

**MODELLING THE DRYING OF SPENT GRAINS
IN SUPERHEATED STEAM**

BY
ZHONGWEI TANG

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

Department of Biosystems Engineering
University of Manitoba
Winnipeg, Manitoba

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ABSTRACT

Spent grains are usually required to be dried to about 0.11 kg/kg db for prolonging the storage time and reducing the mass and transportation cost of the products. Superheated steam can be used for the direct drying of spent grains for saving energy compared with conventional rotary-drum drying. The drying dynamics of spent grains in superheated steam can be studied by simulating the drying process with mathematical models. The principal objective of this research was, therefore, to develop the mathematical models describing the drying of thin layers and deep beds of spent grains in superheated steam. To achieve this objective, three aspects of work were done in this research: 1) determination of the equilibrium moisture content (EMC) of spent grains in superheated steam, which is the important parameter for the modelling of drying, 2) development of the mathematical models for drying thin layers of spent grains in superheated steam, which also provide the base for modelling deep-bed drying, and 3) development of the mathematical model for drying fixed beds of spent grains in superheated steam and validation of the drying model.

Two equations with regression-determined coefficients were developed for describing the EMC of spent grains in superheated steam. The steam temperature had a significant effect on the EMC. Under atmospheric pressure, the EMC decreased substantially from 9.3 to 1.7 kg/100 kg dry solids for brewers' spent grain (BSG) and from 6.7 to 1.4 kg/100 kg dry solids for distillers' spent grain (DSG) with an increase in the steam temperature from 105 to 140°C. The EMC reduced slightly beyond 140°C and approached zero at 200°C.

A mathematical model was proposed for describing the drying of thin-layer spent grains in superheated steam. Not only the temperature but also the velocity of steam had a significant effect on the steam drying process. Increasing steam temperature from 110 to 180°C decreased the drying time by 80% for drying of BSG and by 85% when drying DSG at a steam velocity of 0.7 m/s. At 145°C, an increase in steam velocity from 0.3 to 1.1 m/s cut the drying time by half for both spent grains.

A partial-differential-equation (p.d.e.) model describing the steam drying of spent grains in a fixed bed was developed using the mass flow rate of steam as one of the important variables. The model was solved with a finite-difference method, which was accomplished by a computer program written in the FORTRAN language. A good agreement was obtained between the calculated and measured average moisture contents in BSG samples during the drying process.

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LIST OF SYMBOLS

a	Specific area, surface area per unit volume, m^2/m^3
c	Specific heat of dry material, $\text{J}/(\text{kg} \cdot ^\circ\text{C})$
c_a	Specific heat of dry air, $\text{J}/(\text{kg} \cdot ^\circ\text{C})$
c_s	Specific heat of steam, $\text{J}/(\text{kg} \cdot ^\circ\text{C})$
c_v	Specific heat of water vapour, $\text{J}/(\text{kg} \cdot ^\circ\text{C})$
c_w	Specific heat of water, $\text{J}/(\text{kg} \cdot ^\circ\text{C})$
dt	Time increment, s
dx	Distance increment in drying bed, m
h	Heat transfer coefficient, $\text{J}/(\text{s} \cdot \text{m}^2 \cdot ^\circ\text{C})$, or $\text{J}/(\text{s} \cdot \text{m}^3 \cdot ^\circ\text{C})$
h_v	Latent heat of evaporation, J/kg
h_v^*	Latent heat of evaporation of free water, J/kg
k	Drying constant
q	Heat flux, $\text{J}/(\text{m}^2 \cdot \text{s})$
r	Spherical or cylindrical coordinate, m
t	Drying time, s or min
v	Velocity of material moving in a cross-flow dryer, m/s
v_a	Velocity of drying air, m/s
x	x coordinate, distance in bed depth, m
y	y coordinate, m
z	z coordinate, m

D_m	Moisture diffusion coefficient, m^2/s
G	Mass flow rate of material to be dried, $\text{kg}/(\text{m}^2 \cdot \text{s})$
G_a	Mass flow rate of dry air, $\text{kg}/(\text{m}^2 \cdot \text{s})$
G_s	Mass flow rate of steam, $\text{kg}/(\text{m}^2 \cdot \text{s})$
G_{se}	Mass flow rate of exhaust steam at outlet, $\text{kg}/(\text{m}^2 \cdot \text{s})$
G_{so}	Mass flow rate of steam at inlet, $\text{kg}/(\text{m}^2 \cdot \text{s})$
H	Specific (or absolute) humidity of air, $\text{kg water vapour}/\text{kg dry air}$
L	Depth of grain bed in a counter-flow dryer, m
M	Moisture content, $\text{kg H}_2\text{O}/\text{kg dry mass}$, or $\text{kg}/\text{kg db}$
$\bar{M}$	Average moisture content, $\text{kg}/\text{kg db}$
M_e	Equilibrium moisture content, $\text{kg}/\text{kg db}$
M_{eo}	Equilibrium moisture content at temperature T_{so} , $\text{kg}/\text{kg db}$
M_o	Initial moisture content, or moisture content at inlet, $\text{kg}/\text{kg db}$
MR	Moisture ratio, $(\bar{M} - M_e)/(M_o - M_e)$, or $(M - M_e)/(M_o - M_e)$
P_r	Relative pressure of steam, decimal
R	Radius of a body, m
S	Cross-sectional area in an elemental control volume, m^2
T	Temperature of material to be dried, $^{\circ}\text{C}$
T_a	Air temperature, $^{\circ}\text{C}$
T_{ao}	Air temperature at inlet, $^{\circ}\text{C}$
T_{ae}	Equilibrium value of air temperature in a bed of infinite depth, $^{\circ}\text{C}$

T_o	Initial temperature of material to be dried, °C
T_s	Temperature of steam, °C
T_{se}	Temperature of exhaust steam at outlet, °C
T_{so}	Temperature of steam at inlet, °C
T_{sur}	Surface temperature of material to be dried, °C.
T_∞	Temperature of drying medium, °C
V_s	Velocity of steam, m/s

GREEK SYMBOLS

ρ	Bulk density of material to be dried or density of a solid, kg/m ³
ρ_a	Density of air, kg/m ³
ρ_e	Final bulk density of material dried to the equilibrium, kg/m ³
ρ_s	Density of steam, kg/m ³
ρ_o	Initial bulk density of material to be dried, kg/m ³
ε	Porosity of deep bed
∇	Symbol of gradient
∇^2	Laplacian operator
Δt	Time increment, s
Δx	Distance increment in drying bed, m
Δx_e	Final thickness of a layer dried to the equilibrium, m
Δx_o	Initial thickness of a layer, m

1 INTRODUCTION

Spent grains are the by-products from the production of alcoholic beverages and ethanol fuels in breweries or distilleries. Brewers' spent grain (BSG) is the residue of beer making in breweries, which use malted barley as the major raw material (Johnson and Peterson 1974). Distillers' spent grain (DSG) is the product left in distilleries after alcohol is removed by distillation from the fermented grains such as corn, wheat, barley, rice, and rye (Wampler and Gould 1984; Woods et al. 1994).

Most of the starch in the raw materials is fermented to produce alcohol, but almost all the protein, fat, and fibre remain and are concentrated in the spent grains (Kissell and Prentice 1979; Wampler and Gould 1984). Therefore, both BSG and DSG are excellent sources of protein and energy. They are mainly used as feed for animals such as cattle and poultry (Ranhotra et al. 1982; Woods et al. 1994). Spent grains can also be used as a flour supplement to produce human food products such as baked foods (brownies, cookies, yeast breads, quick breads), extruded snacks, and baby foods (Kim et al. 1989; Rasco et al. 1990; Wampler and Gould 1984; Wu et al. 1984). In addition, dried spent grains can be used as fuel, but this is a less lucrative option than the use of spent grains as animal feed or flour supplements for human foods (Richards 1997b).

Normally, wet spent grains contain 75% to 85% moisture (wet basis, wb), which can be reduced to 60% - 70% by mechanical de-watering using a screw press or centrifuge (Woods et al. 1994). The wet spent grains are heavy, likely to drip during transportation, and easily

spoiled. To reduce the mass (and thereby reduce the transportation cost) of spent grains and to prolong their storage time, spent grains need to be dried to about 10% moisture content (wb) (Woods et al. 1994). Direct rotary-drum dryers are conventionally employed for this purpose, and other dryers such as direct flash dryers, indirect steam-tube dryers, and indirect steam-disk dryers can also be found in some distilleries or breweries (Richards 1997a; Woods et al. 1994).

Drying spent grains is a very energy-intensive operation in the alcohol and beer industry. Drying spent grains with superheated steam could be an alternative for saving energy. Woods et al. (1994) proposed a fluid-bed steam drying system to dry DSG. The circulation of superheated steam in a closed-loop drying system can reduce the energy wastage that occurs with hot-air drying. Also, the exhaust steam produced from the evaporation of moisture from the wet product can be used in other operations in distilleries, such as cooking raw materials, stripping and rectifying distillation of ethanol, and concentrating residual stillage. Although steam drying makes DSG darker than air drying, the material remains a relatively good colour compared with the dried DSG available on the market. In addition, the stripping capacity of the superheated-steam can remove the acetic acid during drying and make the dried DSG aroma similar to baked goods. Therefore, it seems reasonable to dry spent grains with superheated steam.

To my knowledge, drying spent grains with superheated steam has not been used commercially, and no systematic studies on it have been reported in the literature except for wheat-derived stillage which was experimentally dried in Europe (Woods et al. 1994). To

optimize the design parameters of dryers for steam drying of spent grains, it is necessary to know the drying dynamics of the spent grains in superheated steam.

One of the important parameters in describing a drying process is equilibrium moisture content (EMC), which is defined as the moisture content of a product after the product has been exposed to a particular drying medium for a sufficiently long (infinite) period of time (Brooker et al. 1974; Pabis et al. 1998). The EMC represents the lowest moisture content which can be reached in the drying process for given drying conditions. It depends on the nature of the product and the conditions of the drying medium. For non-hygroscopic materials, the EMC is essentially zero at any drying conditions. For biological materials which are hygroscopic, the EMC varies over a wide range as the drying conditions change.

Mathematical modelling of drying processes is one of the most important research aspects of drying studies. The principle of modelling is based on having a set of equations which completely describe the drying process or drying system (Strumillo and Kudra 1986). The history of modelling of drying began with an often quoted paper by Lewis (1921) and with the famous paper by Sherwood (1929). Only after 1950's, a variety of mathematical models describing the drying of biological materials, especially grains, appeared in the literature. Various drying models are normally categorized into thin-layer (or single-particle) and deep-bed drying models.

The term "thin layer" is defined as a layer of drying material which is dried by convection and the drying can be modelled by equations describing the drying of a single particle of the

material suspended in the drying medium (Pabis et al. 1998). A thin-layer drying model can be applied to a single particle suspended in the drying medium, one layer (mono-granular layer) of particles in the drying stream, or multilayer of drying material if the conditions of the drying medium can be considered the same at any position in the multilayer (Jayas et al. 1991). In contrast, in deep-bed drying, the drying condition changes in the direction of the flow of drying medium. In practice, the forced-convective drying operations of biological products almost always happen in deep-bed drying.

The modelling of thin-layer drying provides not only a good tool for studying the drying kinetics of a single particle or a thin-layer of material but also the base for modelling practical deep-bed drying. The equation describing thin-layer drying can be incorporated into a group of equations to describe the drying process of a deep-bed material. In addition, for the purpose of computation, a deep bed can be thought of as a series of thin-layers (Henderson and Henderson 1968; Thompson et al. 1968). Each layer is dried for a short time interval using the exhaust drying medium from the previous layer as the input drying medium.

Solving the set of equations in a deep-bed drying model, usually by computer simulation, results in describing the moisture and temperature changes in the product to be dried, consequently predicting the drying rate and drying time, at different drying conditions or with different design parameters of the system. Thus modelling of deep-bed drying can be used for: i) predicting the behaviour of the modelled drying processes or systems and getting a good understanding of them, ii) controlling drying processes or systems, iii) improving existing drying systems and promoting their operation efficiencies, and iv) optimizing the design

parameters for new systems (Brooker et al. 1974; Cenkowski et al. 1993; Jayaraman and Das Gupta 1992; Parry 1985; Sharp 1982; Thompson et al. 1968).

The objectives of this study were: i) to obtain the EMC data of spent grains dried in superheated steam and determine the sorption relationship between spent grains and superheated steam, ii) to develop mathematical models for drying of thin layers of spent grains in superheated steam and analyse the drying characteristics of thin layers of spent grains in superheated steam, iii) to develop a fixed-bed drying model for the simulation of drying of fixed-beds of spent grains with superheated steam as well as solve and validate the drying model.

The thesis was written in a publication-manuscript format, but much more details were put in the thesis than in the publications. Besides INTRODUCTION (Chapter 1), LITERATURE REVIEW (Chapter 2), GENERAL CONCLUSIONS (Chapter 6), and RECOMMENDATIONS FOR FUTURE WORK (Chapter 7), the major contents of the thesis were written in Chapters 3, 4, and 5. Chapter 3 entitled EMC OF SPENT GRAINS IN SUPERHEATED STEAM UNDER ATMOSPHERIC PRESSURE came from a publication (Tang and Cenkowski 2001); Chapter 4 entitled MODELLING THE DRYING OF THIN-LAYER SPENT GRAINS IN SUPERHEATED STEAM was recently submitted to the Journal of Food Engineering for publication (Tang et al. 2002); and Chapter 5, MODELLING THE DRYING OF FIXED-BED SPENT GRAINS IN SUPERHEATED STEAM, will be submitted for publication in September 2002.

2 LITERATURE REVIEW

2.1 Mechanism of drying and modelling the drying of biological products

2.1.1 Introduction to drying of biological products

Drying or dehydration is the process that uses heat to remove moisture from wet materials. It is an important operation in processing biological materials such as grains, fruits, and vegetables. The objectives for the drying of biological materials are: i) to remove the moisture from the materials to a level at which microbial spoilage and deteriorating reactions are minimized or prevented; ii) to reduce the product mass and volume, which promotes the efficiencies and minimises the costs in the packing, transportation, and storage of the products; and iii) to produce final products of a great variety and convenience for consumers (Chung and Chung 1982; Cohen and Yang 1995; Cunningham 1982; Fortes and Okos 1980; Jayaraman and Das Gupta 1992; King 1974).

Initially, biological products were dried in the sun; mechanical drying appeared at the turn of the 20th century. Some excellent drying techniques such as fluidized drying and vacuum drying that were efficient and produced high-quality products were available only after the mid of the 20th century (Hayashi 1989).

Drying operation may be conducted in a number of ways (Brennan et al. 1990; Cohen and Yang 1995; Cunningham 1982; Jayaraman and Das Gupta 1992; Strumillo and Kudra 1986). In convective drying, the product is placed in contact with a moving stream of heated

medium, and the heat for the vaporization of moisture is supplied to the product by thermal convection. In conductive drying, the product is dried by a direct contact with a heated surface; heat is supplied mainly by thermal conduction. In radiative drying, the product is dried by the application of energy from a radiant source, and heat is supplied by thermal radiation. In microwave drying, the product is dried by microwave energy which is supplied by electromagnetic energy generated at microwave frequencies. In freeze drying, the moisture in the product is frozen first and then sublimed directly to vapour, usually by the application of heat under a very low pressure. Other drying techniques include: vacuum drying, osmotic drying, and explosive puffing (Cohen and Yang 1995; Jayaraman and Das Gupta 1992).

Due to the change of life style in the world, there exists a great demand for a wide variety of dried products, such as instantly reconstitutable ingredients with high quality and convenience for fast foods (Jayaraman and Das Gupta 1992). This has stimulated the advances in drying techniques. On the other hand, the development of drying techniques and drying equipment have made available a wide range of dried biological products. In fact, most of the biological products can be dried. Biological materials can be generally distinguished as three main types: liquid solutions and gels (e. g. milk, coffee extracts, fruit juice, and gelatinized products), capillary-porous rigid materials (e.g. grains and spent grains), and capillary-porous colloidal materials (e.g. vegetables, fruits, meats, and beef) (Bruin and Luyben 1980; Cunningham 1982). Each drying technique or dryer has its own characteristics and is suitable for drying specific biological materials.

The knowledge of the mechanism and mathematical modelling of drying is very important

for developing novel drying systems and upgrading existing drying equipment to improve the drying efficiency and product quality. Based on the fact that convective drying is the most commonly used drying technique and solid biological materials are most often required to dry, this review will only focus on the mechanism of convective drying and modelling the convective drying of solid biological materials.

2.1.2 Basic concepts and theories applicable to drying

Moisture in biological materials

Basically, moisture held in biological materials may be distinguished as unbound water (i.e. free water) and bound water (Harper 1976; Okos et al. 1992). Unbound water is kept in the interstitial spaces and within the pores of the material by capillary absorption. This water is held in liquid form by the force of surface tension and behaves physically as free water. It has the same vapour pressure and same latent heat of evaporation as pure water at the same temperature. The amount of free water in biological products is closely related to the physical structures of the products. Free water is removed during the constant-rate drying period in which the nature of the product does not have a great effect on the drying process. Bound water is held on the internal and external surfaces of the material by interactions between the water molecules and those of the solid material to form a mono-layer of water or by interactions between the water molecules to form a multi-layer of water. Bound water exhibits a lower vapour pressure and a lower mobility than pure water at the same temperature. The energy required to evaporate the bound water is much greater than the heat of vaporization

of pure water, especially in a low moisture range. The amount of bound water held in biological products is closely associated with the chemical structures of the products. The removal of bound water happens in the falling-rate drying period.

Sorption phenomena

A consideration of water-sorption phenomena is essential in understanding drying principles (Chung and Chung 1982; Fortes and Okos 1980). Both the wet product and the moist air exert a water-vapour pressure. At equilibrium, the water-vapour pressure in the product is equal to that in the air, and the moisture content of the product reaches the equilibrium moisture content (EMC). If the water-vapour pressure in a product at a given moisture content is higher than that in the surrounding air, the product will lose moisture until equilibrium is achieved, which is a desorption process. If the water-vapour pressure in the product is lower than that in the surrounding air, the product will gain moisture from the air, which is an adsorption process.

The most convenient method to show the EMC of a product in the surrounding air is to develop sorption isotherms, which are the curves relating the EMC to the relative humidity (RH) or water activity (a_w) at constant temperatures (Chung and Chung 1982; Fortes and Okos 1980). The RH or a_w is defined as the ratio of the equilibrium water-vapour pressure (P) to the vapour pressure (P_o) of pure water at a given temperature, i.e. $RH = a_w = P/P_o$ (Cenkowski et al. 1992). Many products exhibit different equilibrium moisture characteristics depending upon whether the equilibrium is reached by desorption or adsorption of the

moisture. In general, the EMC reached by desorption is greater than that by adsorption (Yang and Cenkowski 1993). For the storage of dried products, the EMC reached by adsorption is of a particular interest. However, the EMC reached by desorption is of a particular interest in drying operations.

