0.04	0.08
20	0.51	0.17	54	0.31	0.10	125	0.12	0.09	210	0.05	0.07
22	0.49	0.19	56	0.32	0.10	130	0.12	0.08	215	0.03	0.06
24	0.45	0.18	58	0.32	0.09	135	0.12	0.08	220	0.05	0.06
26	0.42	0.15	60	0.29	0.11	140	0.09	0.07	225	0.03	0.06
28	0.40	0.17	60	0.30	0.11	145	0.09	0.06	230	0.03	0.04
30	0.40	0.16	65	0.26	0.09	150	0.07	0.06	235	0.01	0.06
32	0.40	0.17	70	0.26	0.09	155	0.06	0.06	240	0.03	0.06
34	0.38	0.13	75	0.28	0.10	160	0.08	0.06			

[a] MR = Moisture Ratio (average, n=6)

Table B2.22. Change in moisture ratio of Asian noodles dried in superheated steam at 145°C and 0.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.08	0.04	52	0.72	0.05	160	0.22	0.06	285	0.04	0.04
4	1.09	0.04	54	0.71	0.06	165	0.20	0.05	290	0.04	0.05
6	1.13	0.06	56	0.70	0.05	170	0.18	0.05	295	0.03	0.05
8	1.13	0.07	58	0.69	0.05	175	0.17	0.05	300	0.03	0.05
10	1.10	0.07	60	0.68	0.05	180	0.16	0.05	305	0.03	0.05
12	1.08	0.07	60	0.67	0.05	185	0.15	0.05	310	0.03	0.05
14	1.06	0.06	65	0.65	0.06	190	0.14	0.05	315	0.03	0.05
16	1.04	0.06	70	0.62	0.05	195	0.13	0.05	320	0.02	0.05
18	1.02	0.06	75	0.59	0.05	200	0.12	0.05	325	0.02	0.05
20	1.00	0.05	80	0.57	0.05	205	0.11	0.04	330	0.02	0.05
22	0.97	0.07	85	0.54	0.05	210	0.10	0.04	335	0.02	0.05
24	0.95	0.05	90	0.51	0.05	215	0.10	0.04	340	0.02	0.05
26	0.92	0.07	95	0.48	0.05	220	0.09	0.04	345	0.02	0.05
28	0.90	0.06	100	0.46	0.05	225	0.09	0.04	350	0.02	0.05
30	0.88	0.06	105	0.44	0.05	230	0.08	0.04	355	0.02	0.05
32	0.86	0.06	110	0.41	0.05	235	0.08	0.04	360	0.02	0.05
34	0.85	0.05	115	0.39	0.05	240	0.07	0.04	365	0.02	0.05
36	0.84	0.05	120	0.37	0.05	245	0.06	0.04	370	0.02	0.05
38	0.81	0.06	125	0.35	0.05	250	0.06	0.04	375	0.02	0.05
40	0.80	0.05	130	0.32	0.06	255	0.06	0.04	380	0.02	0.05
42	0.79	0.05	135	0.30	0.05	260	0.05	0.05	385	0.02	0.05
44	0.77	0.06	140	0.28	0.05	265	0.05	0.04			
46	0.75	0.06	145	0.26	0.05	270	0.05	0.04			
48	0.75	0.05	150	0.25	0.05	275	0.04	0.04			
50	0.73	0.06	155	0.23	0.05	280	0.04	0.04			

[a] MR = Moisture Ratio (average, n=6)

Table B2.23. Change in moisture ratio of Asian noodles dried in superheated steam at 145°C and 1.0 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.08	0.13	42	0.41	0.08	110	0.21	0.05	210	0.07	0.05
4	0.88	0.06	44	0.39	0.08	115	0.19	0.04	215	0.07	0.06
6	0.75	0.11	46	0.38	0.07	120	0.19	0.05	220	0.06	0.05
8	0.65	0.11	48	0.38	0.07	125	0.17	0.05	225	0.06	0.05
10	0.61	0.10	50	0.38	0.08	130	0.16	0.04	230	0.05	0.05
12	0.58	0.15	52	0.36	0.07	135	0.15	0.04	235	0.05	0.05
14	0.57	0.12	54	0.36	0.07	140	0.15	0.05	240	0.05	0.05
16	0.54	0.10	56	0.35	0.06	145	0.14	0.05	245	0.04	0.05
18	0.53	0.11	58	0.35	0.07	150	0.14	0.05	250	0.05	0.05
20	0.49	0.10	60	0.34	0.07	155	0.12	0.05	255	0.05	0.05
22	0.49	0.10	60	0.33	0.06	160	0.12	0.05	260	0.05	0.05
24	0.48	0.11	65	0.32	0.06	165	0.12	0.05	265	0.05	0.04
26	0.48	0.11	70	0.31	0.06	170	0.11	0.05	270	0.05	0.05
28	0.46	0.09	75	0.30	0.07	175	0.10	0.05	275	0.04	0.05
30	0.44	0.09	80	0.28	0.06	180	0.09	0.04	280	0.04	0.05
32	0.44	0.09	85	0.27	0.06	185	0.09	0.05	285	0.04	0.05
34	0.44	0.08	90	0.25	0.05	190	0.08	0.05	290	0.05	0.05
36	0.43	0.08	95	0.24	0.05	195	0.07	0.04	295	0.04	0.04
38	0.43	0.09	100	0.23	0.04	200	0.07	0.05	300	0.03	0.05
40	0.43	0.09	105	0.21	0.05	205	0.07	0.05	305	0.04	0.05

[a] MR = Moisture Ratio (average, n=6)