In the past, many researchers attempted to formulate mathematical models of the equilibrium isotherms for biological materials. Fortes and Okos (1980) and Pabis et al. (1998) summarized the most commonly found isotherm equations.

Characteristics of drying process

A typical convective drying process for a high-moisture-content product is composed of initial, constant-rate, and falling-rate drying periods which can be illustrated by a drying curve and a drying-rate curve (Fig. 2.1).

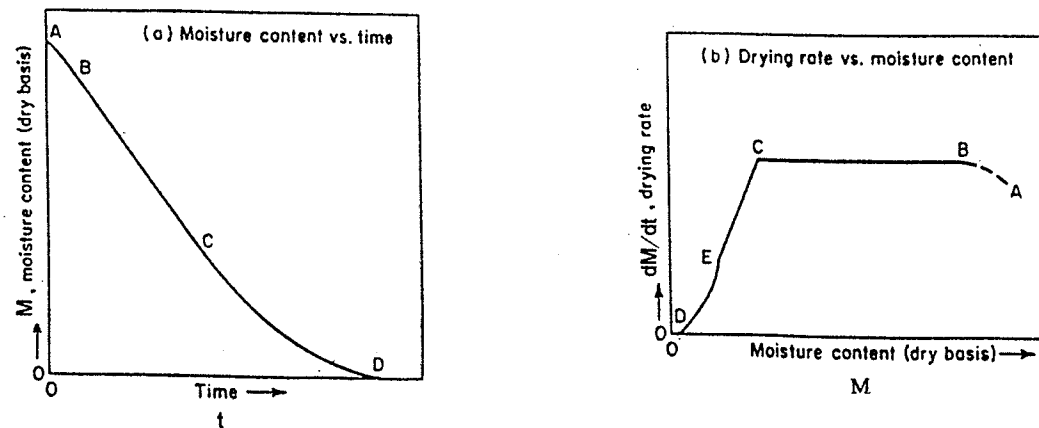


Figure 2.1 (a) Drying curve

(b) Drying-rate curve (Strumillo and Kudra 1986)

The initial period (section AB) is usually a short period during which the material comes

into balance with the drying conditions. Generally, the temperature of material rises to wet-bulb temperature during this period, and the drying rate rises accordingly. This period seldom has any practical importance, and its effect on the drying process can be ignored (Chung and Chung 1982).

In the constant-rate period (section BC), moisture movement in the material is rapid enough to maintain a saturated condition at the surface. The internal resistance to moisture transport is much less than the external resistance to water vapour removal from the product surface (Brooker et al. 1974). The internal mechanism of liquid flow does not affect the drying rate. The limiting factors are external such as the heat and mass transfer coefficients, the area exposed to the drying medium, and the difference in temperature between the drying medium and the product surface (Cohen and Yang 1995; Fortes and Okos 1980). The rate of mass transfer balances the rate of heat transfer, and the temperature of the saturated surface remains constant, which approaches the wet-bulb temperature and is near the boiling point of water if the drying medium is superheated steam (Chu et al. 1953). When the rate of moisture movement to the surface is lower than the rate of evaporation, some dry spots appear on the product surface and the falling rate period begins.

In the falling-rate period (section CD), the rate decreases continuously as long as the drying process is continued. At the same time, the temperature of the product increases gradually from the wet-bulb temperature to the air temperature. This period can be divided into two stages. In the first falling-rate drying stage (portion CE), the saturated surface area decreases, and the drying rate decreases (Fortes and Okos 1980). Generally, the drying rate

depends on factors affecting the diffusion of moisture away from the evaporating surface and those affecting the internal moisture movement. When the saturated surface disappears, the second falling-rate drying stage (portion ED) begins. The drying rate is now governed by the rate of internal moisture movement, and the influence of external variables diminishes (Strumillo and Kudra 1986). The drying rate falls even more rapidly than before. Finally the moisture content of the product reaches the EMC for the given drying conditions, and the drying process stops.

At point C on the drying and drying-rate curves (Fig. 2.1), the constant-rate period ends and the falling-rate period begins. The moisture content at this point is termed critical moisture content which depends on the characteristics of the product and the drying conditions. When the initial moisture content of the material is above the critical moisture content, the drying process starts in the constant-rate drying period. If, on the other hand, the initial moisture content is below the critical moisture content, the entire drying process occurs in the falling-rate drying period.

For most biological materials, the initial moisture contents are close or below the critical moisture contents, so the importance of the constant-rate period in drying of biological materials is diminished (Chirife 1983). Cereal grains do not display a constant-rate drying period unless they are harvested at a very immature state or have had water condensed or rained on their surface (Brooker et al. 1974). Only the drying of some high-moisture products, such as potato and sugar beet, at a low drying potential (low temperature and high relative humidity of air) shows a relatively short constant-rate drying period.

2.1.3 Modelling the drying of biological materials in a thin layer

It is generally admitted that the drying of biological materials in a thin layer happens in the falling-rate drying period, in which the drying kinetics is often described by Fick's law (Rizvi 1986). The drying model can be theoretically expressed as exact diffusion equations. This approach, however, is not always applicable due to the complexity of the transport mechanism in biological materials during drying. In some cases, simplified semi-theoretical or empirical equations may give reasonable predictions of the drying characteristics when experimental drying data are correlated with the equations.

Diffusion models

To simplify the analysis of drying process, it is often assumed that the moisture diffusion due to concentration gradient is the controlling mechanism in the drying of biological materials, especially in the drying of cereal grains (Pabis and Henderson 1961). The Fick's law in terms of moisture content is often used for describing the drying behaviour of grains. It is generally expressed as:

$$\frac{\partial M}{\partial t} = \nabla (D_m \nabla M) \quad (2.1)$$

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

$$\frac{\partial M}{\partial t} = D_m \nabla^2 M \quad (2.2)$$

In order to solve this kind of equations analytically, an appropriate geometric shape is

usually assumed for the approximate representation of individual grain kernels, e.g. a sphere, cylinder, or rectangular parallelepiped. The diffusion equation is then written in terms of appropriate coordinates, e.g. spherical, cylindrical, or rectangular coordinates. Equations for moisture-content distribution and corresponding series solutions for the moisture ratio for different geometries are summarised in the literature (Brooker et al. 1974; Crank 1975; Pabis et al. 1998; Parry 1985).

The choice of spherical body for the grain kernels is often made by the researchers to make the model simple (Hustrulid and Flikke 1959; Jaros 1991, cited by Pabis et al. 1998). It was shown that at the values of $MR \geq 0.4$, the drying curves predicted by diffusion models using different geometries were very similar (Chu and Hustrulid 1968). For a sphere assumed purely radial asymmetry, Eq. 2.2 takes the following form in spherical coordinates:

$$\frac{\partial M}{\partial t} = D_m \left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r} \right) \quad (2.3)$$

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

$$\begin{aligned} M(r,0) &= M_o, \quad r \leq R \\ M(R,t) &= M_e, \quad t \geq 0 \end{aligned} \quad (2.4)$$

The moisture ratio over a spherical kernel is given by

$$MR(t) = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-D_m n^2 \pi^2 t / R^2) \quad (2.5)$$

In practical cases, the diffusion coefficient is not constant, but changes with moisture content and / or temperature; the diffusion equations should be derived from Eq. 2.1.

Diffusion in a spherical body with D_m dependent on air temperature was used to describing the drying of ryegrass seeds (Nellist 1976) and shelled corn (Pabis and Henderson 1961). Marchant (1976, cited by Jayas et al. 1991) gave the following diffusion equation, in which D_m is a function of moisture content, for describing the drying of a spherical kernel.

$$\frac{\partial M}{\partial t} = D_m \left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r} \right) + \left(\frac{\partial M}{\partial r} \right)^2 \frac{\partial D_m}{\partial M} \quad (2.6)$$

Bruce (1985) used Eq. 2.6 with D_m dependent on moisture content and grain temperature to predict the average moisture content of barley samples dried in thin layers.

In convective air drying, the heat and moisture transfer phenomena take place simultaneously. The moisture in the solid is diffused towards the external surface and evaporated on the surface, and the vapour is convectively transferred into air stream; meanwhile, the heat is convectively transferred from the air to the surface of the solid and is conducted within the solid. To describe the drying characteristics accurately, some researchers have coupled heat and mass transfer equations in thin-layer drying models (Maroulis et al. 1995; Miketinac et al. 1992).

As drying is a simultaneous heat and moisture transfer process, both moisture and temperature changes would be involved in the solution of coupled differential equations. In some simplified cases, only a moisture diffusion equation needs to be solved. In most cases, however, the kinetic parameters such as moisture diffusivity and thermal conductivity are not constant, the boundaries are of irregular shapes, and / or the boundary conditions are not of the first kind (the first kind of boundary conditions: $M|_{r=R} = M_e$, $T|_{r=R} = T_a$, at $t \geq 0$), so the

equations are non-linear and must be solved by numerical methods: finite-difference method (FDM) and finite-element method (FEM).

The FDM approximates the quantities in the governing differential equations (Incropera and DeWitt 1985). It is simple for solving regular-boundary problems. However, it is rather cumbersome when regions have curved or irregular boundaries, and it is difficult to write general computer programs for the method. The FEM utilizes an integral formulation to generate a system of algebraic equations and uses continuous piecewise smooth functions for approximating the unknown quantities (Incropera and DeWitt 1985). It provides the flexibility and versatility necessary for the analysis of continuum field problems, such as mass and heat transfer problems, where material behaviour, configuration, and boundary are complex.

Semi-theoretical models

The diffusion equation with the first kind of boundary condition can be solved analytically for regular geometries. The solution is presented in form of infinite exponential series such as Eq. 2.5. To simplify the solution, only the first term or the first several terms of the infinite series is often employed to calculate the drying rate. Several researchers (Becker and Sallans 1955; Henderson and Pabis 1961; Hustrulid 1963) reported that the solution for spherical bodies can be reduced to

$$MR(t) = \frac{6}{\pi^2} \exp(-D_m \pi^2 t / R^2) \quad (2.7)$$

To simulate the drying of wheat and in-shell pecans, Waston and Bhargava (1974) and Chhinnan (1984) used the following simple equation:

$$MR(t) = a \exp(-kt) \quad (2.8)$$

where a and k are constants. The simplification of using one term of exponential series has a great advantage that the resulting equation can be linearized by using a logarithmic transformation, and therefore can be fitted to experimental data by simple linear regression. However, this approach may result in an inaccuracy, mainly during the initial stage of drying operation.

Nellist and O'Callaghan (1971) applied two terms of exponential series to describe the drying of ryegrass seed and shelled corn:

$$\overline{M} - M_e = a \exp(-k_1 t) + b \exp(-k_2 t) \quad (2.9)$$

where a , b , k_1 and k_2 are constants. For describing the drying of shelled corn, Henderson (1974) proposed an equation of two-term exponential series in the form:

$$MR(t) = a \exp(-k_1 t) + (1 - a) \exp(-k_2 t) \quad (2.10)$$

where a , k_1 , and k_2 , are constants. For simulating the thin-layer drying of shelled corn, Sharaf Eldeen et al. (1978, cited by Parry 1985) took the equation:

$$MR(t) = a_1 \exp(-b_1 kt) + a_2 \exp(-b_2 kt) \quad (2.11)$$

where a_1 , a_2 , b_1 , b_2 , and k are constants. In thin-layer drying models with two terms of exponential series, the constants must be obtained by fitting the equations to experimental data with non-linear regressions.

Empirical models

Lewis (1921) suggested an equation analogous to Newton's law of cooling, which was

formulated by assuming that the rate of moisture loss is proportional to the instantaneous difference between the moisture content of the material and the EMC:

$$\frac{d\bar{M}}{dt} = -k(\bar{M} - M_e) \quad (2.12)$$

Equation 2.12 may also be written as:

$$MR(t) = \exp(-kt) \quad (2.13)$$

where k is drying constant. Many researchers (Bruce 1985; Hall and Rodriques-Arias 1958; O'Callaghan et al. 1971; Westerman et al. 1973; White et al. 1981) employed this model for characterizing drying thin layer of various grains such as shelled corn, barley, and wheat. In the model for drying of thin-layer barley, Bruce (1985) correlated the drying constant k with drying-air temperature by

$$k = a \exp[b/(T_a + 273)] \quad (2.14)$$

where a and b are constants. It was shown that the model underestimates the initial drying rate and overestimates the rate when the moisture content approaches the EMC. It gives a poor predication of the shape of drying curve. However, it could be used for simplifying the drying simulation and enhancing the computational speed.

Chen and Johnson (1969a; 1969b) proposed the following equation by modifying Eq. 2.12:

$$\frac{d\bar{M}}{dt} = -k(\bar{M} - M_e)^n \quad (2.15)$$

where k and n are empirical constants. Troeger and Hukill (1971) fitted this model to the experimental data of drying thin-layer shelled corn.

To improve the accuracy of modelling the drying of thin-layer shelled corn, Page (1949, cited by Jayas et al. 1991) put an exponent n to time t in the Newton's model and obtained:

$$MR(t) = \exp(-kt^n) \quad (2.16)$$

where k and n are drying parameters dependent on the product and drying conditions. This equation has been used extensively for characterizing thin-layer drying of oilseeds, clover, grass seeds, sunflower seeds, shelled corn, wheat, barley, canola, and shell pecans (Bruce 1985; Farmer et al. 1983; Jayas and Sokhansanj 1986; Jayas and Sokhansanj 1989; Li and Morey 1987; Misra and Brooker 1980; Sokhansanj et al. 1984; White et al. 1973). Bruce (1985) showed that the drying curve produced by this model is much closer to the observed curve than that given by the Newton's model (Eq. 2.13), but the predicted initial drying rate is much higher than the observed one.

To fit the drying data of soybeans better than Eq. 2.16, one further modified Newton's model was proposed by Overhults et al. (1973):

$$MR(t) = \exp[-(kt)^n] \quad (2.17)$$

where $n = a_o + aT_a$; $k = \exp(b_o + b/T_a)$; a_o , a , b_o , and b are constants.

Another empirical model was employed by Thompson et al. (1968) as well as Paulsen and Thompson (1973) for thin-layer drying of shelled corn and sorghum:

$$t = a \ln(MR) + b[\ln(MR)]^2 \quad (2.18)$$

where a and b are functions of air temperature. Wang and Singh (1978) took the following equation for drying thin layer of rice:

$$MR(t) = 1 + at + bt^2$$

$$a = c_1 T_a^{c_2} H^{c_3}; \quad b = d_1 T_a^{d_2} H^{d_3} \quad (2.19)$$

where c_1 , c_2 , d_1 , and d_2 are constants.

Although the empirical drying models can not give an exact description of the moisture profile inside the solid, they can reasonably predict the average behaviour of the drying characteristics of thin-layer biological materials as long as they are suitably fitted to experimental data by linear or non-linear regressions. In addition, all the equations are in simple mathematical forms. Therefore, they are often used when computation must be minimised, for example, in deep-bed drying simulations.

2.1.4 Modelling the drying of biological materials in a deep bed

Classifications for deep-bed drying models and deep-bed drying systems

Deep-bed drying is a continuous process with simultaneous changes in moisture content and temperature of the material to be dried, as well as in humidity and temperature of the drying air during the air passes through a stack of material (Thompson et al. 1968). Many deep-bed models for drying biological materials have been developed. They are generally divided into four types: layer-by-layer simulation models, partial-differential-equation models, logarithmic models, and equilibrium models (Pabis et al. 1998; Parry 1985; Rotstein and Cornish 1978). This classification, however, is somewhat arbitrary because there are overlapping features in these models. The models can be used for characterizing the drying process happening in different convective deep-bed drying systems.

Convective deep-bed drying systems fall into two major categories, namely batch drying systems (i.e. fixed-bed drying systems) and continuous-flow drying systems. Continuous-flow drying systems are normally classified as cross-flow, concurrent-flow, and counter-flow systems according to the relatively directions of the flow of material to be dried and drying air (Fig. 2.2).

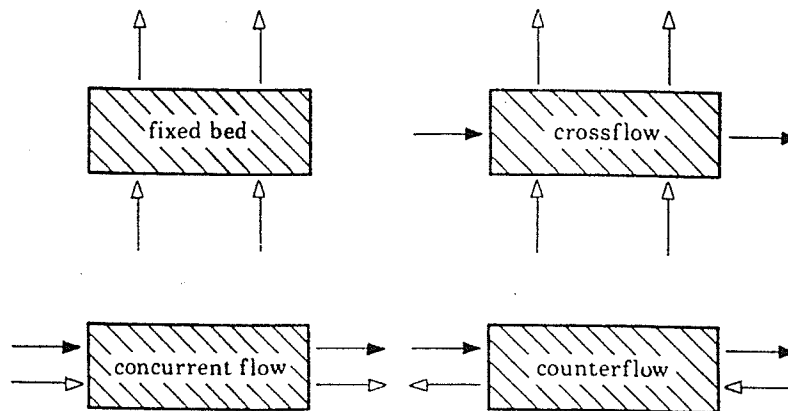


Figure 2.2 Schematics for four basic types of convective dryers. The directions of the flow of material to be dried and drying air are indicated by black and white arrows respectively (Laws and Parry 1983).

Layer-by-layer simulation models

A layer-by-layer drying simulation is based on heat and mass balances taken over a thin layer of material in which it is assumed that air conditions are constant over a given increment in time (Laws and Parry 1983; Parry 1985). For fixed-bed drying, the basic approach to describe the drying process is to divide the bed into many thin layers, and calculate changes in the moisture content and temperature of the material in a thin layer as well as changes in

the temperature and humidity of the drying air passing through the layer in a given time interval. The procedure is to be carried out from layer to layer, i.e. from the bottom to the top layer. Each layer is dried for a short time interval. The conditions of the air at the outlet of a layer are used as the air conditions at the inlet of the next layer. Each layer is assumed to have uniform moisture content and temperature. The process is then repeated with a second time interval, a third time interval, and etc., until the final average moisture has reached the desired value. The thickness of the layer and the interval of time are so selected that changes occur in such small steps are nearly continuous (Boyce 1965). Generally, the calculated quantities are expressed by explicit expressions with known parameters and can be easily calculated step by step.

Boyce (1965; 1966) first presented a model for the layer-by-layer calculation of the temperatures and moisture contents of the grain in a fixed bed as well as the temperature and humidity changes in the drying air passing through the bed. Henderson and Henderson (1968) developed a similar model to Boyce's for drying grain in a fixed bed and investigated the effects of several parameters on the drying process. Thompson (1968) proposed a layer-by-layer simulation model for drying corn in a fixed bed and also presented the basic approaches for simulating cross-flow, concurrent-flow, and counter-flow drying.

In cross-flow drying, the flow of air is perpendicular to the flow of material to be dried (Fig. 2.2). The drying process can be simulated by the same method used for the simulation of a fixed-bed drying. The total drying time is determined by the moving velocity of the material and the distance moved by the material in the drying system.

In concurrent-flow drying, the drying air and the material to be dried travel through the drying system in the same direction (Fig. 2.2). Considering the material bed a group of thin layers with the drying air blowing down through the layers consecutively, and visualizing that at each time interval a new layer is placed on the top and a dried layer is removed from the bottom, the concurrent-flow drying process can be simulated.

In counter-flow drying, the drying air and the material to be dried travel through the drying system in opposite directions (Fig. 2.2). Again considering the grain in the system a group of thin layers with the drying air blowing up through the layers, and envisioning that at each time interval a new layer is placed on the top and a dried layer is removed from the bottom, the counter-flow process can be simulated. At the beginning, the state of the drying air at the top of the bed and the moisture content of the last layer at the bottom of the bed are not known, so initial and boundary conditions are not sufficient to assure the direct simulation of the drying process. An iterative solution of this process is necessary.

Partial-differential-equation (p.d.e.) models

This kind of model is formulated based on the physical characteristics of convective heat and moisture transfers, as well as heat and moisture balances in the drying process. Generally there exist four equations in a p.d.e. model, which contains four basic dependent quantities: M , T , H , and T_a . Van Arsderson (1955, cited by Laws and Parry 1983) was among the first to produce a p.d.e. model. The work begun in 1966 at Michigan State University led to the development of a number of p.d.e. models for simulating the drying of deep-bed grains, which

were reported in the literature (Bakker-Arkema et al. 1967; Brooker et al. 1974). Other contributions have been made by Spencer (1969), O'Callaghan et al. (1971), Ingram (1976), Sharp (1982), Laws and Parry (1983), and Parry (1985). Although the attentive inspection of some early work often reveals flaws in the mathematics, most models have been used with reasonable success for various grains.

The typical p.d.e. models for fixed-bed drying include Bakker-Arkema model (Bakker-Arkema et al. 1967; Brooker et al. 1974), Spencer model (Spencer 1969), and Sharp model (Sharp 1982). They have the similar forms and were developed in similar approaches. Here only the Bakker-Arkema model is summarized.

In order to obtain the equations describing $M(x,t)$, $T(x,t)$, $H(x,t)$ and $T_a(x,t)$ in a fixed bed of biological material, heat and moisture balances were written for an elemental control volume Sdx (Fig. 2.3).

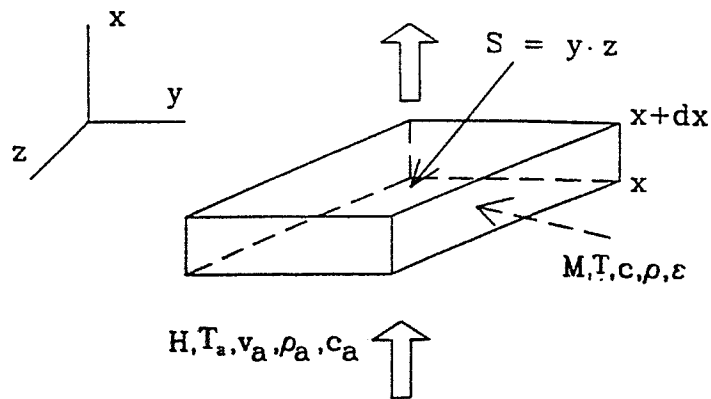


Figure 2.3 Elemental control volume of a fixed bed (Bakker-Arkema et al. 1967)

Some assumptions were made in developing the model:

- the temperature and moisture gradients within individual particles are negligible;
- the thermal properties of the particles are constant within the temperature range studied;
- conductive heat transfer by particle to particle contact is negligible;
- the volume shrinkage is negligible during the drying process;
- there is no temperature and moisture gradients in the y and z directions;
- $\partial T_a / \partial t$ and $\partial H / \partial t$ are negligible compared with $\partial T_a / \partial x$ and $\partial H / \partial x$;
- the thin-layer drying equation and the moisture equilibrium isotherm are known.

The model was written as the following four equations.

Energy balance of air:

$$\frac{\partial T_a}{\partial x} = \frac{-ha}{G_a c_a + G_a c_v H} (T_a - T) \quad (2.20)$$

Energy balance of grain:

$$\frac{\partial T}{\partial t} = \frac{ha(T_a - T)}{\rho c + \rho c_w M} - \frac{h_v + c_v(T_a - T)}{\rho c + \rho c_w M} G_a \frac{\partial H}{\partial x} \quad (2.21)$$

Moisture balance:

$$\frac{\partial H}{\partial x} = -\frac{\rho}{G_a} \frac{\partial M}{\partial t} \quad (2.22)$$

Thin-layer drying equation:

$$\frac{\partial M}{\partial t} = f(M, M_e, T, T_a \dots) \quad (2.23)$$

By modifying the basic fixed-bed drying model of Bakker-Arkema type, Brooker et al. (1974) developed models for cross-flow, concurrent-flow, and counter-flow drying. In a cross-flow drying system, air flows in the x direction and grain in the y direction. The drying time t depends on the distance grain moves in the y direction and the velocity of the movement v . Making the same assumptions as for the fixed-bed drying, the cross-flow drying model was developed in a similar manner to the fixed-bed model. Actually, by directly replacing the term ∂t with $\partial y/v$ and introducing $G = \rho v$ in the fixed-bed model of Bakker-Arkema type, the cross-flow drying model was obtained as:

$$\frac{\partial T_a}{\partial x} = \frac{-ha}{G_a c_a + G_a c_v H} (T_a - T) \quad (2.24)$$

$$\frac{\partial T}{\partial y} = \frac{ha(T_a - T)}{Gc + Gc_w M} - \frac{h_v + c_v(T_a - T)}{Gc + Gc_w M} G_a \frac{\partial H}{\partial x} \quad (2.25)$$

$$\frac{\partial H}{\partial x} = - \frac{G}{G_a} \frac{\partial M}{\partial y} \quad (2.26)$$

$$\frac{\partial M}{\partial y} = f(M, M_e, T, T_a \dots) \quad (2.27)$$

The concurrent-flow and counter-flow drying models were developed in a similar way to the cross-flow drying model.

Logarithmic models

A logarithmic model is a simplification of a p.d.e. model. It was developed based on the following assumptions: the sensible heats to raise the temperatures of the grain and the

moisture removed from the grain are negligible comparing with the latent heat of vaporization of the water; the increase in sensible heat of the air due to the increase in relative humidity of the air is negligible; and the grain density is constant. The first model of logarithmic type was presented by Hukill (1954, cited by Laws and Parry 1983; Parry 1985; Sharp 1982) for a simplified analysis of deep-bed drying. It built a unique relation connecting the rate of moisture-content change with time ($\partial M/\partial t$) and the air temperature gradient with respect to depth ($\partial T_a/\partial x$):

$$G_a c_a \frac{\partial T_a}{\partial x} = \rho h_v \frac{\partial M}{\partial t} \quad (2.28)$$

The initial and boundary conditions were assumed as:

$$\begin{aligned} M(x,0) &= M_o; \quad \frac{T_a(x,0) - T_{ae}}{T_{ao} - T_{ae}} = \exp(-k_1 x) \\ MR(0,t) &= \exp(-k_2 t); \quad T_a(0,t) = T_{ao} \end{aligned} \quad (2.29)$$

where k_1 and k_2 are constants, and a solution in form of moisture ratio was obtained as:

$$MR(x, \tau) = 2^x / (2^x + 2^\tau - 1) \quad (2.30)$$

where x and τ are dimensionless depth and time variables, respectively.

Barre et al. (1971) solved Eq. 2.28 with initial and boundary conditions of the form:

$$MR(x,0) = 1; \quad MR(0, \tau) = \exp(-\tau) \quad (2.31)$$

and got the result:

$$MR(x, \tau) = e^x / (e^x + e^\tau - 1) \quad (2.32)$$

The logarithmic models were later applied to low-temperature drying in fixed beds by a

number of researchers (Barre and Hamdy 1974; Sabbah et al. 1979) . Although several researchers found that these models were not very accurate, they still employed the models in low-air-speed and low-temperature applications because of the simplicity and computational economy.

Equilibrium models

In principle, the equilibrium model is also a simplification of the p.d.e. model, achieved by the introduction of assumptions that near equilibrium conditions exist between the drying air and the material and that the air temperature T_a is equal to the grain temperature T in each layer during each time interval. The assumptions may be true for low-temperature and low-airflow drying. The equations describing the balances of air and grain enthalpies in the p.d.e. model are not needed. The thin-layer drying equation in the p.d.e. model must be replaced by a simple expression for the equilibrium moisture content of the grain. Therefore, the assumptions reduce the four equations in a p.d.e. model to two equations: one describing the moisture balance between air and grain, and the other describing the equilibrium, i.e. $M = M_e$. This kind of models allow for much reduced computational time.

Equilibrium models were first developed by Bloome and Shove (1971) as well as Thompson (1972). Sharma and Muir (1974) used the Bloome and Shove's model to simulate heat and moisture transfer during the ventilation of rapeseed bulks. Pfost et al. (1977, cited by Sharp 1982) tested the Thompson's model with experimental data and found the model inadequate. Further development of an equilibrium model and its validation were carried out

by Morey et al. (1979) who found it suitable for predicting the moisture changes in a solar grain-drying system.

2.1.5 Suggestions for future research in drying of biological materials

Although much progress has been made in investigating the drying theories, our knowledge of the mechanism and modelling of drying biological materials is still limited, mainly due to the fact that drying is a rather complicated process and biological materials are quite complex and of great varieties. The following points should be emphasized in future research.

The data about thermal properties and hygroscopic properties of some biological materials are scarce and incomplete in terms of drying analysis, and efforts should be made in this area.

During drying, biological materials often shrink to a large extent with consequent changes in size and shape. The shrinkage has a significant effect on the drying behaviour. However, researchers usually tend to assume the shrinkage to be negligible for the purpose of simplification. The shrinkage of biological materials needs to be considered in drying analysis.

No general theories or equations are valid for predicting the drying kinetics of biological products, especially fruits and vegetables, and actual experiments with particular materials are essential for describing their drying behaviours, or for determining the parameters in drying models.

There exist a lot of models for drying of biological materials in the literature. Verifying the applicability of the models requires broad experimental studies carried out for various equipment and various materials.

Most of the models developed so far are one-dimensional. For cognitive and practical purposes, it is necessary to develop and test two or three-dimensional models for drying biological materials.

2.2 Superheated-steam drying

2.2.1 Characteristics of superheated-steam drying

The concept of superheated-steam drying (SSD) was first proposed by the German scientist Hausbrand (1924) in the book “Drying by Means of Air and Steam” published in the first edition (in Germany) in 1908 and the third edition (in English) in 1924. However, the technique gained little research interest until the 1950's, when researchers began studying the kinetics associated with SSD (Beeby and Potter 1985; Wimmerstedt 1995). Only after the “oil crisis” in 1970's, many papers were published on fundamental studies and applications of SSD. Conventional hot-air drying (HAD) is a very energy-intensive operation, which accounts for about 15% of the industrial energy consumption in France (Topin and Tadrist 1997) and 25% in Canada (Drouet 1984, cited by Woods et al. 1994). The feature of energy saving in SSD makes the technique a desirable alternative, and strict laws regarding environmental pollution offer another incentive to SSD (Beeby and Potter 1985). Although a broad industrial acceptance has not been reached so far because of a lack of suitable equipment, it

seems safe to predict a growing importance of this technique in the future due to its merits (Wimmerstedt 1995).

Numerous advantages of SSD compared with HAD have been reported by a number of authors (Beeby and Potter 1985; Bonazzi et al. 1996; Erdesz and Kudra 1990; Franics and Di Bella 1996; Jensen 1992; Lane and Stern 1956; Meunier and Munz 1986; Wimmerstedt 1995; Woods et al. 1994):

- A steam dryer is usually a closed-loop system. The circulation of superheated steam reduces the energy wastage that occurs in HAD. Only the amount of steam evaporated from the material to be dried leaves the drying system. In addition, the heat energy (latent heat of vaporization) within the exhaust steam can be recovered or directly used in other processes. This results in an energy saving, which may be up to more than 50% (Woods et al. 1994).
- The high heat-transfer coefficient in SSD, especially in the operation under pressure, results in enhancing the drying rate, improving the production efficiency, and consequently reducing the equipment size and capital cost.
- As steam drying takes place in an air-free environment, there is no oxidation in drying process. This, in some cases, can improve the product quality in terms of colour, digestibility, etc. Materials, which are oxygen-sensitive when dried in hot air, can be dried successfully in superheated steam. No oxidation in SSD also eliminates fire and explosion hazards during drying. This is particularly important in drying fuel such as coal, bark, and peat.

- The environmental pollution caused by SSD can be significantly reduced or eliminated. The small amount of exhaust vapour can carry only a little amount of dust from the product to be dried to the atmosphere. Also, the exhaust vapour can be condensed and the dust present in the vapour can be collected easily.
- Superheated steam has the property of stripping volatile or semi-volatile organic substances from drying products. The aroma of feed or food products dried with superheated steam could be improved due to the stripping loss of some acids in the products. In addition, some valuable volatile organic compounds generated from the materials to be dried could be recovered and separated by a condenser.
- The control of steam-drying process is easier than that of HAD. The drying rate and the final moisture content of the product can be controlled by simply monitoring the steam temperature and velocity in SSD, but a more complex control of humidity is necessary in HAD.

Superheated-steam drying, as a new technique, also has some limitations (Beeby and Potter 1985; Bonazzi et al. 1996; Erdesz and Kudra 1990; Kumar and Mujumdar 1990; Lane and Stern 1956; Meunier and Munz 1986; Shibata 1991; Woods et al. 1994):

- Superheated-steam drying results in a high product temperature, which is equal to or above the boiling point of free water. This imposes a limitation on the application of SSD to temperature-sensitive products. To solve this problem, SSD under a vacuum can be used because the boiling point is reduced as the pressure is decreased.
- In SSD, difficulties may be encountered with the feeding of wet materials and the

discharge of dried products without excessive steam leaking out or air leaking into the drying system. More complex drying systems are needed, especially for drying under pressure or vacuum.

- The initial moisture condensation on the surface of the products to be dried may increase the drying time in some cases.
- It is difficult to achieve a low moisture content level in the dried products if the superheat of the drying steam is relatively low.

2.2.2 Drying principles of superheated steam

Drying ability of superheated steam

Superheated steam is a kind of unsaturated steam which has a temperature above saturation or boiling point. At any specific pressure, saturated steam is generated when water or moisture is heated to the boiling point. If it is heated to above the boiling point, the steam is getting unsaturated or superheated. This kind of steam has the ability to transfer heat to materials to be dried and carry the evaporated moisture from the materials. During drying, superheated steam gives up heat to the material to be dried by losing some sensible heat but without reaching its condensation point except for in the initial heating of the material (Bonazzi et al. 1996).

Superheated-steam drying does not alter the general characteristics of the drying process. Similar to HAD, a typical SSD process also compromises three basic drying periods: initial heating period, constant-rate drying period, and falling-rate drying period. Compared with

HAD, however, some special phenomena such as steam condensation, inversion-temperature point, and building-up of overpressure happen in SSD processes.

Steam condensation during the initial heating period

During the initial heating period, the temperature of material to be dried changes from the initial value to the boiling point of free water at operating pressure (e.g. 100°C at atmospheric pressure) as heat is transferred from superheated steam to the material (Bonazzi et al. 1996). The heat, particularly if the degree of superheat (the difference between the temperature of superheated steam and the boiling point of free water) is not high, is transferred through the condensation of steam on the cold surface of the material (Wimmerstedt and Hager 1996). The moisture of the material then increases at the beginning of drying. This means that more drying needs to be accomplished.

The quantity of the condensed moisture depends on various factors such as the thermal diffusivity of the material to be dried, the initial moisture content of the material, and the superheat of the steam (Beeby and Potter 1985). Trommelen and Crosby (1970) reported that drops of water initially at 30°C get an increase in mass of about 12.5% when exposed to the superheated steam of 150°C at atmospheric pressure.

The time for drying materials, which are predominantly liquid such as solution droplets, will be little affected by the increase in moisture during the initial heating period. However, for materials initially containing low moisture, the increase of moisture may represent a major portion of moisture to be removed and may extend the time required for drying (Beeby and

Potter 1985). For instance, sand initially at 30°C and containing 10% moisture increases moisture to 14% during the initial heating in 150°C superheated steam, which means a 40% increase in the amount of water to be removed during drying.

Inversion temperature

In the constant-rate drying period, there exists an inversion temperature at which the evaporation rates in air and in superheated steam are equal under the same mass or volume flow rates of the drying media. Below this inversion temperature, the drying rate is lower in superheated steam than in hot air; above this point, superheated steam dries faster than hot air. Therefore, drying with superheated steam could be more effective than drying with hot air under some conditions during the constant-rate drying period.

Yoshida and Hyodo (1966, cited by Keey 1972) gave the data on the evaporation of water into air, superheated steam, and a mixture of air and steam in which steam content was 50% and showed that an inversion temperature appears to fall between 160 and 180°C at equal mass flow rates. For drying alumina at atmospheric pressure, Faber et al. (1986) confirmed an inversion temperature of about 160°C in the constant-rate drying period at the same mass flow rates of the drying media. For evaporation from a horizontal surface into a laminar flow at equal mass flow rates, an inversion temperature of about 250°C was reported by Chow and Chung (1983). At equal volume flow rates, however, the drying rates become the same at a temperature higher than 400°C (Faber et al. 1986; Trommelen and Crosby 1970). The inversion phenomenon was also reported in other publications (Bond 1992; Nomura and

Hyodo 1985; Sheikholeslami and Watkinson 1992; Yoshida and Hyodo 1970).

The inversion phenomenon could be explained by combined effects of the higher driving force (the difference between the temperature of drying medium and the temperature at the surface of material to be dried) in HAD and the higher heat-transfer coefficient in SSD (Mujumdar 1990, cited by Johansson et al. 1997). Normally, for either HAD or SSD, the limiting factor of drying rate in the constant-rate drying period is the external heat transfer, which is estimated as:

$$q = h(T_{\infty} - T_{sur}) \quad (2.33)$$

T_{sur} represents the wet-bulb temperature (greatly less than 100 °C at atmospheric pressure) in HAD, but in SSD T_{sur} indicates the saturation temperature (100 °C at atmospheric pressure). At the same temperature of the drying media, the heat-transfer coefficient in SSD (h_s) is much higher than that in HAD (h_a). For example, h_s equals to $1.37h_a$ for drying a cylindrical product in turbulent flow at 227 °C (Woods et al. 1994). A larger temperature difference available in HAD than in SSD especially at drying-medium temperature just above the boiling temperature of water causes more heat to be transferred to material to be dried in HAD than in SSD. The effect of the temperature difference on the heat transfer is diminished at high temperatures because of the higher heat-transfer coefficient in SSD than in HAD. This results in that the heat-transfer rate is higher in SSD than in HAD above a certain temperature.