Table B2.24. Change in moisture ratio of Asian noodles dried in superheated steam at 145°C and 1.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.69	0.29	40	0.35	0.14	100	0.16	0.11	195	0.02	0.07
4	0.96	0.09	42	0.34	0.16	105	0.15	0.10	200	0.01	0.07
6	0.78	0.16	44	0.34	0.12	110	0.15	0.10	205	0.01	0.07
8	0.76	0.15	46	0.33	0.12	115	0.11	0.10	210	0.01	0.07
10	0.69	0.15	48	0.34	0.12	120	0.11	0.09	215	0.01	0.07
12	0.67	0.14	50	0.33	0.13	125	0.11	0.09	220	0.02	0.08
14	0.62	0.16	52	0.33	0.12	130	0.09	0.08	225	0.00	0.09
16	0.61	0.15	54	0.32	0.14	135	0.07	0.09	230	0.01	0.10
18	0.56	0.17	56	0.31	0.13	140	0.07	0.10	235	0.01	0.09
20	0.47	0.18	58	0.30	0.12	145	0.06	0.10			
22	0.50	0.15	60	0.29	0.11	150	0.06	0.10			
24	0.46	0.17	60	0.31	0.12	155	0.05	0.11			
26	0.44	0.17	65	0.26	0.12	160	0.05	0.10			
28	0.42	0.17	70	0.27	0.10	165	0.04	0.11			
30	0.42	0.15	75	0.24	0.10	170	0.05	0.11			
32	0.43	0.12	80	0.25	0.10	175	0.05	0.10			
34	0.41	0.13	85	0.22	0.10	180	0.02	0.10			
36	0.39	0.18	90	0.19	0.12	185	0.01	0.10			
38	0.34	0.17	95	0.18	0.09	190	0.04	0.08			

[a] MR = Moisture Ratio (average, n=6)

Table B2.25. Change in moisture ratio of Asian noodles dried in superheated steam at 150°C and 0.5 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2	1.06	0.03	52	0.63	0.02	160	0.14	0.01	285	0.03	0.01
4	1.10	0.04	54	0.62	0.03	165	0.13	0.01	290	0.03	0.01
6	1.08	0.03	56	0.60	0.03	170	0.12	0.01	295	0.03	0.01
8	1.05	0.04	58	0.59	0.02	175	0.11	0.01	300	0.03	0.01
10	1.02	0.04	60	0.58	0.02	180	0.11	0.01	305	0.03	0.01
12	1.00	0.03	60	0.56	0.02	185	0.10	0.01	310	0.03	0.01
14	0.97	0.03	65	0.54	0.02	190	0.09	0.01	315	0.02	0.01
16	0.95	0.02	70	0.51	0.03	195	0.09	0.01	320	0.02	0.01
18	0.92	0.02	75	0.48	0.03	200	0.08	0.01	325	0.02	0.01
20	0.90	0.02	80	0.45	0.03	205	0.07	0.01	330	0.02	0.01
22	0.88	0.00	85	0.42	0.02	210	0.07	0.01	335	0.02	0.01
24	0.86	0.02	90	0.40	0.02	215	0.07	0.01	340	0.02	0.01
26	0.84	0.01	95	0.37	0.02	220	0.06	0.01	345	0.02	0.01
28	0.83	0.01	100	0.35	0.03	225	0.06	0.01	350	0.02	0.01
30	0.81	0.01	105	0.32	0.03	230	0.05	0.01			
32	0.79	0.01	110	0.30	0.03	235	0.05	0.01			
34	0.78	0.01	115	0.28	0.03	240	0.05	0.01			
36	0.75	0.01	120	0.26	0.02	245	0.04	0.01			
38	0.75	0.01	125	0.24	0.02	250	0.04	0.01			
40	0.73	0.02	130	0.22	0.02	255	0.04	0.01			
42	0.71	0.02	135	0.21	0.02	260	0.04	0.01			
44	0.69	0.02	140	0.19	0.02	265	0.04	0.01			
46	0.68	0.01	145	0.18	0.02	270	0.04	0.01			
48	0.66	0.02	150	0.17	0.02	275	0.03	0.01			
50	0.65	0.02	155	0.16	0.02	280	0.03	0.01			

[a] MR = Moisture Ratio (average, n=6)

Table B2.26. Change in moisture ratio of Asian noodles dried in superheated steam at 150°C and 1.0 m/s.

Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)	Time (s)	MR[a] (avg)	(std dev)
2			36	0.45	0.12	80	0.24	0.07	165	0.06	0.05
4			38	0.42	0.09	85	0.21	0.08	170	0.06	0.06
6			40	0.41	0.10	90	0.19	0.08	175	0.06	0.06
8			42	0.41	0.10	95	0.17	0.05	180	0.04	0.06
10			44	0.40	0.09	100	0.16	0.06	185	0.03	0.06
12			46	0.38	0.09	105	0.13	0.07	190	0.02	0.06
14			48	0.37	0.09	110	0.12	0.07	195	0.03	0.06
16			50	0.37	0.07	115	0.10	0.06	200	0.04	0.06
18			52	0.35	0.07	120	0.09	0.06	205	0.04	0.07
20			54	0.35	0.09	125	0.10	0.07	210	0.03	0.06
22	0.48	0.11	56	0.35	0.08	130	0.09	0.07	215	0.04	0.06
24	0.48	0.10	58	0.34	0.08	135	0.09	0.06	220	0.03	0.06
26	0.48	0.10	60	0.32	0.09	140	0.08	0.06	225	0.02	0.05
28	0.47	0.11	60	0.32	0.09	145	0.07	0.09	230	0.02	0.06
30	0.46	0.10	65	0.29	0.08	150	0.07	0.07	235	0.01	0.06
32	0.45	0.10	70	0.27	0.08	155	0.06	0.07	240	-0.01	0.06
34	0.44	0.11	75	0.26	0.08	160	0.06	0.06	245	-0.01	0.07