Lowering the critical moisture content

The use of superheated steam for drying has an effect on the critical moisture content. Shibata (1991) studied the drying mechanism of sintered spheres of glass beads in superheated steam, and revealed that SSD can reduce the critical moisture content compared with HAD. The higher mobility of moisture inside material to be dried due to the higher temperature in superheated steam than in air could give an explanation for the phenomenon. During the constant-rate drying period, the moisture movement to the surface is caused mainly by capillary forces and is significantly affected by liquid density and viscosity. The density and viscosity depend on the temperature in such a way that the mobility of the liquid increases with increasing temperature (Johansson et al. 1997). The temperature inside the drying product is close to or at the boiling point of free water for SSD, but close to or at the wet-bulb temperature for HAD. Since the boiling point in SSD is always higher than the wet-bulb temperature in HAD, the mobility of moisture inside the drying product is higher and the product surface has a greater tendency to be kept wet in SSD than in HAD.

Overpressure inside the product during the falling-rate drying period

After entering the falling-rate drying period, the surface of the drying product is dry and the temperature of the product exceeds the boiling point of free water. An overpressure is built up inside the product during this period if the product is compact or large in size (Fyhr and Rasmuson 1996; Johansson et al. 1997; Moyne et al. 1990; Perre et al. 1993; Wimmerstedt and Hager 1996). The overpressure can enhance the movement of moisture and

vapour inside the product, which is favourable to drying. The greater the superheat of the steam, the larger the building-up of the overpressure could be. When the local moisture approaches its equilibrium value, the local overpressure tends to zero, so the overpressure moves with the drying front towards the centre of the product. For drying most fragmented products such as sugar-beet pulp and spent grains, however, the overpressure inside the product is negligible (Bonazzi et al. 1996).

2.2.3 Industrial applications of superheated-steam drying

Due to the lack of suitable equipment, a broad industrial acceptance of SSD has not been reached. The application of this technique is limited to only a few industrial drying fields.

Drying of sugar-beet pulp

Sugar-beet pulp, the remains from sugar beets after sugar extraction, is mainly used as feed for animals. For long-time storage and convenient transportation, the sugar-beet pulp needs to be dried from a moisture content of 70-80% to a final moisture content of about 10% (Jensen 1992; Urbaniec and Malczewski 1997; Wimmerstedt and Hager 1996). The pulp is conventionally dried in rotary-drum dryers by passing the pulp through the flue gases from a directly-fired furnace. Now superheated steam has been successfully used for drying sugar-beet pulp. The steam-dried pulp seems to have higher digestibility as animal feed because it is not contaminated by impurities from flue gases and no part of it is burnt away as it is in drum drying (Jensen 1992). A full-scale steam dryer for drying sugar-beet pulp started operation in Sweden in 1983 (Svensson 1985). At Villenoy, France, a steam dryer with a 30-

m long belt was developed for drying 25 t of sugar-beet pulp per hour (Miranda-Bernardo et al. 1990). A pressurized fluid-bed steam dryer of the Niro type with the capacity of 9 t/h evaporation was installed in a sugar factory at Stege, Denmark in 1985; and another Niro-type steam dryer was built at Nangis Sugar Factory in France (Bruce and Hulkkonen 1998). Bruce and Hulkkonen (1998) also reported 15 steam dryers of Niro type had been installed in several countries in Europe, and most of them were used for drying sugar-beet pulp.

Drying of lumber

Drying lumber is a very energy-intensive operation in wood processing, and can consume 40-70% of the total energy in the wood industry (Rosen 1987, cited by Woods et al. 1994). The total energy for lumber drying in Canada during 1990 was about 2% of total energy used in all Canadian industry (Woods et al. 1994). Much interest has been devoted to SSD of lumber because the technique can save energy compared with HAD. Kollmann (1961) reported that a number of dryers operating with either superheated steam or a mixture of steam and air were employed for drying lumber in Germany. Drying with superheated steam in a vacuum has been developed for lumber precessing. The new technique increases the drying rates by 3 to 7 times and provides high energy efficiency and excellent wood quality compared with conventional air drying with kiln dryers (Woods et al. 1994). Till 1994, more than 50 lumber dryers using superheated steam under vacuum were operated in Europe and Asia; only one was in British Columbia, Canada, and two in Pennsylvania and West Virginia, USA.

Drying of wood pulp and paper

A pneumatic-conveying dryer with a capacity of 150 t pulp per day for pulp drying with superheated steam was built by MoDo Chemetics at Rockhammars Bruk in Sweden in 1979 (Svensson 1980; Svensson 1985). The pulp is mechanically dewatered to a moisture content of about 55% and then is dried to 10-15% moisture content. Compared with conventional flash dryers, the total energy cost is reduced by about 50%. The concept of drying paper with superheated steam was proposed by Mujumdar (1981, cited by Woods et al. 1994). Considerable research regarding SSD of paper has been carried out in Canada, primarily at McGill University (Douglas 1994; McCall and Douglas 1994; Mujumdar 1991), and in Finland (Malinen et al. 1994).

Drying of fuels

A number of fuels from brown coal, peat, to bio-fuels such as bark and wood chips contain considerable amounts of moisture. Removing most of the moisture can significantly reduce the cost of transportation and improve the combustion efficiency of the fuels. A superheated-steam dryer for peat drying has been operating in Sweden since 1988 (Woods et al. 1994). Another superheated-steam dryer with a capacity of 20 t water evaporation per hour for drying peat from the moisture content of 50-55% to 10-15% started operation at Tornaki Power and Heat Plant in Kuusamo, Finland in 1994 (Bruce and Hulkkonen 1998). It can also dry other fuels such as sawdust. In 1993, a fluid-bed steam-drying plant with a capacity of 44 t water evaporation per hour was installed near Cologne, Germany for drying brown coal

from the moisture content of 60% to 12% (Bruce and Hulkkonen 1998). A similar dryer for brown coal drying was also constructed in Australia (Potter and Beeby 1994). Woods (1994) reported that SSD can improve the grindability of coal and reduce the sulphur content by up to 50%. A Niro-type steam dryer of 35 t water evaporation per hour for drying wood residues such as bark and wood chips was installed at a municipal heating and power plant in Borås Energi, Sweden (Bruce and Hulkkonen 1998).

Drying of sludge

The TECOGEN Division of Thermo Power Corporation in USA developed a waste treatment system using an anaerobic digester with a superheated-steam dryer (Franics and Di Bella 1996). The system dries and sterilizes sludge from the digester and produces a potentially saleable product. A fluidized-bed dryer for drying sludge with superheated steam was mounted at a landfill in Northern Germany in 1993 (Wimmerstedt and Hager 1996).

Drying of other products

The first industrial-scale steam dryer in South Africa was used for drying activated carbon pellets from an initial moisture content of 50% to 2% (Faber et al. 1986). The main reason for selecting steam as the drying medium was the combustion hazard when drying in air. A fluidized-bed dryer for drying salts was developed in Kassel, Germany (Woods et al. 1994). It uses 65% of the energy consumed by a conventional rotary-drum dryer. Zhao and Yang (1996) stated that the technique of SSD had been applied to noodle production, and that the drying time reduced from 20-40 min to 50 s compared with the conventional air-drying

method. The breaking strength of noodles dried in superheated steam increases with the decrease in drying temperature and drying time (Markowski and Cenkowski 2000).

2.2.4 Mathematical modelling of superheated-steam drying

Superheated steam drying is a process involving simultaneous mass, heat, and momentum transfers in multi-phase systems. The main differences from HAD are the significant overpressure built-up inside the compact or large-size product during the falling-rate drying period and the negligible resistance to mass transfer outside the drying product (Hager 1998). Different transport equations derived based on moisture, heat, and momentum transports, combining with some initial and boundary conditions, constitute a mathematical model of the drying process. Solving the equations gives moisture, temperature, and overpressure profiles within the material to be dried and predicts the kinetic parameters of the modelled drying process, such as the drying rate and drying time.

The mathematical description of SSD has received much attention and many models have been developed for the steam drying of different materials in the last 20 years. A transient model for combined impingement and through drying of newsprint in superheated steam was developed by Loo and Mujumdar (1984). Mass and heat transfers within the paper sheet were neglected. Crowe et al. (1985) presented a heat-transfer controlled model for spray drying in superheated steam. The drying rate was dependent on the temperature difference between the steam and the droplets, and the moisture and temperature gradients inside the droplets were neglected due to the small size of the droplets. Meunier and Munz (1986) developed a simple

one-dimensional model for simulating the steam drying of spherical particles in a flash dryer operating in the constant-rate drying period. They examined the effects of drying conditions, such as steam temperature, steam pressure, and particle size, on the dryer design parameters. Shibata et al. (1988) proposed a simple model for drying glass beads in superheated steam based on the assumption that evaporation takes place not only on the surface but also in a thin layer below the surface of the sample during the constant-rate drying period. The drying process was described by an evaporation-zone model during the constant-rate drying period and a receding-evaporation-front model during the falling-rate drying period. Another heat-transfer-controlled model for the steam drying of a single porous sphere with a receding evaporation front was reported by Khan and Beasley (1988). The evaporation rate was solely controlled by the rate of heat transfer to the receding front. The model was used to predict the temperature distribution and the movement of the drying front inside the sphere. This single-particle model was later incorporated into a deep-bed drying model to predict local and overall drying rates as well as the temperature distribution in a packed bed of alumina particles (Khan et al. 1991). A more advanced steam-drying model, including heat and mass transfers within porous materials and considering a third drying force, overpressure gradient, in addition to temperature and moisture gradients, was proposed by Moyne et al. (1990). The model assumed that the overpressure inside the material was equal to the saturation pressure at the prevailing temperature. Ramamurthy et al. (1992) developed a diffusion model describing the internal transports of heat and moisture and solved the model numerically using the finite-element method to simulate the SSD of a black liquor film. Much research interest has been devoted to the modelling of drying wood with superheated steam (Fyhr and

Rasmuson 1996; Fyhr and Rasmuson 1997; Johansson et al. 1997; Perre et al. 1993). Due to the strong anisotropy of wood, the mathematical models are generally developed for two dimensional coordinates to handle transport processes in two directions. Because of the large size of the wood products, the overpressure has a significant influence on the drying process and is normally considered in the modelling. The models are used to investigate the effects of external conditions such as steam temperature, pressure, and velocity on the drying rate as well as the distributions of moisture, temperature, and overpressure within the wood chip. A model with an adjustable parameter in it was presented by Hager et al. (1997) for the steam drying of a porous ceramic sphere. It was derived based on mass and heat transfers, considering three driving forces: the gradients of moisture, temperature, and overpressure. It assumed local thermodynamic equilibrium inside the material. The transport coefficients in the model were either measured experimentally or derived theoretically from the pore-size distribution of the material. The model was solved by a finite-difference method. Daurelle et al. (1998) developed a 2-dimensional numerical model for describing heat and moisture transfers in porous material being dried with superheated steam. The model was based on a finite-element method and took into account the pressure gradient in gaseous phase, the capillary and sorption effects, as well as the phase changes. It allows one to determine the variables difficult to measure, such as the phase-change rates and transport coefficients. Recently, Heinrich et al. (1999) developed a mathematical model for a batch treatment of wet granular solids with superheated steam in a fluidized bed. The model allows for the calculation of the time-dependent process parameters such as solid-temperature and moisture distributions in the bed, steam temperature changes in the bed, and apparatus-wall

temperatures.

In the complex steam-drying modelling which considers the overpressure gradient as a third driving force inside the material, it is hard to get a fully quantitative prediction of the drying process. In particular, the prediction of the drying time is often not accurate (Daurelle et al. 1998; Topin and Tadrist 1997). The agreement between the predicted values and the experimental data is obtained only after adjusting one or more parameters such as physical properties and boundary or initial conditions, and the simulation is still not fully predictive (Hager et al. 1997).

3 EQUILIBRIUM MOISTURE CONTENT (EMC) OF SPENT GRAINS IN SUPERHEATED STEAM UNDER ATMOSPHERIC PRESSURE

3.1 Experimental determination of EMC

3.1.1 Equipment

The main equipment used in the experiments was the superheated-steam drying system developed in the Department of Biosystems Engineering at the University of Manitoba. The system consisted of a steam generator, steam conveying pipelines, a drying chamber, auxiliary heaters (a superheater and heating tapes), a hot-air supply system, and a data acquisition and control system (Fig. 3.1).

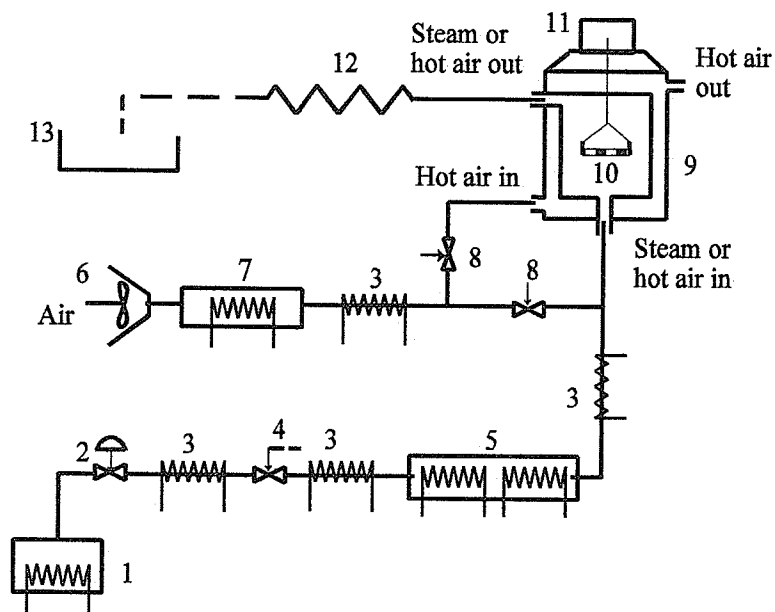


Figure 3.1 Superheated steam dehydration system. (1) steam generator; (2) pressure regulator; (3) heating tape; (4) steam flow valve; (5) steam superheater; (6) air fan; (7) air heater; (8) airflow valve; (9) drying chamber; (10) tray with sample; (11) balance; (12) condenser; (13) condensate collector.

Saturated steam at 580 kPa and 158°C was produced by the steam generator (1). Its pressure was reduced to 130 kPa by a pressure regulator (2), and thus superheated steam was generated. The pressure regulator ensured a steady flow of steam through the pipelines and drying chamber (9). The flow rate was adjusted by the steam flow valve (4), which was actuated by a computer. After passing through the electrical superheater (5), where the steam temperature was adjusted to the desired level, the steam went through the drying chamber (9). The steam pressure in the drying chamber dropped down to 100 kPa due to the friction loss in the pipelines. Finally, the steam passed through the condenser (12) and was condensed. The heating tapes (3) on the pipelines kept the pipes warm to reduce heat loss and possible steam condensation inside the pipes. Several thermocouples placed at different points on or in the pipes (not shown in Fig. 3.1) monitored and controlled the temperatures of the pipes and the steam inside the pipes. In addition, hot air was used to insulate the drying chamber. Air moved by a fan (6) was heated by a heater (7) and heating tape (3) on the airflow line. The airflow was adjusted by controlling the speed of the fan (6) with a variable auto-transformer. The temperature of the hot air was adjusted by a computer-controlled unit that turned the heater (7) and heating tape (3) on or off.

The drying chamber itself consisted of an inner rectangular cavity (i.e., the inner chamber) and a surrounding air jacket (Fig. 3.2). The air jacket ensured adiabatic conditions in the inner chamber. Hot air was forced through the air jacket during superheated-steam drying and could also be forced through the inner chamber for hot-air drying. A mesh tray (55 mm × 55 mm) to hold the sample was hung in the chamber by a thin string attached to an

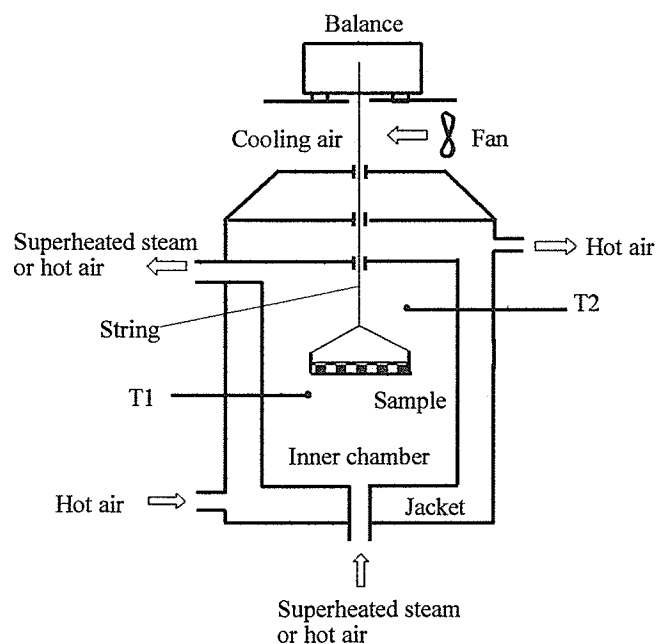


Figure 3.2 Simplified diagram of drying chamber

electronic balance (B120S, 0.001 g accuracy), which was connected to a computer to allow for continuous weighing of the sample. To avoid overheating the balance, a cooling fan was installed between the chamber and the balance to prevent any rise in temperature due to steam or hot air leaking from the small opening in the inner chamber. Thermocouples T1 and T2 monitored and controlled the temperature inside the chamber.

Besides the steam drying system, a vacuum oven (TempCon Vacuum Oven N7592-2) was used for determining the final moisture contents of steam-dried samples.

3.1.2 Materials

The materials used in the experiments were brewers' barley spent grain and distillers' wheat spent grain which was obtained from a local brewery (Fort Garry Company Ltd.,

Winnipeg, MB) and a distillery (Mohawk Canada Ltd., Minnedosa, MB). Dry distillers' wheat spent grain contains approximately 37% protein, 4.5% fat, 8% fibre, and 5.5% ash. The materials were stored in a freezer at -15°C and thawed before the drying experiments. The initial moisture contents of the BSG and DSG determined by the vacuum-oven drying method (AACC 1995) were 3.16 and 3.71 ± 0.15 kg/kg dry basis (db), respectively.

3.1.3 Drying conditions

Drying experiments were conducted under atmospheric pressure. The temperature of steam passing through the chamber was controlled at different levels ranging from 105 to 200°C with an accuracy of $\pm 3^\circ\text{C}$. The velocity of steam passing through the sample was set at 0.32 m/s with an accuracy of ± 0.02 m/s.

3.1.4 Experimental procedure

The experimental procedure involved exposing a sample of spent grains to steam at a preselected temperature in the drying chamber for a sufficient time, and then drying the steam-dried sample completely in the vacuum-oven dryer. At each level of steam temperature, experiments were conducted in triplicate. During the steam drying, each sample of approximately 12 g was placed in a thin layer on the mesh tray hung in the drying chamber. The change in the mass of the sample was continuously monitored by a computer. The time of drying in steam ranged from 25 to 200 min depending on the steam temperature. The steam drying process was stopped when the mass of the sample remained constant at least for 5 to 30 min depending on the total drying time. The sample was then immediately

weighed and placed into the vacuum-oven dryer to remove the remaining moisture. The vacuum drying was conducted for 18 to 20 h at the temperature of 98 to 100°C and the vacuum of -80 to -100 kPa (AACC 1995). The moisture determined for that sample was the EMC of the sample dried in the superheated steam of known parameters. The experimental results are tabulated in Appendices A.1 and A.2.

3.2 Graphical representation for the EMC of spent grains

During hot-air drying, wet material will lose moisture until the remaining moisture exerts the same partial pressure of vapour as the surrounding drying medium (Beeby and Potter 1985). The remaining moisture content is the EMC. The partial pressure of vapour in hot air depends on the temperature and relative humidity of the hot air. At a selected temperature, the EMC of a product decreases with the reduction in the relative humidity of hot air. Therefore, the sorption relationship between a product and hot air is usually shown as isotherms by plotting the EMC of the product against the relative humidity of hot air at different temperatures.

In superheated-steam drying, the partial pressure of vapour is the same as the total pressure of the drying medium because there is only the vapour component in the drying medium. For drying non-capillary porous solids, in which the moisture is held as free water in large pores, the solids will dry completely if the temperature is maintained above the boiling point of free water. The reason is that the vapour pressure of free water at the boiling point or at a temperature a little bit higher than the boiling point is equal to or higher than the

pressure of steam. Chu et al. (1959) noted that drying sand with superheated steam gives an EMC of zero just as in hot-air drying. However, Lane and Stern (1956) pointed out that the void spaces of the dried product are still filled with steam, which should be considered residual moisture.

For drying capillary porous material or a hygroscopic product with steam, the removal of the bound water requires that the steam temperature be above the boiling point of free water at the operating pressure (Beeby and Potter 1985). The higher the temperature or superheat of steam and the lower the pressure of steam, the more bound water can be removed. At a selected steam pressure, the EMC of a product reduces with increasing steam temperature. Therefore, it is reasonable to present the EMC data of spent grains dried in superheated steam as isobars by plotting the EMC against the temperature or superheat of steam at different pressures (Beeby and Potter 1985; Rosen 1981). In addition, the isobars can be shown by plotting the EMC against the relative pressure of steam, which is the ratio of the working pressure of the steam to the pressure of saturated steam at the working temperature (Beeby and Potter 1985; Hager 1998; Hager et al. 1997; Wimmerstedt and Hager 1996).

3.3 Equations for describing isobars of spent grains in superheated steam

Based on the experimental observation (Appendices A.1 and A.2), the EMC of the BSG and DSG in superheated steam changed substantially with changes in the superheat or relative pressure of steam when the steam was close to the saturation condition (100°C at atmospheric pressure), but the EMC changed only a little when the steam was far from the

saturation point. At atmospheric pressure, the EMC of the spent grain exposed to superheated steam decreased from 9.3 to 1.7 kg/100kg dry solids for BSG and from 6.7 to 1.4 kg/100kg dry solids for DSG when the steam temperature changed from 105 to 140°C or the relative pressure of steam from 0.84 to 0.28. The EMC changed by only 1.3 kg/100kg dry solids when the steam temperature increased between 140 and 180°C or the relative pressure of steam decreased between 0.28 and 0.1; it was further reduced to almost zero when the steam temperature increased to 200°C, at which the relative pressure of steam was 0.07.

Based on the above discussion and compared the probable isobars with the curves in the Handbook of Mathematics (Wang et al. 1979), a number of possible equations for describing the sorption relationship between the spent grains and the surrounding steam were proposed.

The possible EMC-temperature equations were:

$$M_e = k(T_s - 100)^n \quad (3.1)$$

$$M_e = k_1(T_s - 100)^{n_1} + k_2(T_s - 100)^{n_2} \quad (3.2)$$

$$M_e = k \exp[n(T_s - 100)] \quad (3.3)$$

$$M_e = k_1 \exp[n_1(T_s - 100)] + k_2 \exp[n_2(T_s - 100)] \quad (3.4)$$

$$M_e = k \exp[n(T_s - 100)^m] \quad (3.5)$$

$$M_e = k_1 \exp[n_1(T_s - 100)^{m_1}] + k_2 \exp[n_2(T_s - 100)^{m_2}] \quad (3.6)$$

$$M_e = k \exp[n/(T_s - 100)] \quad (3.7)$$

$$M_e = k_1 \exp[n_1/(T_s - 100)] + k_2 \exp[n_2/(T_s - 100)] \quad (3.8)$$

where $k, n, m, k_1, n_1, m_1, k_2, n_2, m_2$ were coefficients and M_e was in the unit of kg/100kg dry solids.

The possible EMC-relative pressure equations were:

$$M_e = kP_r^n \quad (3.9)$$

$$M_e = k_1P_r^{n_1} + k_2P_r^{n_2} \quad (3.10)$$

$$M_e = k \exp(nP_r) \quad (3.11)$$

$$M_e = k_1 \exp(n_1P_r) + k_2 \exp(n_2P_r) \quad (3.12)$$

$$M_e = k \exp(nP_r^m) \quad (3.13)$$

$$M_e = k_1 \exp(n_1P_r^{m_1}) + k_2 \exp(n_2P_r^{m_2}) \quad (3.14)$$

$$M_e = k \exp(n/P_r) \quad (3.15)$$

$$M_e = k_1 \exp(n_1/P_r) + k_2 \exp(n_2/P_r) \quad (3.16)$$

where the relative pressure of steam, P_r , was defined as the ratio of the working pressure of the steam to the pressure of saturation steam at the working temperature.

By non-linear regressions with M_e , T_s , and P_r as the regression variables, all the coefficients in Eqs. 3.1 through 3.16 were determined and shown in Table 3.1 for BSG and Table 3.2 for DSG. The regressions were accomplished by the NLIN procedure in the SAS system, a statistical analysis system (SAS 1985). Two example programs for the regressions were listed in Appendices A.3 and A.4.

As shown in Tables 3.1 and 3.2, the regression equations have different accuracies for fitting the experimental data. The accuracy can be expressed by the mean residual squares

Table 3.1 Regression-analysis results for BSG

Equation No. ^[a]	Coefficients		Mean residual square	Mean deviation (kg/100 kg d.s. ^[b])	Rank of accuracy
(3.1)	k = 40.2783	n = -0.8975	0.3249	0.5700	6
(3.2)	k ₁ = 59.0165 k ₂ = -1.8×10 ¹⁵	n ₁ = -1.0208 n ₂ = -21.3442	0.2869	0.5357	5
(3.3)	k = 11.5258	n = -0.0627	0.4758	0.6898	7
(3.4)	k ₁ = 5.8471 k ₂ = 16.0452	n ₁ = -0.0341 n ₂ = -0.2618	0.2233	0.4726	1
(3.5)	k = 61.9989 m = 0.3339	n = -1.1166	0.2427	0.4927	4
(3.6)	k ₁ = 15.2199 n ₁ = -0.2770 m ₁ = 0.5832	k ₂ = 6.918×10 ¹⁷ n ₂ = -1.0000 m ₂ = 2.300	0.2367	0.4865	3
(3.7)	k = 1.2692	n = 10.1800	1.1862	1.0891	8
(3.8)	k ₁ = -4.4748 k ₂ = 3.5519	n ₁ = -22.6033 n ₂ = 4.8182	0.2320	0.4816	2
(3.9)	k = 11.9449	n = 1.9314	0.4420	0.6496	7
(3.10)	k ₁ = 6.7220 k ₂ = 17.1648	n ₁ = 1.2093 n ₂ = 8.5965	0.2270	0.4764	3
(3.11)	k = 0.4586	n = 3.5683	0.3040	0.5513	6
(3.12)	k ₁ = 0.5396 k ₂ = -1.0136	n ₁ = 3.3566 n ₂ = -10.8538	0.2666	0.5163	4
(3.13)	k = 0.2496 m = 0.7519	n = 4.0863	0.2936	0.5418	5
(3.14)	k ₁ = 0.3488 n ₁ = 4.0176 m ₁ = 1.4454	k ₂ = 1.3883 n ₂ = -0.00003 m ₂ = -7.1378	0.2112	0.4596	1
(3.15)	k = 33.2845	n = -1.1797	0.7175	0.8471	8
(3.16)	k ₁ = 1454.7 k ₂ = 5.3731	n ₁ = -4.6639 n ₂ = -0.3328	0.2166	0.4654	2

^[a] The equation numbers are same as in the text.

^[b] d.s. = dry solids.

Table 3.2 Regression-analysis results for DSG

Equation No.	Coefficients		Mean residual square	Mean deviation (kg/100 kg d.s.)	Rank of accuracy
(3.1)	$k = 24.8401$	$n = -0.7822$	0.2493	0.4993	7
(3.2)	$k_1 = 16.1539$ $k_2 = -0.1355$	$n_1 = -0.5182$ $n_2 = 0.5365$	0.0927	0.3045	4
(3.3)	$k = 7.8051$	$n = -0.0481$	0.1788	0.4229	6
(3.4)	$k_1 = 5.9222$ $k_2 = 18.4770$	$n_1 = -0.0369$ $n_2 = -0.4635$	0.0888	0.2980	2
(3.5)	$k = 14.6376$ $m = 0.5502$	$n = -0.3276$	0.0995	0.3154	5
(3.6)	$k_1 = 5.8572$ $n_1 = -0.0295$ $m_1 = 1.0595$	$k_2 = 6.961 \times 10^{17}$ $n_2 = -1.0000$ $m_2 = 2.3000$	0.0900	0.3000	3
(3.7)	$k = 1.2280$	$n = 8.8243$	0.8920	0.9445	8
(3.8)	$k_1 = -4.3833$ $k_2 = 2.8185$	$n_1 = -37.1589$ $n_2 = 4.3658$	0.0860	0.2933	1
(3.9)	$k = 8.1659$	$n = 1.5299$	0.1581	0.3977	6
(3.10)	$k_1 = 56.3299$ $k_2 = 6.5893$	$n_1 = 20.7539$ $n_2 = 1.2637$	0.0954	0.3089	3
(3.11)	$k = 0.5207$	$n = 3.0619$	0.2045	0.4522	7
(3.12)	$k_1 = 0.7250$ $k_2 = -1.6052$	$n_1 = 2.6244$ $n_2 = -8.2085$	0.1082	0.3289	4
(3.13)	$k = 0.0382$ $m = 0.3783$	$n = 5.4832$	0.1217	0.3489	5
(3.14)	$k_1 = -3.2747$ $n_1 = -5.7336$ $m_1 = 1.7328$	$k_2 = 3.1392$ $n_2 = 1.8079$ $m_2 = 4.8392$	0.0834	0.2889	2
(3.15)	$k = 16.2235$	$n = -0.8542$	0.3073	0.5544	8
(3.16)	$k_1 = 803.5$ $k_2 = 5.2199$	$n_1 = -4.6051$ $n_2 = -0.3627$	0.0744	0.2730	1

or mean deviations. The equations in complex forms have higher accuracies than the equations in simple forms. Except for Eqs. 3.3, 3.7, 3.9, and 3.15 for the BSG and Eq. 3.7 for the DSG, all the equations have acceptable accuracies to describe the isobars, as indicated by the small mean residual squares or mean deviations. Among them, Eqs. 3.5 and 3.13 have a simple form and have medium but acceptable accuracies. Therefore, the two equations were recommended to describe the isobars for the spent grains in superheated steam under the conditions specified for the experiments. The isobars of the BSG and DSG in superheated steam predicted by Eqs. 3.5 and 3.13 with regression-determined coefficients were plotted in Figs. 3.3 through 3.6, which also show that the two regression equations fit the experimental data well.

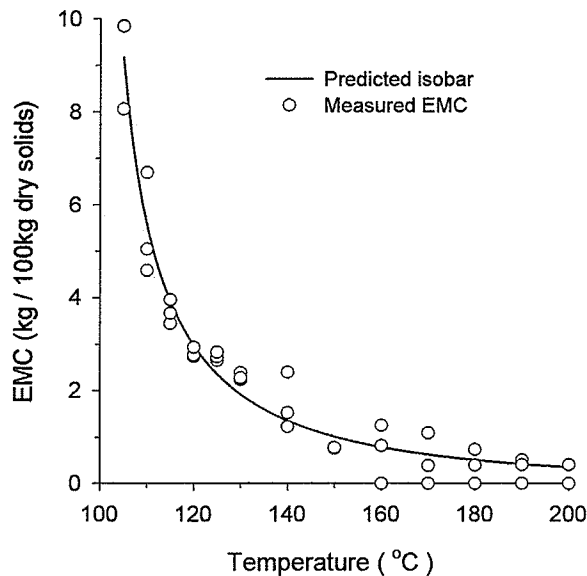


Figure 3.3 Comparison of the predicted results with measured EMC of BSG in superheated steam under atmospheric pressure.
The solid line is plotted based on equation 3.5 with $k = 62.00$, $n = -1.12$, and $m = 0.33$.

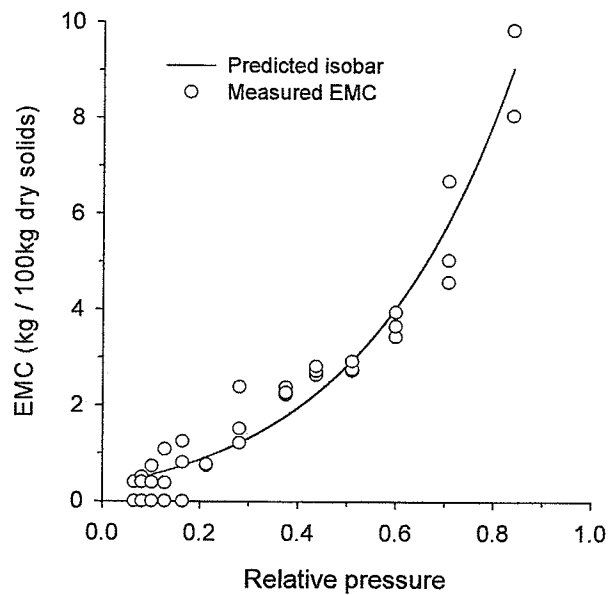


Figure 3.4 Comparison of the predicted results with measured EMC of BSG in superheated steam under atmospheric pressure.
The solid line is plotted based on equation 3.13 with $k = 0.25$, $n = 4.09$, and $m = 0.75$.

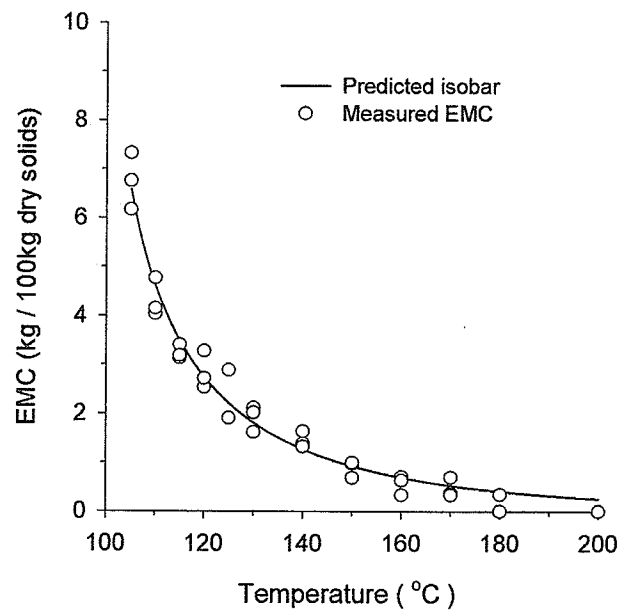


Figure 3.5 Comparison of the predicted results with measured EMC of DSG in superheated steam under atmospheric pressure.
The solid line is plotted based on equation 3.5 with $k = 14.64$, $n = -0.33$, and $m = 0.55$.

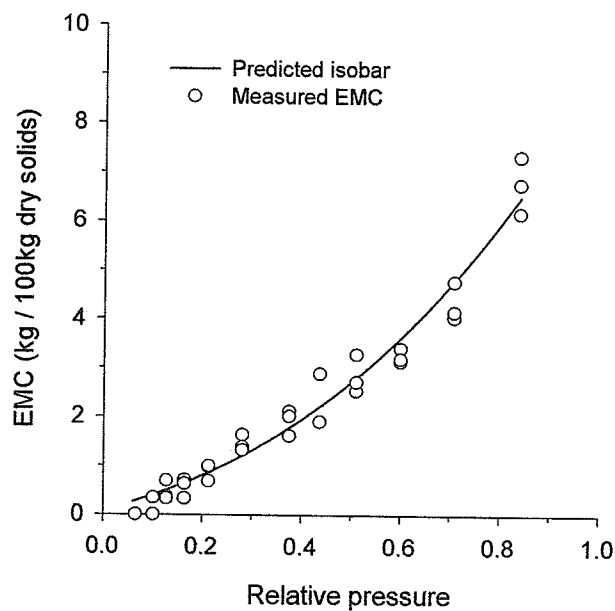


Figure 3.6 Comparison of the predicted results with measured EMC of DSG in superheated steam under atmospheric pressure.
The solid line is plotted based on equation 3.13 with $k = 0.038$, $n = 5.48$, and $m = 0.38$.

A similar pattern of EMC-superheat relationship was also reported by several researchers (Beeby and Potter 1985; Hager 1998; Hager et al. 1997; Wimmerstedt and Hager 1996). Figure 3.7 shows EMC-superheat isobars obtained from the literature in comparison with my data. The isobars of ceramic spheres, wood chips, paper pulp, and Al_2O_3 spheres are similar in shape to that of BSG or DSG and can also be well described by Eq. 3.5 with the coefficients listed in Table 3.3. Ceramic spheres has a much lower EMC due to their non-capillary porous structure, but wood chips, paper pulp, and Al_2O_3 spheres have higher water capacities than BSG and DSG. Particularly, F.C.C. (crystalline silica) and brown coal have an enhanced moisture absorption capacity below 120 and 140°C, respectively, and their isobars can not be described by Eq. 3.5.