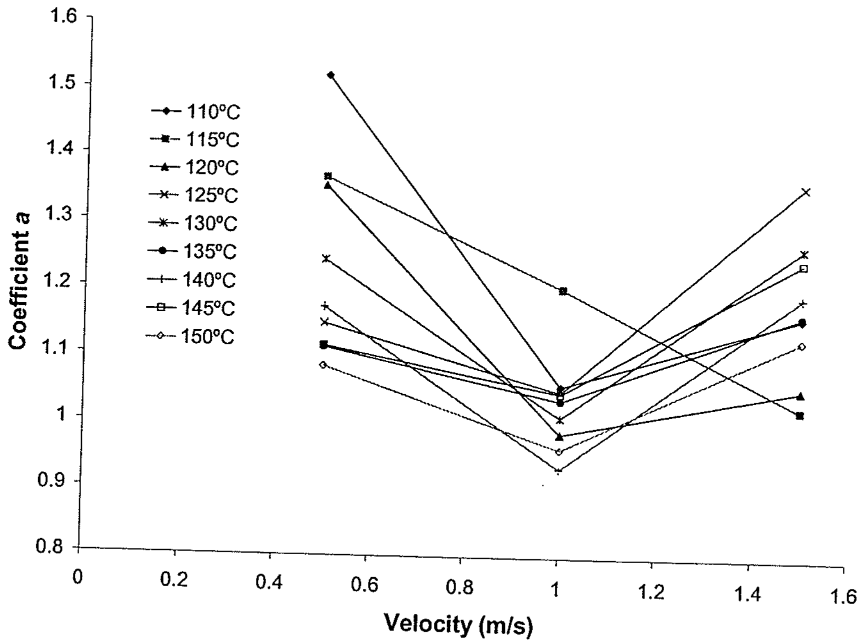
[a] MR = Moisture Ratio (average, n=6)

Table B2.27. Change in moisture ratio of Asian noodles dried in superheated steam at 150°C and 1.5 m/s.

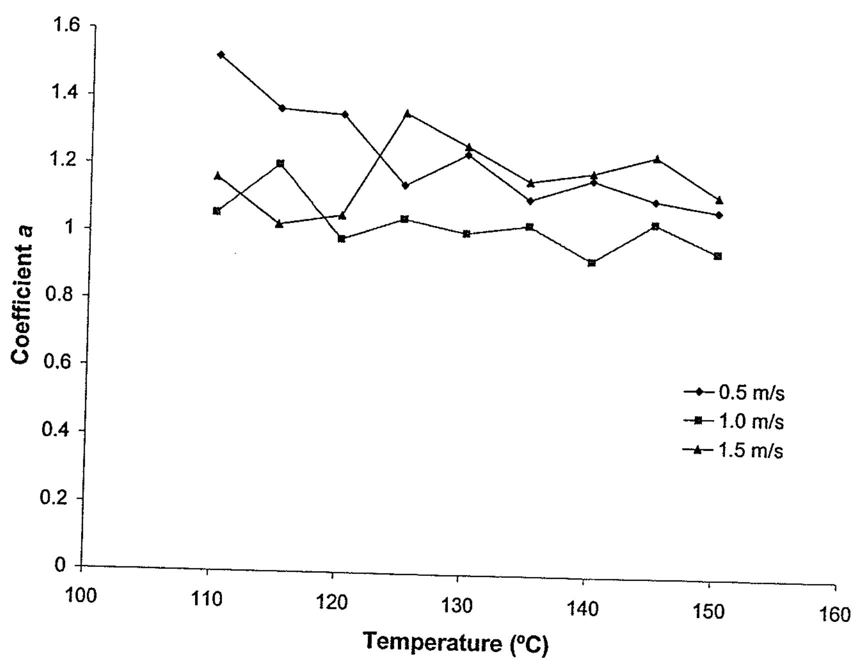
Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)	Time (s)	MR[(a)] (avg)	(std dev)
2	1.33	0.34	38	0.31	0.06	90	0.16	0.04	180	0.00	0.05
4	0.84	0.16	40	0.31	0.05	95	0.13	0.05	185	0.01	0.04
6	0.69	0.17	42	0.29	0.04	100	0.11	0.05	190	0.01	0.03
8	0.64	0.10	44	0.29	0.04	105	0.10	0.06	195	0.01	0.04
10	0.61	0.12	46	0.28	0.05	110	0.08	0.04	200	0.00	0.04
12	0.54	0.12	48	0.29	0.03	115	0.09	0.04			
14	0.52	0.11	50	0.27	0.05	120	0.08	0.05			
16	0.52	0.06	52	0.27	0.06	125	0.08	0.05			
18	0.46	0.10	54	0.25	0.05	130	0.06	0.05			
20	0.45	0.08	56	0.24	0.05	135	0.05	0.04			
22	0.43	0.07	58	0.25	0.06	140	0.04	0.04			
24	0.41	0.09	60	0.25	0.06	145	0.03	0.04			
26	0.38	0.07	60	0.25	0.04	150	0.03	0.05			
28	0.36	0.09	65	0.23	0.04	155	0.02	0.04			
30	0.35	0.09	70	0.22	0.05	160	0.02	0.04			
32	0.35	0.09	75	0.19	0.03	165	0.01	0.05			
34	0.34	0.08	80	0.18	0.06	170	0.02	0.05			
36	0.33	0.07	85	0.16	0.06	175	0.01	0.04			

[(a)] MR = Moisture Ratio (average, n=6)

Appendix B3. Regression analysis results for Eqs. 5.8 and 5.6 (Chapter 5.2.2)

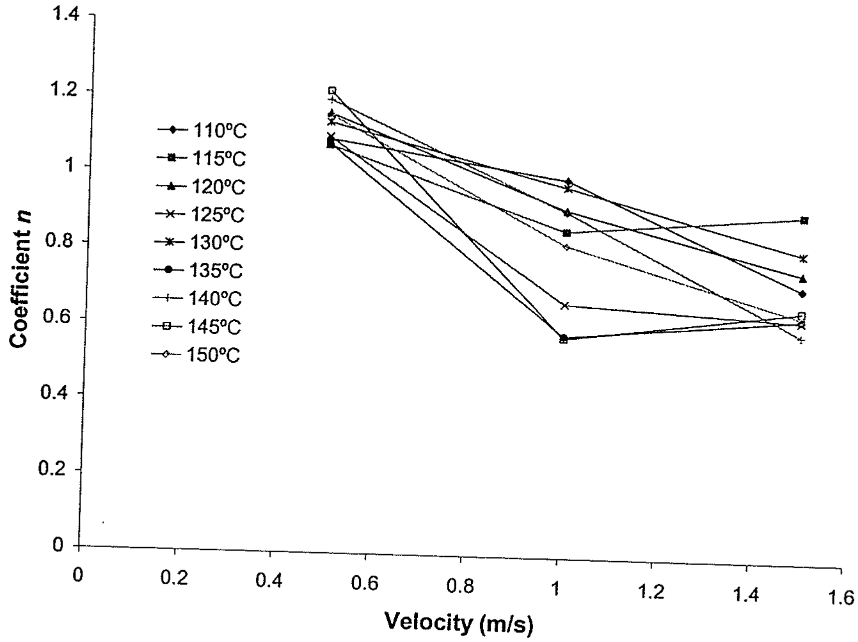


(a) Changes in coefficient a with steam velocity

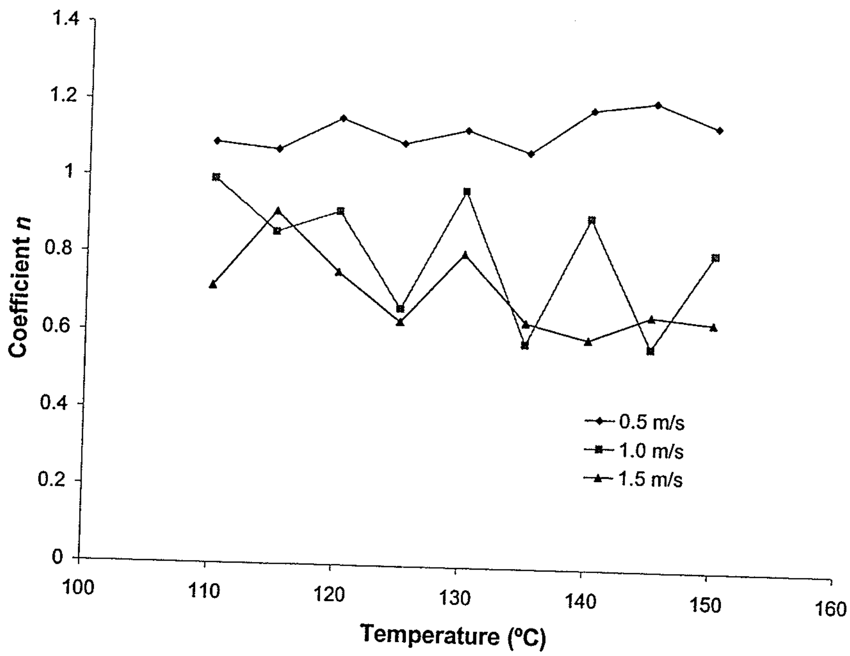


(b) Changes in coefficient a with steam temperature

Fig. B3.1. Effect of steam temperature and velocity on coefficient a in Page's model (Eq. 5.8).

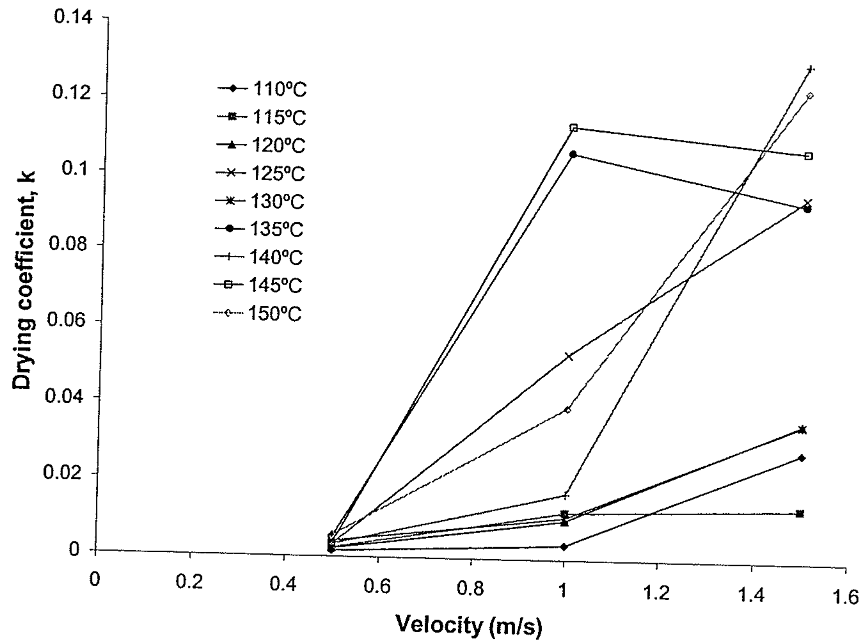


(a) Changes in coefficient n with steam velocity

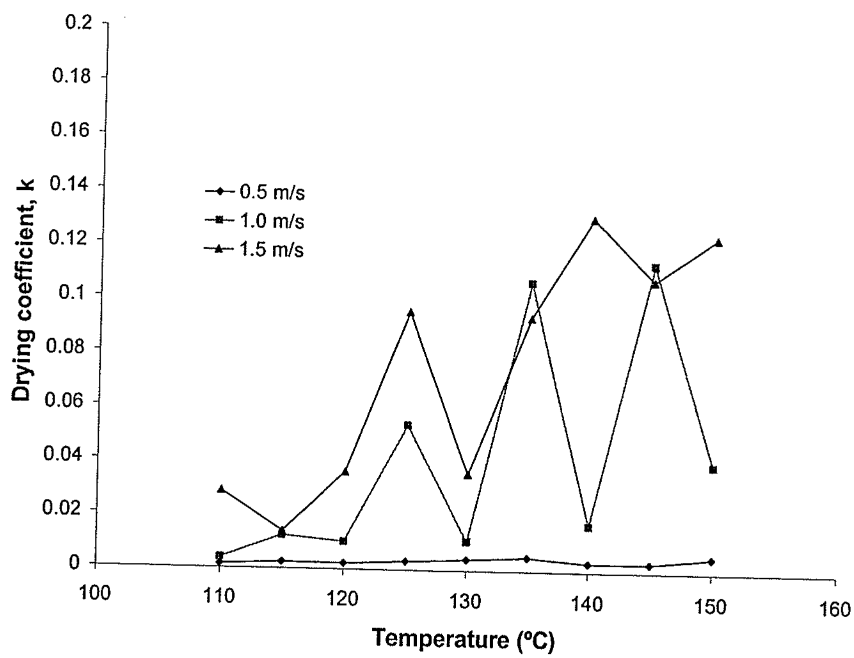


(b) Changes in coefficient n with steam temperature

Fig. B3.2. Effect of steam temperature and velocity on coefficient n in Page's model (Eq. 5.8).