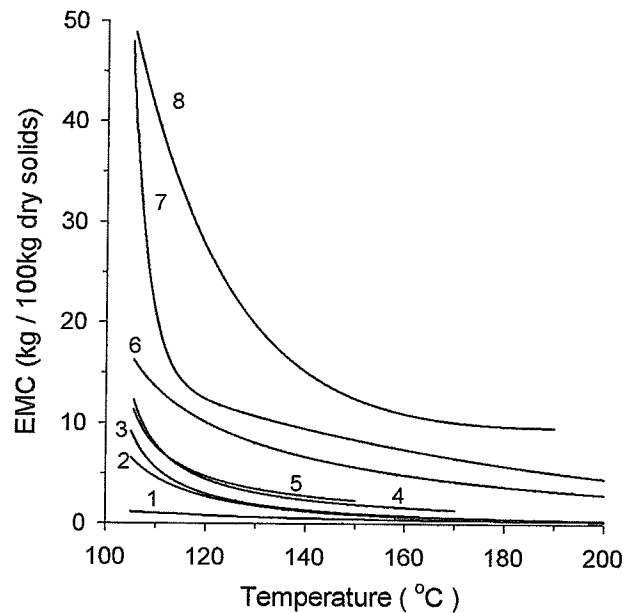


Figure 3.7 The EMC-temperature isobars for different materials in superheated steam under atmospheric pressure.

1 = ceramic spheres (Hager et al. 1997); 2 = DSG; 3 = BSG;
4 = wood chips (Kollmann 1961); 5 = paper pulp (Beeby and
Potter 1985); 6 = Al_2O_3 spheres (Hager 1998); 7 = F.C.C.
(Beeby and Potter 1985); 8 = brown coal (Ho 1984).

Table 3.3 Regression-analysis results and the coefficients in Eq. 3.5 for other materials

Coefficients		Mean residual square	Mean deviation (kg/100 kg d.s.)	Material
$k = 1.9344$ $m = 0.4610$	$n = -0.2430$	0.0012	0.0349	Ceramic spheres
$k = 3053.1$ $m = 0.1315$	$n = -4.4053$	0.1657	0.407	Wood chips
$k = 2320.0$ $m = 0.1188$	$n = -4.3430$	0.1343	0.3665	Paper pulp
$k = 27.8251$ $m = 0.4950$	$n = -0.2304$	0.082	0.2864	Al_2O_3 spheres

3.4 Conclusions on EMC of spent grains in superheated steam

The temperature of superheated steam had a significant effect on the EMC of spent grains exposed to superheated steam at atmospheric pressure. The EMC decreased substantially, from 9.3 to 1.7 kg/100 kg dry solids for BSG and from 6.7 to 1.4 kg/100 kg dry solids for DSG, with an increase in the steam temperature from 105 to 140°C; but it changed by only 1.3 kg/100kg dry solids with increasing the steam temperature from 140 to 180°C and approached zero at the temperature of 200°C.

At atmospheric pressure, the sorption relationships between the spent grains and superheated steam can be represented on isobars by plotting the EMC against the temperature or relative pressure of steam. The isobars were well described by two proposed equations; the coefficients in which were obtained by non-linear regressions with the SAS system based on the experimental data.

4 MODELLING SUPERHEATED-STEAM DRYING OF THIN LAYERS OF SPENT GRAINS

4.1 Drying experiments of thin-layer spent grains in superheated steam

4.1.1 Materials

The materials used in the experiments were the same as those used in the EMC-determination experiments (Chapter 3). The initial moisture content of the two tested products was 4.22 ± 0.15 kg/kg db for BSG and 2.17 ± 0.15 kg/kg db for DSG. The moisture content was determined by the vacuum-oven drying method (AACC 1995). Each sample was weighed around 8.8 g for BSG drying and 6.1 g for DSG drying.

4.1.2 Equipment

The equipment used in the experiments was the superheated-steam drying system described in the Section 3.1.1. To force most of the steam through the sample to be dried, the drying chamber was modified slightly (Fig. 4.1). A metal plate with a central round opening (69 mm in diameter) was set in the middle section of the drying chamber. During drying, a circular mesh tray (68 mm in diameter) with the sample was placed in the central hole and hung from the electronic balance.

4.1.3 Drying conditions

Drying experiments were conducted under atmospheric pressure. The steam temperature

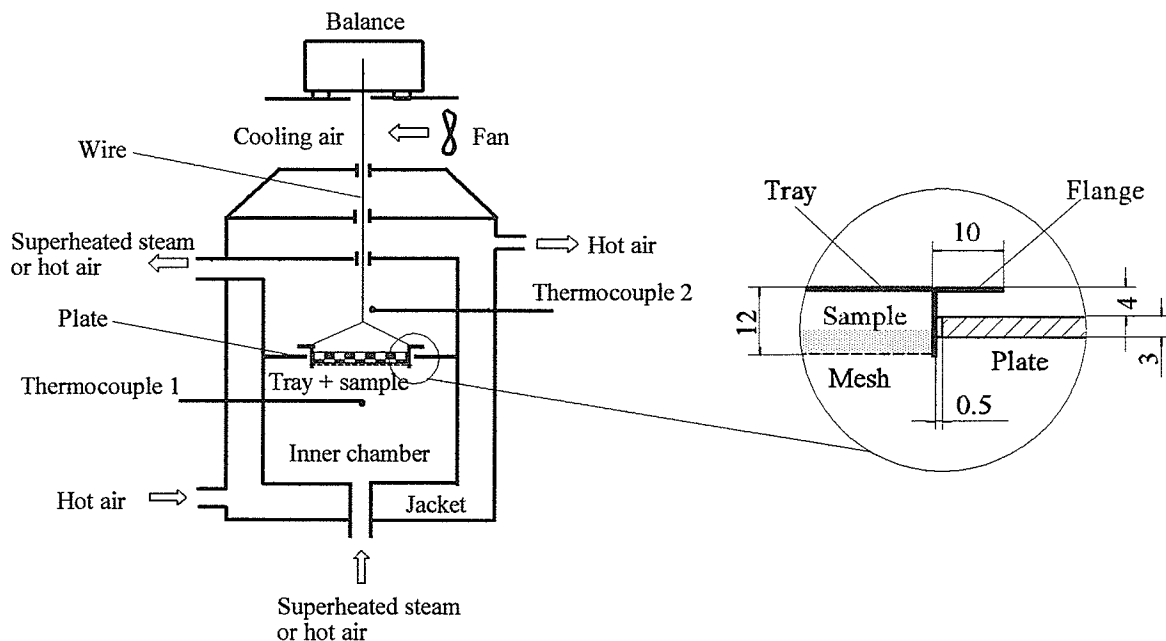


Figure 4.1 Modified drying chamber (Dimensions are in mm)

at the inlet to the drying chamber was controlled at seven levels: 110, 115, 120, 130, 145, 160, and 180°C with an accuracy of $\pm 3^\circ\text{C}$. The velocity of steam passing through the drying sample was set at five values: 0.25, 0.47, 0.66, 0.86, and 1.08 m/s with an accuracy of ± 0.06 m/s for BSG drying; and 0.28, 0.49, 0.70, 0.92, and 1.15 m/s with an accuracy of ± 0.06 m/s for DSG drying. The steam velocity was adjusted by the steam flow valve and was calculated based on the amount of condensed water collected from the condenser in a certain time and the steam temperature inside the drying chamber.

4.1.4 Determining the percentage of the steam passing through the sample

During drying, not all the steam passed through the sample to be dried. A small amount of steam passed through the gap between the sample tray and the plate (Fig. 4.1). The

percentage of the steam passing through the sample must be known for the calculation of steam velocity. Therefore, some special tests were conducted to determine this percentage.

In this series of tests, hot air (70°C) instead of steam was used as the drying medium for convenience. The tray with the same amount of sample as in normal drying experiments was changed alternatively several times during the test between two positions: A and B. Position A was the normal drying position in which the tray was hung in the drying chamber from the balance and the flange of the tray was about 4 mm above the plate. At position B, the tray was seated on the plate with its flange contacting the plate forcing all the hot air to pass through the sample. At each position, the air velocities were measured with a thermal anemometer (Model HHF50, OMEGA Engineering, Inc., Stamford, CT) at two or three selected points approximately 20 mm above the sample (Appendices B.1 and B.2.). Four runs of tests were conducted at different air-velocity levels which were in the range of the steam velocity (0.25 to 1.15 m/s) for the normal drying experiments. The average velocity of the air passing through the sample at position A was lower by 14.8% for BSG drying and 13.9% for DSG drying compared with that at position B. This means that 14.8% and 13.9% of the steam passing through the chamber escaped through the gap between the sample tray and the plate during the normal experiments for BSG and DSG drying, respectively.

4.1.5 Experimental procedure for drying tests

During drying, the sample was placed in a thin layer on the mesh tray which was hung in the drying chamber by a thin wire attached to an electronic balance. The mass change was

recorded every 2 or 3 s by a computer connected to the balance. The drying process was ended when the mass of the sample remained constant for 2 to 5 min depending on the total drying time. Under each set of drying conditions, tests were conducted in triplicates.

The flow of steam created a “lifting force” which affected the mass-change readings. The “lifting force” changed during drying due to the shrinkage of the sample. To compensate for this apparent loss in mass, a calibration test was conducted immediately after each drying test mentioned above. In the calibration test, the steam conditions were kept the same as in the previous drying test; however, the drying medium was manually controlled to bypass the drying chamber for 10 to 15 s every 0.5 to 2 min. The difference between the readings with and without steam passing through the chamber was the “lifting force”, which was incorporated into the calculation of true mass loss of the sample.

4.1.6 Determination of nutrient composition

The utilization of BSG and DSG depends on the composition and nutritional benefits of these materials. To find out the effects of drying conditions on the nutrient composition of spent grains, the samples dried under selected steam temperatures and for different drying times were collected for composition analysis. Four major nutrient components (starch, β -glucan, pentosan, and protein) in the samples were chosen to be determined. Beta-glucan and pentosan were determined because both of these non-starch polysaccharides are constituents of dietary fiber. The presence of dietary fiber makes spent grains attractive for human consumption (but not necessary for animal feeds). The mixed-linkage β -glucan assay kit (Megazyme International Ireland, Ltd) was used for β -glucan determination (McCleary and

Codd 1991). The phloroglucinol method of Douglas (1981) was used for colorimetrically determining the content of pentosan. Starch content was determined enzymatically using the Megazyme kit for total starch assay (Megazyme International Ireland, Ltd) (McCleary et al. 1994). Protein content was determined by combustion nitrogen analysis (CNA) using a LECO Model FP-428 CNA analyzer (Leco Corp. St. Joseph, MI) calibrated against ethylenediaminetetraacetic acid.

4.2 Modelling the steam drying of thin-layer spent grains

4.2.1 Development of thin-layer drying model

In most models developed for drying large-size or compact products with superheated steam, an overpressure built-up inside the products is considered one of the important driving forces during the falling-rate drying period (Fyhr and Rasmuson 1997; Hager et al. 1997; Moyne et al. 1990; Perre et al. 1993). The involvement of the overpressure makes the modelling more complex. However, there is no significant overpressure inside spent grains during steam drying because spent grains are in chopped or ground state (Bonazzi et al. 1996). Therefore, the general modelling technique considering the overpressure the third driving force is not suitable for modelling the steam drying of thin-layer spent grains.

Based on the observation in previous studies (Tang and Cenkowski 2000; Tang et al. 2000), it is known that the drying curves for superheated-steam drying and hot-air drying are of similar shapes, so the same forms of mathematical models for air drying can be used for superheated-steam drying. Several mathematical models have been developed for the air

drying of thin-layer biological materials, especially grains, which was summarized in Section 2.1.3. They may be diffusion models, semi-theoretical models, or empirical models. Diffusion models are based on diffusion theories and can accurately describe moisture and temperature distributions inside the drying product. In this kind of modelling, the particles of the product are required to have the same shape (regular or non-regular) and the same size; otherwise, these models can not be solved by theoretical methods or numerical techniques. Obviously, diffusion models are not useful for modelling the steam drying of thin-layer spent grains because of the unfixed shapes of BSG particles and the predominant slurry consistency of DSG.

The models describing the steam drying of thin-layer spent grains could be semi-theoretical or empirical. Equation 4.1 is one of the most often used drying models for describing the air drying of thin-layer biological materials (Page 1949, cited by Jayas et al. 1991).

$$MR = \exp(-K t^N) \quad (4.1)$$

where K and N are experimental parameters and t has the unit of min.

The moisture ratio is defined as:

$$MR = \frac{M - M_e}{M_o - M_e} \quad (4.2)$$

Equation 4.1 gives the initial moisture ratio 1 at time zero. In superheated-steam drying, however, a small amount of moisture is gained from steam condensation on the sample surface at the beginning of drying (Tang and Cenkowski 2000; Tang et al. 2000). As a result, the initial moisture ratio for superheated-steam drying should be a little bit greater than 1.

Therefore, a third experimental parameter A was introduced in Eq. 4.3 to model the drying of thin-layer spent grains in superheated steam:

$$MR = A \exp(-K t^N) \quad (4.3)$$

In Eq. 4.3, the parameters A , K , and N are functions of steam temperature and/or steam velocity. The equilibrium moisture content M_e which appears in Eq. 4.2 is dependent on the steam temperature T . The relationship between M_e and T are described by Eqs. 4.4 and 4.5 which were developed in Section 3.3.

$$M_e = 0.6538 \exp[-1.1605(T_s - 100)^{0.3269}] \text{ (for BSG)} \quad (4.4)$$

$$M_e = 0.1389 \exp[-0.3024(T_s - 100)^{0.5609}] \text{ (for DSG)} \quad (4.5)$$

4.2.2 Determination of coefficients in the drying model

Based on the mass changes, initial moisture content, and equilibrium moisture content of the samples, the changes in moisture ratio were calculated for the drying tests under different conditions (Appendices B.3 and B.4).

Using non-linear regression and considering MR and t the regression variables, the parameters A , K , and N in the drying model (Eq. 4.3) were determined under each set of drying conditions (Appendices B.5 and B.6). The regression was accomplished by the NLIN procedure in SAS system (SAS 1985). The SAS program for the regression was shown in Appendix B.7.

From the regression results, it was noted that parameter A decreased and parameter K

increased approximately linearly with the increase in steam temperature T_s and velocity V_s , and parameter N increased following approximately a linear function as a result of the steam temperature increase only (Appendices B.8 and B.9). Therefore, these relationships were represented as:

$$A = (a_1 T_s + a_2)(a_3 V_s + a_4) \quad (4.6)$$

$$K = (k_1 T_s + k_2)(k_3 V_s + k_4) \quad (4.7)$$

$$N = n_1 T_s + n_2 \quad (4.8)$$

Where $a_1, a_2, a_3, a_4, k_1, k_2, k_3, k_4, n_1$, and n_2 are coefficients.

All the coefficients in Eqs. 4.6 through 4.8 were obtained by further regression in which parameters A (or K , or N), T_s , and V_s were considered the regression variables (Table 4.1).

Appendix B.10 gives the SAS program for the regression analysis.

Table 4.1 Results of the second-step regression

Parameter	BSG drying model			DSG drying model		
	Regression value	Mean residual square	Mean deviation	Regression value	Mean residual square	Mean deviation
A	a_1	-0.00058		-0.00135		
	a_2	1.2925	0.00079	0.8375	0.0027	0.052
	a_3	-0.0963		-0.2778		
	a_4	0.9991		1.9578		
K	k_1	0.00273		0.00388		
	k_2	-0.2609	0.00078	-0.3741	0.00094	0.0307
	k_3	2.0984		2.0399		
	k_4	0.2174		0.2199		
N	n_1	0.00222	0.075	0.00557	0.00577	0.0759
	n_2	0.9599		0.5185		

The small mean residual squares shown in Appendices B.5 & B.6 and Table 4.1 indicate that the regression equations have an acceptable accuracy for fitting the experimental data. Three drying curves predicted by the drying model under selected drying conditions and the corresponding measured data points were plotted in Figs. 4.2 and 4.3. The figures also show that the equations with the obtained regression coefficients fit the experimental data well.

4.3 Drying dynamics of thin-layer spent grains in superheated steam

Based on the drying model, the moisture ratio, moisture content, and drying rate of thin-layer spent grains at any time during drying in superheated steam can be calculated. Therefore, the drying curves and drying rate curves for thin-layer spent grains in superheated steam under any drying conditions in the range defined in this study can be plotted and analysed. Generally, a drying curve shows the changes of moisture ratio with drying time, and a drying rate curve represents the changes of drying rate with moisture content. Here, the drying rate is defined as the change of moisture content in unit time, i.e. the derivation of moisture content dM/dt :

$$\frac{dM}{dt} = -A K N (M_0 - M_e) t^{(N-1)} \exp(-K t^N) \quad (4.9)$$

To analyse the drying dynamics of thin-layer spent grains in superheated steam, a number of drying curves and drying rate curves for selected drying conditions were plotted in Figs. 4.4 through 4.7.

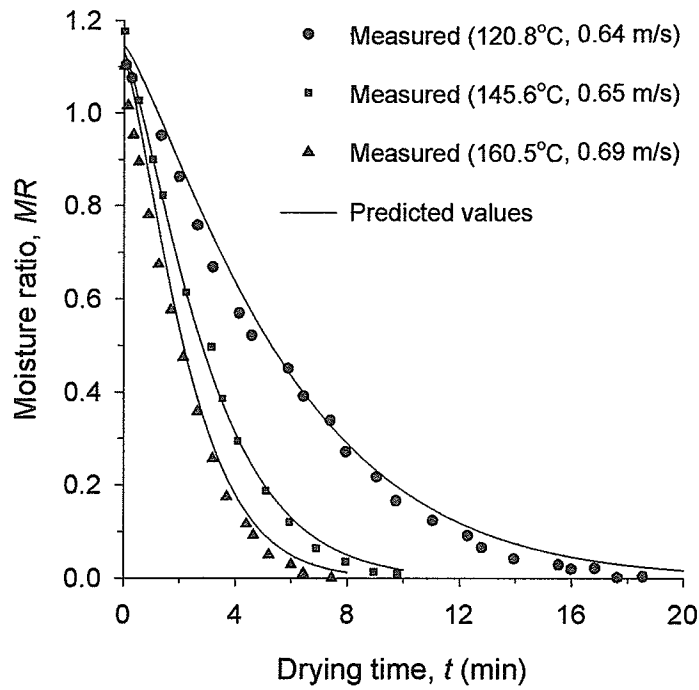


Figure 4.2 Comparison of predicted results with measured moisture ratios of BSG in superheated steam.