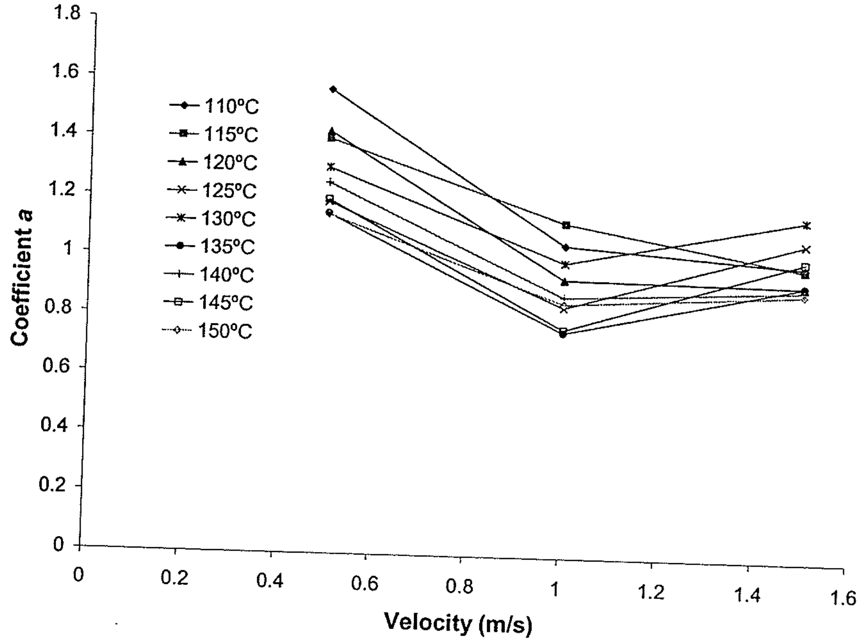


(a) Changes in drying coefficient k with steam velocity

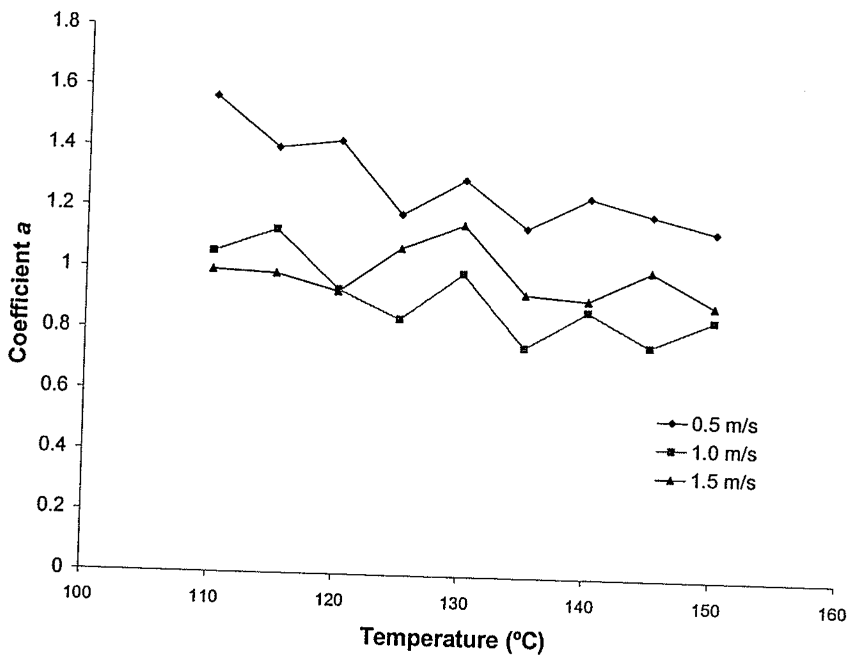


(b) Changes in drying coefficient k with steam temperature

Fig. B3.3. Effect of steam temperature and velocity on drying coefficient k in Page's model (Eq. 5.8).