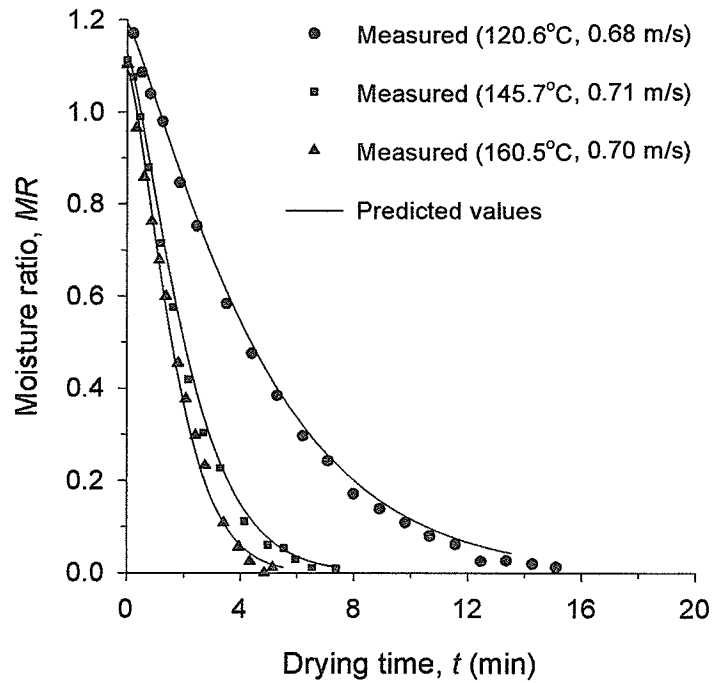


Figure 4.3 Comparison of predicted results with measured moisture ratios of DSG in superheated steam.

Because of steam condensation, the samples gained a small amount of moisture in the first several seconds of drying. The samples gained more moisture in low-temperature or low-velocity steam than in high-temperature or high-velocity steam. At 0.7 m/s, for example, the samples of BSG gained moisture to reach the moisture ratios of 1.15, 1.13, and 1.11 (or 1.21, 1.13, and 1.05 for DSG samples) for the steam temperatures of 110, 145, and 180°C, respectively (Fig. 4.4). At 145°C, the moisture ratios of BSG samples at the beginning of drying reached 1.18, 1.13, and 1.08 (or 1.20, 1.13, and 1.06 for DSG samples) for the steam velocities of 0.3, 0.7, and 1.1 m/s, respectively (Fig. 4.5).

Moisture contents decreased faster at high temperature or high velocity than at low temperature or low velocity. At 0.7 m/s, the drying times for reaching the equilibrium at the temperatures of 110, 145, and 180°C were 40, 13, and 8 min for BSG drying (or 40, 10, and 6 min for DSG drying), respectively (Fig. 4.4). Increasing the temperature of steam from 110 to 180°C decreased the drying time by 80% for BSG drying (or 85% for DSG drying). At 145°C, the drying times were 21, 13, and 9 min for BSG drying (or 16, 10, and 7 min for DSG drying) at the velocities of 0.3, 0.7, and 1.1 m/s, respectively (Fig. 4.5). Increasing the velocity of steam from 0.3 to 1.1 m/s decreased the drying time by 57% for BSG drying (or 56% for DSG drying).

There was no constant-rate drying period noticeable in the steam drying of thin-layer spent grains. The drying rate decreased gradually during the drying process except for a short initial warm-up period, during which the drying rate increased rapidly due to the warm-up (Figs. 4.6 and 4.7).

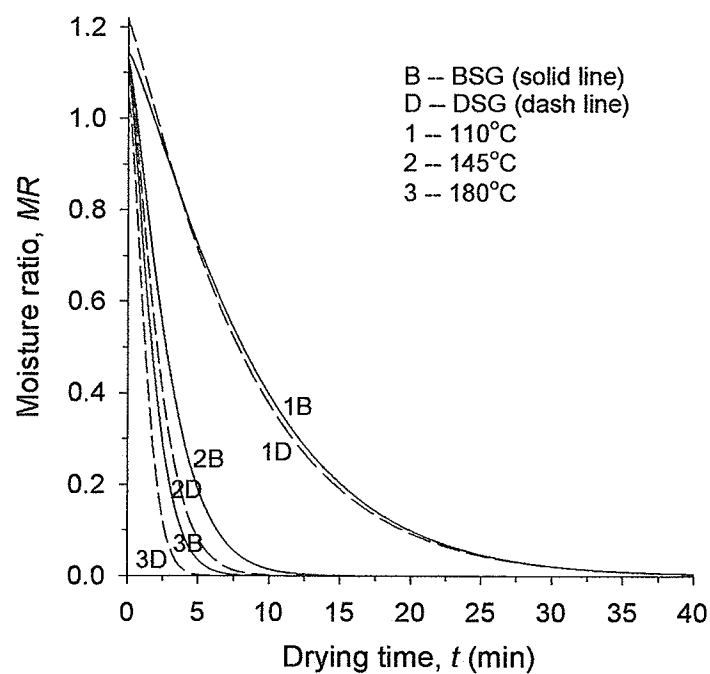


Figure 4.4 Predicted drying curves for thin-layer BSG and DSG in superheated steam at 0.7 m/s and various temperatures.

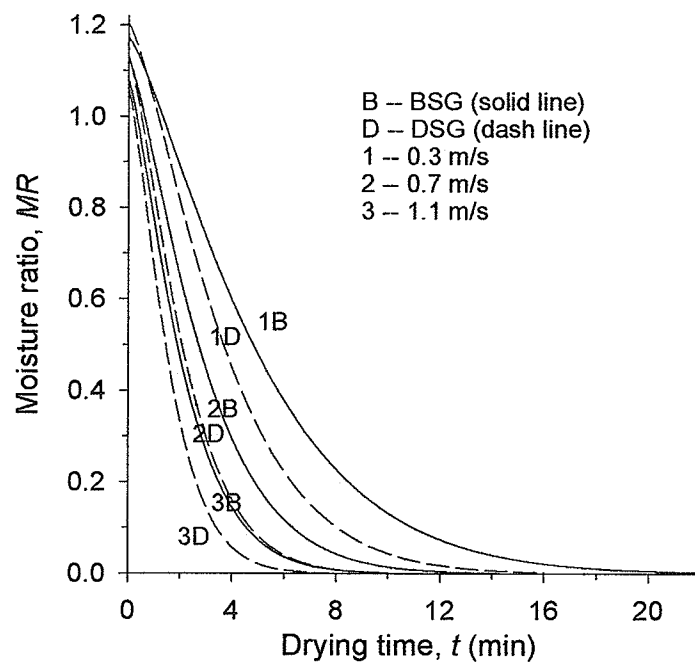


Figure 4.5 Predicted drying curves for thin-layer BSG and DSG in superheated steam at 145°C and various velocities.

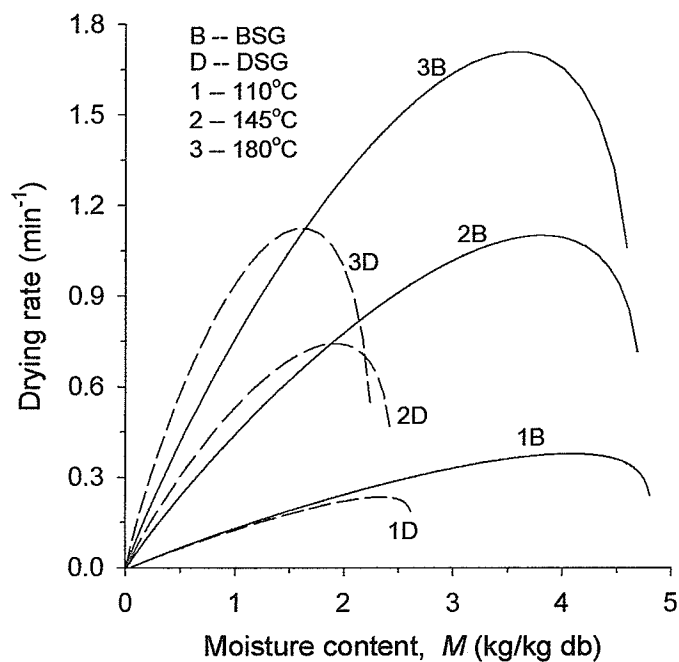


Figure 4.6 Predicted drying rates for thin-layer BSG and DSG in superheated steam at 0.7 m/s and various temperatures.

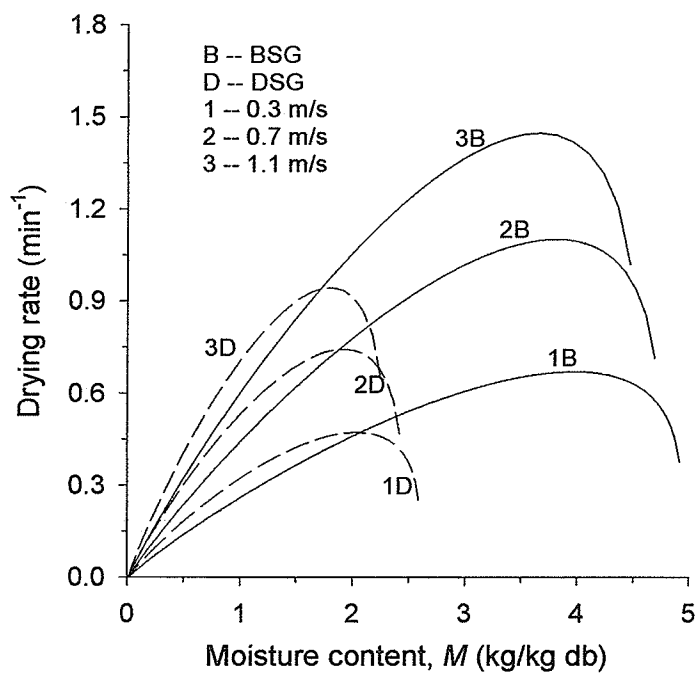


Figure 4.7 Predicted drying rates for thin-layer BSG and DSG in superheated steam at 145°C and various velocities.

The effects of steam temperature and velocity on drying were also shown on drying rate curves. The higher the steam temperature or velocity, the higher the drying rate was. During the falling-rate drying period, the drying rate changed near linearly with the change of steam temperature or velocity. For example, at 0.7 m/s and when the samples were dried to the moisture content of 1 kg/kg db, increasing steam temperature from 110 to 145 and 180°C increased the drying rate from 0.13 to 0.44 and 0.76 for BSG drying (or from 0.12 to 0.53 and 0.94 for DSG drying), respectively (Fig. 4.6). At 145°C and when the samples were dried to the moisture content of 1 kg/kg db, an increase of steam velocity from 0.3 to 0.7 and 1.1 m/s caused an increase of the drying rate from 0.26 to 0.44 and 0.60 for BSG drying (or from 0.32 to 0.53 or 0.71 for DSG drying), respectively (Fig. 4.7).

4.4 Effects of drying temperature and time on nutrient composition

The nutrient composition of undried BSG and DSG as well as of the samples dried in superheated steam under various conditions is presented in Table 4.2. The undried BSG contained more starch but less β -glucans, compared with the undried DSG. Both materials contained considerable amounts of pentosans and proteins. In general, the effects of drying on the amounts of nutrients in the samples were rather small. Among the four components measured, starch was affected to the greatest extent. Both drying temperature and time had some effect on the starch content in the dried samples. All dried BSG and DSG had lower starch content than the undried samples. Increasing the drying temperature from 110 to 180°C decreased the starch in the samples dried to the equilibrium at the steam velocity of 0.66 m/s from 6.83 to 5.84% (decrease by 14.5%) for BSG and from 2.08 to 1.84% (decrease by

Table 4.2 Nutrient composition of undried and dried^[a] spent grain samples

	Temp (°C)	Time (min) ^[b]	Starch (% db)		β-glucans (% db) ^[d]		Pentosans (% db) ^[d]		Proteins (% db)	
			Ave ^[c]	Std dev	Ave ^[c]	Std dev	Ave ^[c]	Std dev	Ave ^[c]	Std dev
BSG										
	110	36	6.83	0.49	0.76	0.03	19.45	1.04	24.51	0.06
	145	11.5	5.84	0.03	0.76	0.01	19.48	1.93	22.90	0.26
	180	7.5	5.84	0.21	0.75	0.02	22.64	1.84	24.43	0.06
Undried			7.49	0.02	0.78	0.03	24.97	4.78	24.51	0.29
	145	(3)	7.22	0.12	0.76	0.03	20.64	4.25	24.66	
	145	(6)	6.27	0.29	0.77	0.01	22.09	4.08	23.30	
	145	11.5	5.84	0.03	0.76	0.01	19.48	1.93	22.90	0.26
DSG										
	110	49	2.08	0.01	1.62	0.03	19.73	1.65	27.21	
	145	17	1.93	0.01	1.49	0.01	20.86	0.67	27.30	
	180	10	1.84	0.00	1.44	0.01	21.20	4.79	28.15	
Undried			2.50	0.03	1.50	0.01	21.59	2.37	26.50	
	145	(4.5)	2.38	0.10	1.70	0.07	17.93	0.56	27.35	0.11
	145	(9)	2.19	0.04	1.63	0.03	20.68	1.68	27.38	
	145	17	1.93	0.01	1.49	0.01	20.86	0.67	27.30	

[a] Dried in superheated steam at the steam velocity of 0.66 m/s and different temperatures for different times;

[b] Times for drying to equilibrium except those in parentheses;

[c] Average of 2 results;

[d] Samples washed with ethanol prior to treatment;

[e] Average of 2 results with std dev only.

11.5%) for DSG. An increase in drying time from zero to the time when the equilibrium was reached at the steam velocity of 0.66 m/s caused the starch to decrease from 7.49 to 5.84% (decrease by 22%) in BSG samples and from 2.50 to 1.93% (decrease by 23%) in DSG samples. The high drying temperatures and the initially high moisture content of the spent grains are probably responsible for the partial gelatinization of starch and the formation of amylose-lipid complexes or resistant starch or both. The last two phenomena most likely

decreased the amount of starch measured in the samples. In general, β -glucans were affected very little by the drying processes. Only the drying temperature had a small influence on the β -glucan content in the dried DSG samples; it decreased from 1.62 to 1.44% (decrease by 11%) when the temperature used for drying the samples to equilibrium changed from 110 to 180°C. The relatively low precision of the method used for determining pentosans hindered somewhat the interpretation of the results. Nevertheless, it appears that the content of pentosans in DSG and BSG was not affected to any great extent by the drying processes. The proteins in both spent grains were likely denatured during the drying processes, but this did not affect their average content in dried samples.

4.5 Conclusions on modelling of thin-layer drying

A model of drying thin-layer spent grains in superheated steam was developed through modifying a commonly-used air-drying model for thin-layer biological materials. The coefficients in the drying model were determined by fitting the modelling equations to experimental data in two steps of non-linear regression analyses.

At the beginning of drying thin-layer spent grains in superheated steam, a small amount of moisture was gained from steam condensation on the sample surface. The moisture gain increased the initial moisture ratio of the samples from 1 to the range between 1.05 and 1.20 for BSG drying and to the range between 1.00 and 1.30 for DSG drying. It decreased linearly with an increase in steam temperature or velocity.

Both steam temperature and steam velocity had a significant effect on the steam drying of

thin-layer spent grains. Increasing the temperature or velocity increased the drying rate near linearly and consequently decreased the drying time. At the velocity of 0.7 m/s, an increase of steam temperature from 110 to 180°C caused the drying time to decrease by 80% for BSG drying and 85% for DSG drying. Similarly, at 145°C, increasing the steam velocity from 0.3 to 1.1 m/s decreased the drying time by 57% for BSG drying and 56% for DSG drying.

The major nutrient components in BSG and DSG were starch, β -glucan, pentosan, and protein. Increasing drying temperature and time caused a substantial decrease in starch content but a small or no change in β -glucan and pentosan content in the dried samples. A change of protein content in the dried samples was not detectable.

5 MODELLING SUPERHEATED-STEAM DRYING OF FIXED BEDS OF SPENT GRAINS

5.1 Development of the model for drying fixed beds of spent grains in superheated steam

5.1.1 Determination of basic variables in the drying model

Many deep-bed models for drying biological materials with hot air have been developed based on mass and heat balances in an elementary volume of the bed. All the models describe the moisture and temperature changes in the material to be dried, as well as the temperature and humidity changes of the air passing through the bed, as stated in Section 2.1.4. The change of humidity is caused by the moisture evaporation from the material to be dried to the air during the drying process. In superheated-steam drying, the evaporation does not change the composition of the drying medium, but increases the flow rate or velocity of the steam passing through the packed material. Instead of the humidity change of air, the flow-rate change of steam is an import parameter in the modelling of drying deep-bed material with superheated steam. Therefore, models for deep-bed drying with superheated steam can be obtained through the modification of corresponding deep-bed models of air drying by replacing the quantity of air humidity with steam flow rate.

In a partial-differential-equation (p.d.e.) model for drying fixed beds of spent grains in superheated steam, the equations should contain four basic variables: the moisture content of spent grain M , the temperature of spent grain T , the mass flow rate of steam G_s , and the temperature of steam T_s .

5.1.2 Derivation of the fixed-bed drying model

The approach to derivate the equations in the p.d.e. model of fixed-bed drying with superheated steam is similar to the approach for developing the model of fixed-bed drying with hot air (Bakker-Arkema et al. 1967; Brooker et al. 1974; Sharp 1982; Spencer 1969). The following assumptions are made in the development of the drying model:

- The temperature and moisture gradients within the individual particles are negligible.
- The heat capacities of dry spent grain, moisture, and steam are constant during short periods of time and within the temperature range under consideration.
- The conduction heat transfer between particles in the bed is negligible.
- The void space in the bed is filled with steam.

To obtain the equations describing $M(x, t)$, $T(x, t)$, $G_s(x, t)$, and $T_s(x, t)$ in the bed, energy and mass balances are written on an elemental control volume Sdx in the bed (Fig. 5.1).