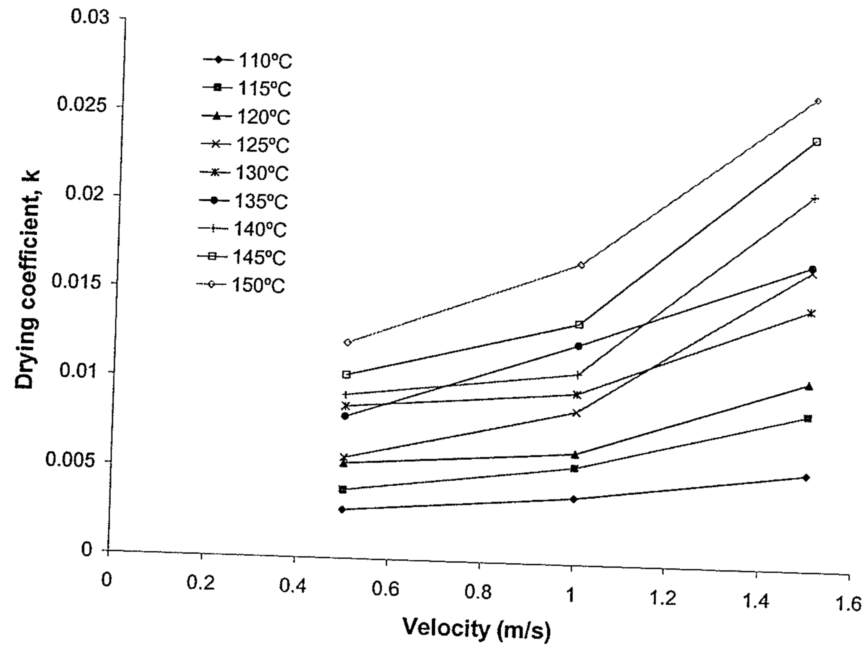


(a) Changes in coefficient *a* with steam velocity

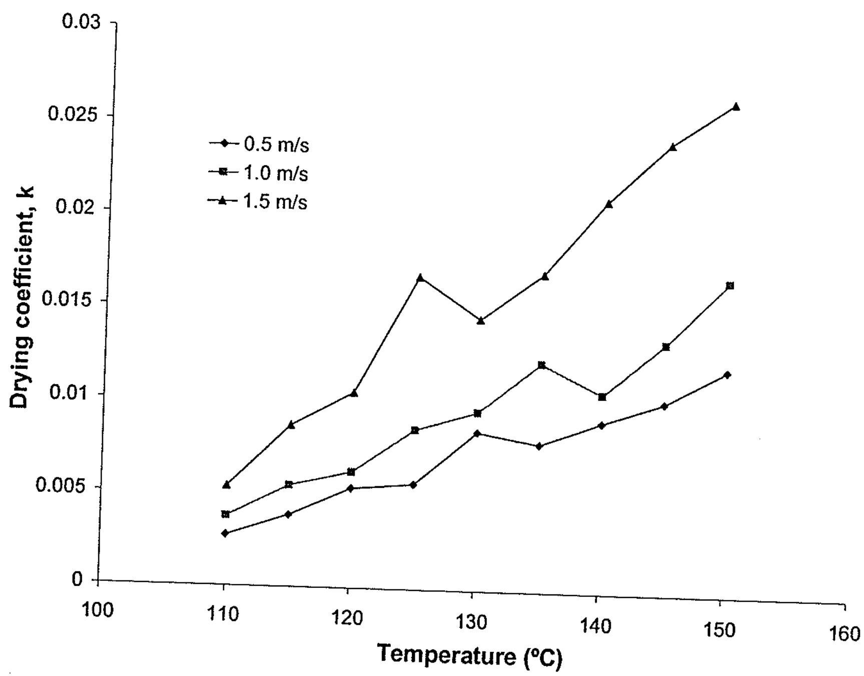


(b) Changes in coefficient *a* with steam temperature

Fig. B3.4. Effect of steam temperature and velocity on coefficient *a* in Newton's model (Eq. 5.6).



(a) Changes in drying coefficient k with steam velocity



(b) Changes in drying coefficient k with steam temperature

Fig. B3.5. Effect of steam temperature and velocity on drying coefficient k in Newton's model (Eq. 5.6).

Appendix B4. TPA results (Chapter 5.4.1)

Table B4.1. Textural properties from TPA tests of noodles processed at 110°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	467	-1.3	1.0	0.976	0.013	0.536	0.003	283.3	13.6	0.498	0.014	541.1	22.8
	934	-1.2	1.1	0.988	0.008	0.542	0.003	310.7	13.0	0.517	0.013	581.0	24.7
	1400	-0.9	1.0	0.976	0.009	0.546	0.005	363.7	11.3	0.514	0.014	682.6	27.4
1	267	-5.0	2.0	0.970	0.011	0.532	0.003	227.6	10.6	0.463	0.013	441.0	22.7
	533	-3.1	1.2	0.983	0.012	0.531	0.006	269.9	9.9	0.471	0.019	517.3	22.6
	800	-0.8	0.5	0.987	0.008	0.544	0.004	306.4	12.9	0.520	0.008	570.8	27.4
1.5	233	-6.9	2.5	0.981	0.010	0.538	0.004	246.9	9.9	0.469	0.029	467.7	18.3
	466	-2.0	1.0	0.979	0.010	0.540	0.004	274.8	17.1	0.506	0.017	519.5	29.8
	700	-0.9	0.6	0.987	0.013	0.547	0.002	307.4	13.1	0.533	0.008	569.2	20.4

Table B4.2. Textural properties from TPA tests of noodles processed at 115°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	367	-3.1	2.5	0.973	0.012	0.534	0.003	253.5	9.4	0.486	0.024	488.1	17.9
	733	-1.1	1.0	0.972	0.007	0.536	0.005	344.7	12.0	0.506	0.015	662.0	25.6
	1100	-0.7	0.5	0.987	0.006	0.552	0.004	406.5	15.9	0.532	0.013	746.5	32.6
1	233	-6.3	3.1	0.982	0.010	0.531	0.005	270.2	11.6	0.450	0.021	518.1	22.2
	466	-2.8	1.6	0.977	0.015	0.531	0.005	333.2	21.1	0.486	0.018	642.8	42.7
	700	-1.3	1.0	0.980	0.010	0.543	0.005	391.6	11.6	0.518	0.015	736.9	22.0
1.5	133	-9.0	6.0	0.974	0.013	0.527	0.004	242.7	13.4	0.434	0.028	473.0	25.6
	266	-7.2	3.9	0.969	0.011	0.525	0.003	287.5	11.9	0.440	0.021	565.4	25.1
	400	-3.2	2.1	0.977	0.010	0.533	0.003	316.0	11.1	0.480	0.010	606.9	20.2

Table B4.3. Textural properties from TPA tests of noodles processed at 120°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	267	-3.9	2.0	0.965	0.016	0.521	0.003	294.5	9.1	0.432	0.009	585.8	15.9
	533	-3.7	1.7	0.968	0.020	0.521	0.005	408.8	10.6	0.444	0.017	811.3	24.0
	800	-1.4	1.0	0.977	0.015	0.540	0.007	452.2	20.2	0.502	0.013	857.2	38.2
1	200	-9.0	3.8	0.965	0.013	0.529	0.004	311.8	12.1	0.437	0.020	610.5	24.8
	400	-2.2	2.0	0.964	0.019	0.522	0.006	383.5	11.6	0.443	0.020	761.8	35.9
	600	-1.7	0.9	0.969	0.014	0.539	0.012	453.9	34.3	0.484	0.018	869.1	50.3
1.5	117	-14.1	6.3	0.979	0.010	0.531	0.006	282.5	16.0	0.408	0.028	543.8	33.8
	233	-7.8	1.9	0.971	0.011	0.518	0.002	343.2	13.6	0.421	0.022	682.9	27.1
	350	-1.8	1.3	0.974	0.019	0.529	0.008	398.3	35.1	0.474	0.027	771.8	58.9

Table B4.4. Textural properties from TPA tests of noodles processed at 125°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	217	-2.3	0.7	0.963	0.018	0.505	0.007	287.2	26.7	0.413	0.022	591.1	50.9
	433	-4.5	3.6	0.974	0.016	0.528	0.004	363.2	18.6	0.461	0.020	705.5	33.0
	650	-2.3	1.3	0.981	0.010	0.540	0.005	452.7	13.1	0.506	0.016	854.5	26.9
1	167	-11.8	6.7	0.978	0.010	0.526	0.003	300.1	20.8	0.406	0.024	583.6	35.4
	333	-4.6	2.6	0.966	0.017	0.523	0.004	368.4	11.9	0.453	0.017	729.6	21.3
	500	-1.0	0.9	0.980	0.011	0.550	0.004	390.1	10.3	0.521	0.021	723.8	15.9
1.5	100	-4.8	1.4	0.951	0.018	0.511	0.006	255.7	17.4	0.400	0.018	525.7	29.6
	200	-4.7	1.8	0.933	0.024	0.506	0.007	297.1	9.3	0.403	0.019	629.1	26.0
	300	-2.8	1.2	0.964	0.022	0.525	0.008	360.0	10.4	0.460	0.029	712.9	29.6

Table B4.5. Textural properties from TPA tests of noodles processed at 130°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	167	-3.3	0.7	0.931	0.020	0.504	0.003	288.5	24.4	0.396	0.010	615.9	54.6
	333	-1.6	1.0	0.962	0.017	0.514	0.006	339.5	17.9	0.444	0.019	686.6	41.7
	500	-1.3	0.8	0.970	0.015	0.525	0.008	419.4	25.3	0.477	0.017	822.8	33.2
1	133	-13.6	5.9	0.948	0.028	0.516	0.004	320.7	13.7	0.381	0.023	655.3	23.5
	266	-2.8	1.6	0.944	0.024	0.505	0.007	393.1	36.7	0.425	0.009	824.5	71.8
	400	-2.9	1.0	0.947	0.017	0.520	0.007	409.7	25.0	0.462	0.014	831.3	40.8
1.5	83	-3.9	1.2	0.959	0.010	0.510	0.003	266.0	20.3	0.410	0.016	544.2	42.8
	167	-5.9	1.7	0.941	0.019	0.516	0.007	349.6	18.6	0.411	0.016	720.2	34.3
	250	-6.6	2.8	0.964	0.019	0.516	0.004	405.9	18.4	0.422	0.023	817.2	32.2

Table B4.6. Textural properties from TPA tests of noodles processed at 135°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	150	-8.3	4.1	0.964	0.007	0.516	0.009	279.0	17.7	0.433	0.032	560.2	31.7
	300	-1.8	0.6	0.956	0.008	0.512	0.009	315.4	13.5	0.442	0.018	644.5	19.9
	450	-1.4	1.6	0.969	0.011	0.531	0.008	455.8	20.4	0.466	0.028	886.7	44.1
1	117	-6.6	2.4	0.964	0.017	0.516	0.008	260.5	11.6	0.433	0.030	523.8	12.9
	233	-6.0	2.1	0.962	0.013	0.517	0.004	330.2	21.6	0.443	0.027	663.7	39.4
	350	-2.4	1.6	0.978	0.010	0.536	0.007	361.2	16.2	0.500	0.021	689.3	32.6
1.5	75	-16.7	3.2	0.965	0.015	0.521	0.004	337.8	18.1	0.375	0.016	671.8	33.9
	150	-3.4	1.4	0.942	0.023	0.512	0.009	288.6	20.5	0.434	0.027	598.1	43.3
	225	-6.4	2.1	0.934	0.016	0.516	0.005	344.4	22.7	0.443	0.014	713.9	39.9

Table B4.7. Textural properties from TPA tests of noodles processed at 140°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	133	-4.6	1.3	0.932	0.017	0.508	0.005	283.5	18.8	0.413	0.008	598.0	31.3
	266	-5.0	6.1	0.969	0.013	0.525	0.007	372.4	24.7	0.442	0.039	732.5	48.6
	400	-2.3	3.1	0.965	0.019	0.533	0.004	444.0	18.2	0.461	0.027	863.6	43.7
1	100	-7.5	4.0	0.947	0.018	0.511	0.009	259.4	20.5	0.406	0.030	535.6	38.3
	200	-7.6	3.3	0.978	0.009	0.529	0.005	324.8	20.5	0.459	0.027	627.3	39.2
	300	-0.5	0.5	0.970	0.014	0.541	0.005	429.1	33.2	0.500	0.014	818.2	57.1
1.5	67	-14.4	4.7	0.964	0.024	0.516	0.009	341.2	26.5	0.374	0.022	685.8	51.5
	133	-8.9	3.2	0.956	0.011	0.513	0.008	325.8	19.7	0.422	0.033	665.1	50.9
	200	-4.6	2.4	0.967	0.016	0.531	0.006	375.7	10.3	0.487	0.012	731.5	12.3

Table B4.8. Textural properties from TPA tests of noodles processed at 145°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	117	-16.0	4.0	0.970	0.010	0.519	0.007	318.1	13.4	0.404	0.031	631.6	27.6
	233	-9.1	2.8	0.977	0.017	0.530	0.007	400.1	17.2	0.457	0.032	773.2	38.1
	350	-1.6	1.7	0.966	0.009	0.541	0.005	423.1	24.8	0.492	0.021	808.5	42.6
1	83	-22.6	11.7	0.964	0.012	0.512	0.004	326.1	13.3	0.349	0.026	660.8	30.2
	167	-13.1	4.5	0.956	0.014	0.512	0.007	364.8	16.3	0.387	0.021	746.0	34.8
	250	-5.0	2.6	0.975	0.014	0.530	0.008	378.9	17.8	0.461	0.026	733.6	41.0
1.5	58	-8.6	1.4	0.947	0.022	0.512	0.002	262.9	15.9	0.401	0.013	543.4	38.6
	117	-10.8	6.6	0.945	0.017	0.516	0.010	342.8	17.8	0.406	0.022	704.4	51.3
	175	-6.6	2.2	0.967	0.016	0.530	0.005	401.5	23.6	0.460	0.028	783.6	48.1

Table B4.9. Textural properties from TPA tests of noodles processed at 150°C in superheated steam.

Velocity (m/s)	Processing Time (s)	Adhesiveness (g•s)		Springiness		Cohesiveness		Chewiness (g)		Resilience		Hardness (g)	
		avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev	avg	std dev
0.5	100	-17.1	5.7	0.958	0.020	0.515	0.005	343.2	15.1	0.391	0.025	695.1	25.8
	200	-11.1	6.6	0.968	0.016	0.511	0.006	383.7	24.3	0.411	0.027	775.1	46.0
	300	-5.6	3.6	0.972	0.014	0.540	0.006	482.0	29.9	0.495	0.023	919.3	58.1
1	67	-19.7	6.1	0.965	0.014	0.518	0.004	283.3	15.0	0.367	0.026	566.5	28.8
	133	-12.8	4.6	0.972	0.015	0.526	0.006	318.9	18.5	0.438	0.037	624.0	34.2
	200	-7.1	3.9	0.977	0.010	0.531	0.008	367.8	18.3	0.494	0.024	709.0	42.5
1.5	50	-13.3	6.2	0.948	0.018	0.520	0.004	270.9	20.7	0.403	0.027	549.9	42.5
	100	-7.4	1.4	0.961	0.014	0.515	0.005	253.0	16.0	0.431	0.011	511.1	27.4
	150	-8.6	3.8	0.980	0.016	0.537	0.004	379.5	20.0	0.479	0.023	722.3	41.2

Table B4.10. Textural properties from TPA tests of raw noodles.

Textural Property	avg	std dev
Adhesiveness (g•s)	-17.9	11.4
Springiness	0.989	0.004
Cohesiveness	0.544	0.010
Chewiness (g)	200.8	20.3
Resilience	0.406	0.030
Hardness (g)	372.7	31.6

Appendix B5. Noodle dimensions (Chapter 5.4.3)

Table B5.1. Dried and cooked noodle dimensions.

Temperature (°C)	Dried		Cooked		% Difference[a]	
	Width (mm)	Thickness (mm)	Width (mm)	Thickness (mm)	Width	Thickness
Raw[b]	1.60 ± 0.04[c]	1.83 ± 0.09[c]	2.13 ± 0.04	2.37 ± 0.10	33.1	29.5
110	1.64	2.01	2.09	2.39	27.4	18.9
115	1.64	2.01	2.07	2.35	26.2	16.9
120	1.66	2.08	2.08	2.37	25.3	13.9
125	1.68	2.11	2.13	2.41	26.8	14.2
130	1.70	2.22	2.17	2.51	27.6	13.1
135	1.76	2.29	2.19	2.54	24.4	10.9
140	1.74	2.23	2.17	2.49	24.7	11.7
145	1.69	2.12	2.14	2.41	26.6	13.7
150	1.69	2.30	2.14	2.56	26.6	11.3
LSD[d]	0.02	0.03	0.02	0.02		

[a] difference between dried and cooked dimensions
[b] raw noodles, average ± standard deviation, n = 100
[c] raw unprocessed noodles
[d] Least significant difference ($\alpha = 0.05$)

Appendix B6. Commercial noodle ingredients (Chapter 5.6)

Table B6.1. Major ingredients of commercial instant noodle products

Brand	Major Ingredients
Rosan	Flour, coconut oil, salt, colour
Nong Shim	Flour, palm oil, potato starch, potassium carbonate, sodium phosphates, sodium carbonate, riboflavin, salt
No Name	Flour, oil, salt, sodium tripolyphosphate, potassium carbonate, sodium carbonate
Noodle Time	flour, starch, oil, onion powder, egg white powder, salt, spice
Six Fortune	Flour, oil, potato starch, salt
Farkay	Flour, oil, egg, water, salt, starch, sodium bicarbonate

Table B6.2. Superheated steam processed noodles with acceptable colour values.

Temperature (°C)	Velocity (m/s)	Processing Time (s)	L* Avg	L* Std Dev	a* Avg	a* Std Dev	b* Avg	b* Std Dev	Moisture (% db)
110	1	267	70.2	0.4	-0.1	0.1	24.1	0.2	26
110	1.5	233	71.6	0.5	-0.9	0.2	23.7	0.3	23
115	1	233	70.4	0.5	-1.2	0.1	25.0	0.2	22
115	1.5	133	72.0	0.6	-2.2	0.2	22.9	0.1	21
120	0.5	267	69.1	0.4	-1.1	0.1	24.3	0.3	22
120	1	200	72.1	0.4	-1.6	0.1	24.7	0.2	19
120	1.5	117	73.0	0.4	-2.2	0.1	23.1	0.1	19
125	1	167	71.5	0.4	-1.9	0.1	23.4	0.1	16
125	1.5	100	72.2	0.3	-2.2	0.1	22.7	0.2	19
125	1.5	200	69.7	0.2	-0.7	0.1	25.2	0.1	11
130	0.5	167	70.5	0.5	-1.3	0.1	24.1	0.1	20
130	1	133	71.2	0.7	-1.5	0.1	23.3	0.4	19
130	1.5	83	70.6	0.7	-1.8	0.1	21.7	0.3	21
130	1.5	167	72.2	0.3	-1.0	0.1	24.8	0.1	12
135	0.5	150	68.3	0.3	-1.3	0.1	24.0	0.2	22
135	1	117	71.7	0.4	-1.9	0.1	22.9	0.1	15
135	1.5	75	73.4	0.6	-1.8	0.1	21.7	0.2	18
135	1.5	150	71.2	0.7	-0.4	0.1	24.8	0.3	11
140	0.5	133	69.8	1.2	-1.8	0.1	22.8	0.5	22
140	1	100	72.4	0.3	-2.0	0.1	21.7	0.2	19
140	1.5	67	71.5	0.7	-1.5	0.1	21.8	0.2	16
140	1.5	133	68.7	0.8	-0.3	0.2	24.5	0.2	10
145	0.5	117	67.5	0.6	-1.3	0.1	22.1	0.4	21
145	1	83	71.2	0.9	-2.0	0.1	20.7	0.3	17
145	1.5	58	70.2	1.3	-1.4	0.1	17.9	0.3	18
150	0.5	100	70.0	0.9	-1.6	0.1	21.4	0.4	20
150	1	67	70.4	1.0	-2.0	0.1	20.2	0.6	17
150	1	133	67.1	0.6	-0.2	0.1	23.6	0.5	8
150	1.5	50	75.4	0.6	-1.1	0.1	19.9	0.2	16
150	1.5	100	73.7	0.5	-0.4	0.1	22.5	0.2	9