Equation for the energy balance of steam

The amount of steam flowing through the elemental bed volume Sdx in time dt is

$$G_s S dt \quad (5.1)$$

The enthalpy of the steam flowing into Sdx in time dt is

$$c_s T_s G_s S dt \quad (5.2)$$

The enthalpy of the same steam flowing out of Sdx in time dt is

$$c_s \left(T_s + \frac{\partial T_s}{\partial x} dx \right) G_s S dt \quad (5.3)$$

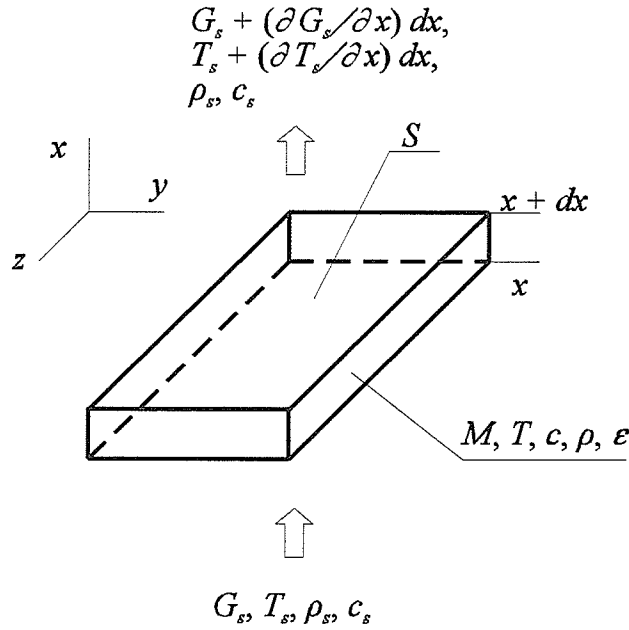


Figure 5.1 Elemental control volume (Sdx) in a fixed bed of particles

The change in enthalpy of the steam flowing across the elemental bed volume in time dt is the difference between equations 5.2 and 5.3:

$$-G_s c_s \frac{\partial T_s}{\partial x} S dx dt \quad (5.4)$$

The change in enthalpy of the steam within Sdt in time dt is

$$c_s \rho_s \varepsilon S dx \frac{\partial T_s}{\partial t} dt \quad (5.5)$$

As steam moves through the elemental bed, a convective heat exchange occurs. The energy transferred from steam to spent grain in Sdt in time dt is

$$h a (T_s - T) S dx dt \quad (5.6)$$

On the energy balance, the enthalpy change of the steam across the elemental bed equals

to the sum of the energy transferred from steam to spent grain and the enthalpy change of steam within Sdx . From equations 5.4, 5.5, and 5.6, the energy balance is expressed as:

$$-G_s c_s \frac{\partial T_s}{\partial x} S dx dt = h a (T_s - T) S dx dt + c_s \rho_s \varepsilon S dx \frac{\partial T_s}{\partial t} dt \quad (5.7)$$

Rearranging equation 5.7 gives

$$\frac{\partial T_s}{\partial x} = -\frac{h a}{G_s c_s} (T_s - T) - \frac{\varepsilon \rho_s}{G_s} \frac{\partial T_s}{\partial t} \quad (5.8)$$

Equation for the energy balance of spent grain

The change in enthalpy of spent grain in the elemental bed volume Sdx in time dt is

$$\rho S dx (c + c_w M) \frac{\partial T}{\partial t} dt \quad (5.9)$$

The amount of moisture evaporated from spent grain within Sdx into steam in time dt is

$$-\rho S dx \frac{\partial M}{\partial t} dt \quad (5.10)$$

The energy required for this evaporation is

$$-h_v \rho S dx \frac{\partial M}{\partial t} dt \quad (5.11)$$

The energy to increase the temperature of the evaporated moisture from T to T_s in time dt is

$$-c_s (T_s - T) \rho S dx \frac{\partial M}{\partial t} dt \quad (5.12)$$

On the energy balance of spent grain in Sdx , the energy transferred by convection from steam to the spent grain is equal to the sum of the enthalpies required for heating the spent grain, evaporating moisture from the spent grain, and increasing the temperature of the

evaporated moisture. Hence, from equations 5.6, 5.9, 5.11, and 5.12, the energy balance equation is presented as:

$$h a (T_s - T) S dx dt = \rho S dx (c + c_w M) \frac{\partial T}{\partial t} dt - h_v \rho S dx \frac{\partial M}{\partial t} dt - c_s (T_s - T) \rho S dx \frac{\partial M}{\partial t} dt \quad (5.13)$$

Rearranging the equation gives

$$\frac{\partial T}{\partial t} = \frac{h a (T_s - T)}{\rho (c + c_w M)} + \frac{h_v + c_s (T_s - T)}{c + c_w M} \frac{\partial M}{\partial t} \quad (5.14)$$

Equation for moisture balance

In time dt , the amount of moisture evaporated from the spent grain within Sdx results in a change in steam flow rate with respect to x . The steam flow rate increases from G_s at x to

$(G_s + \frac{\partial G_s}{\partial x} dx)$ at $(x + dx)$. The mass balance equation is given by

$$-\rho S dx \frac{\partial M}{\partial t} dt = S \frac{\partial G_s}{\partial x} dx dt \quad (5.15)$$

which gives

$$\frac{\partial G_s}{\partial x} = -\rho \frac{\partial M}{\partial t} \quad (5.16)$$

Drying-rate equation

The drying-rate equation is obtained from the thin-layer drying model (Eq. 4.3) determined in Section 4.2. It is presented here as:

$$\frac{\partial M}{\partial t} = -\frac{KN}{60} (M - M_e) \left[\frac{1}{K} \operatorname{Ln} \left(\frac{A (M_o - M_e)}{M - M_e} \right) \right]^{\frac{N-1}{N}} \quad (5.17)$$

In the equation, A , K , and N are linear functions of steam temperature and velocity (Eqs. 4.6 through 4.8); M_e is a function of steam temperature (Eq. 3.5), which was determined in Section 3.3.

Boundary and initial conditions

Boundary and initial conditions provide necessary known data for the numerical solution of a p.d.e. model. The boundary conditions for fixed-bed drying with superheated steam are

$$T_s(0, t) = T_{so}; \quad G_s(0, t) = G_{so} \quad (5.18)$$

At the beginning of steam drying, a small amount of steam is condensed on the product rapidly, which makes the temperature of the product to increase up to 100°C and causes a moisture increment ΔM_o in the product. The moisture increment may be roughly determined by the flowing energy balance equation:

$$\Delta M_o [c_s (T_{so} - 100) + h_v] = (c + c_w M_o) (100 - T_o) \quad (5.19)$$

Hence,

$$\Delta M_o = \frac{(c + c_w M_o) (100 - T_o)}{c_s (T_{so} - 100) + h_v} \quad (5.20)$$

Therefore, the actual initial conditions need to be modified as:

$$T(x, 0) = 100; \quad M(x, 0) = M_o + \frac{(c + c_w M_o) (100 - T_o)}{c_s (T_{so} - 100) + h_v} \quad (5.21)$$

The four equations 5.8, 5.14, 5.16, and 5.17 along with the boundary and initial conditions

(Eqs. 5.18 and 5.21) constitute the mathematical model for describing the drying of fixed beds of spent grains in superheated steam.

Based on the same assumptions as for fixed-bed drying, models for cross-flow, concurrent-flow, and counter-flow drying were formed by modifying the basic fixed-bed drying model developed above. The results were placed in Appendix C.1.

5.1.3 Simplification of the fixed-bed drying model

The solution of a p.d.e. model is usually a very complex task. To reduce the complexity in solving the fixed-bed drying model, some simplifying approximations need to be made.

The change in enthalpy of the drying medium (superheated steam in this case) within the elemental bed volume Sdt in time dt is very small and can be negligible (Bakker-Arkema et al. 1967; Spencer 1969), so the last term in Eq. 5.8 may be removed. The heat transfer coefficient h and the specific area a in Eqs. 5.8 and 5.14 are difficult to determine because the spent grain particles have no regular and fixed shapes and the two coefficients always change during the drying process. For eliminating the term $ha(T_s - T)$ in the model, the two equations 5.8 and 5.14 are combined into one as follows:

$$\frac{\partial T_s}{\partial x} = \frac{\rho [(h_v + c_s (T_s - T))]}{G_s c_s} \frac{\partial M}{\partial t} - \frac{\rho (c + c_w M)}{G_s c_s} \frac{\partial T}{\partial t} \quad (5.22)$$

To simplify the model further, the temperature of spent grains in the bed is assumed to increase linearly with the decrease of moisture content for $M < M_o$ and to be 100°C for

$M \geq M_o$. This is expressed as:

$$\begin{aligned}
 T &= 100 \\
 \frac{\partial T}{\partial t} &= 0 \quad \text{for } M \geq M_o \\
 T &= T_{so} - (T_{so} - 100) \frac{M - M_{eo}}{M_o - M_{eo}} \\
 \frac{\partial T}{\partial t} &= - \frac{T_{so} - 100}{M_o - M_{eo}} \frac{\partial M}{\partial t} \quad \text{for } M < M_o
 \end{aligned} \tag{5.23}$$

Equations 5.16, 5.17, 5.22 and 5.23 with the boundary and initial conditions (Eqs. 5.18 and 5.21) compose the simplified model for fixed-bed drying.

5.1.4 Division of three zones in the fixed bed

During steam drying, the fixed bed can be divided into three zones limited by two interfaces (Fig. 5.2). A dry front separates the dry and drying zones; a wet front partitions the drying and wet zones. In the dry zone, the spent grain has been dried to the equilibrium. The conditions of the superheated steam and product in this zone are kept unchanged. The moisture content of the product equals to the EMC and the temperature of the product is the same as that of the superheated steam. The dry zone appears after a period of drying. In the drying zone, the product is being dried. The moisture content of the product reduces and the temperature of the product increases with drying time. With increasing the distance x in the bed, the moisture content and the steam flow rate increase, and the temperatures of the product and steam decrease. The drying capacity of steam is exhausted after the steam passing through the drying zone. In the wet zone, the temperatures of the product and steam

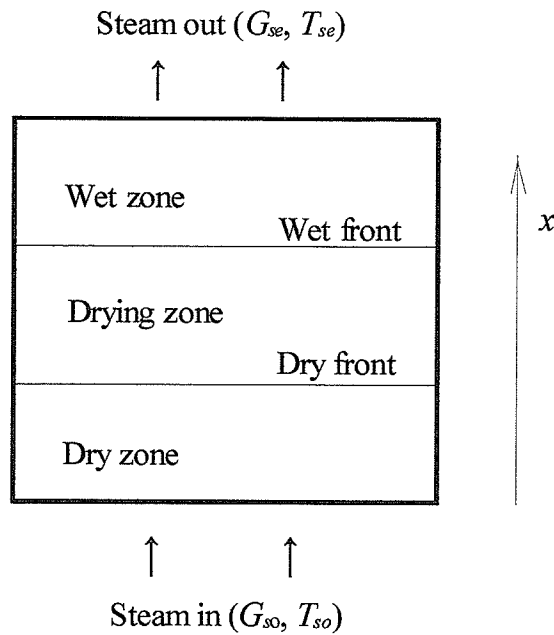


Figure 5.2 The division of three zones in the fixed bed.

are kept at 100°C. The moisture content of the product in this zone is at the initial moisture content composed of the original moisture and the condensed moisture at the beginning of drying. The appearance of the wet zone or wet front depends on the bed depth and the steam conditions at the inlet of the bed. The wet zone or wet front may not exist in the process of drying spent grains in a small-depth bed under certain drying conditions. The wet front, if it exists, and the dry front move up during the drying process.

The equations in the p.d.e. model developed in this chapter describe only the drying characteristics of the drying zone.

5.2 Numerical solution of the fixed-bed model for drying BSG in superheated steam

5.2.1 Finite difference equations for the fixed-bed drying model

For deep-bed steam drying, only the experiments of drying fixed beds of BSG are able to be conducted in the lab in the current stage. Therefore, the model of drying fixed beds of BSG with superheated steam was selected to be solved and validated by experiments.

The set of equations in the fixed-bed drying model can not be solved analytically due to the non-linear equations. The finite-difference technique, however, allows the solution of the model.

The finite-difference scheme is shown in Fig. 5.3. The bed was divided into a number (N_x)

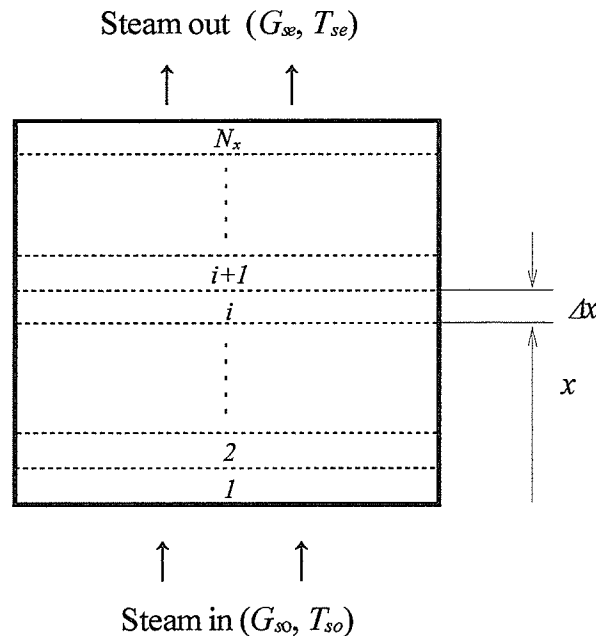


Figure 5.3 The finite-difference scheme in the fixed bed.

of thin layers having the thickness Δx . The position of a layer in the bed was designated by the layer number i . The total drying time was split up into a number (N_t) of time intervals Δt . Any time could be expressed as $t = j\Delta t$, which was denoted by the time increment number j .

For the i^{th} layer at the drying time $j\Delta t$, the equations 5.17, 5.23, 5.16, and 5.22 in the simplified fixed-bed drying model were written in finite-difference form as follows by using forward-difference formulae:

$$\frac{G_{s\ i+1,j} - G_{s\ i,j}}{\Delta x} = -\rho_{i,j} \frac{M_{i,j+1} - M_{i,j}}{\Delta t} \quad (5.24)$$

$$\frac{M_{i,j+1} - M_{i,j}}{\Delta t} = -\frac{K_{i,j} N_{i,j}}{60} (M_{i,j} - M_{e\ i,j}) \left[\frac{1}{K_{i,j}} \ln \left(\frac{A_{i,j} (M_o - M_{e\ i,j})}{M_{i,j} - M_{e\ i,j}} \right) \right]^{\frac{N_{i,j}-1}{N_{i,j}}} \quad (5.25)$$

$$\begin{aligned} \frac{T_{s\ i+1,j} - T_{s\ i,j}}{\Delta x} = & \frac{\rho_{i,j} [(h_{vi,j} + c_s (T_{s\ i,j} - T_{i,j}))]}{G_{s\ i,j} c_s} \frac{M_{i,j+1} - M_{i,j}}{\Delta t} \\ & - \frac{\rho_{i,j} (c + c_w M_{i,j})}{G_{s\ i,j} c_s} \frac{\partial T_{i,j}}{\partial t} \end{aligned} \quad (5.26)$$

$$T_{i,j} = 100$$

$$\frac{\partial T_{i,j}}{\partial t} = 0 \quad \text{for } M_{i,j} \geq M_o$$

$$T_{i,j} = T_{so} - (T_{so} - 100) \frac{M_{i,j} - M_{eo}}{M_o - M_{eo}} \quad (5.27)$$

$$\frac{\partial T_{i,j}}{\partial t} = -\frac{T_{so} - 100}{M_o - M_{eo}} \frac{M_{i,j+1} - M_{i,j}}{\Delta t} \quad \text{for } M_{i,j} < M_o$$

5.2.2 Determination of coefficients in the fixed-bed drying model

Prior to solving the fixed-bed drying model with numerical techniques, the values or expressions for the physical and thermodynamic properties of superheated steam and BSG must be obtained.

The density of superheated steam, ρ_s , decreases proximately linearly with increasing the steam temperature T_s . The relationship was expressed as (Hear et al. 1984):

$$\rho_s = 0.7401 - 0.001505 T_s \quad (5.28)$$

The specific heat of steam, c_s , changes a little in the range between 2042 and 1975 J/(kg · °C) when T_s changes between 100 and 200°C (Hear et al. 1984). A value of 2000 J/(kg · °C) was used in the calculation.

The specific heat of dry BSG, c , was estimated from the values of specific heat for other biological products (Pabis et al. 1998). A medium value of 1245 J/(kg · °C) was set for c .

The specific heat of moisture, c_w , changes a little with temperature. Two average values, 4193 and 4313 J/(kg · °C) were used for the BSG temperature ranges from 0 to 100°C and from 100 to 200°C, respectively (Incropera and DeWitt 1985).

During drying, the bulk density of BSG, ρ , changes with the moisture content of the product because of the volumetric shrinkage. For drying most of the biological products, ρ seems to increase approximately linearly with decreasing moisture content M until 0.11 kg/kg db and then remains relatively constant (Pabis et al. 1998). In the initial stage of steam

drying, M is great than the initial moisture content M_o due to the steam condensation on the product at the beginning of drying, and the moisture change is not supposed to cause volumetric shrinkage and ρ change. The relationship between ρ and M was written as:

$$\begin{aligned}\rho &= \rho_o \quad \text{for } M \geq M_o \\ \rho &= \rho_o - (\rho_o - \rho_e) \frac{M_o - M}{M_o - 0.11} \quad \text{for } 0.11 < M < M_o \\ \rho &= \rho_e \quad \text{for } M \leq 0.11\end{aligned} \quad (5.29)$$

where the initial bulk density ρ_o was calculated according to the initial conditions of BSG in the bed; the final bulk density of the BSG dried to the equilibrium, $\rho_e = \rho_o / 0.867$, was determined based on the reduction of the sample-bed depth in the drying experiments.

The similar expression to Eq.5.29 was used to calculate the distance increment Δx in the bed.

$$\begin{aligned}\Delta x &= \Delta x_o \quad \text{for } M \geq M_o \\ \Delta x &= \Delta x_o - (\Delta x_o - \Delta x_e) \frac{M_o - M}{M_o - 0.11} \quad \text{for } 0.11 < M < M_o \\ \Delta x &= \Delta x_e \quad \text{for } M \leq 0.11\end{aligned} \quad (5.30)$$

where $\Delta x_e = 0.867 \Delta x_o$.

The latent heat of evaporation, h_v , depends on the moisture content and temperature of the product. For most biological products, there is little difference between the latent heat of evaporation from the products and that of free water (h_v^*) for moisture contents above 0.2 kg/kg db. Below that level of moisture, this difference increases significantly. The

relationship was chosen as follows (Cenkowski et al. 1992):

$$\begin{aligned} h_v &= h_v^* \quad \text{for } M \geq 0.2 \\ h_v &= h_v^* [1 + \exp(-19.9 M)] \quad \text{for } M < 0.2 \end{aligned} \quad (5.31)$$

The latent heat of evaporation of free water changes with temperature (Zhao 1990):

$$h_v^* = 2257000 - 2916.7 (T-100) \quad (5.32)$$

5.2.3 Computer program for simulating the fixed-bed drying process

Based on the finite-difference equations (Eqs. 5.24 through 5.27), the initial and boundary conditions (Eqs. 5.18 and 5.21), and the known coefficients in the model, as well as considering the division of three possible zones in the fixed bed, a computer program was developed for the simulation of drying fixed beds of BSG with superheated steam. The structure of the program was shown in a flow chart (Fig. 5.4); the program was written in FORTRAN language (Appendix C.2).

The major function of the program was to iteratively calculate the changes in M , T , G_s , and T_s at any position in the bed at any drying time. In a time interval Δt , the changes of M and T in a layer were directly calculated with Eqs. 5.25 and 5.27 based on the known data for BSG in the layer and the steam passing through the layer. The changes in G_s and T_s were then determined by Eqs. 5.24 and 5.26. The exhaust steam from one layer was used as the input steam to the next layer. The calculations were conducted layer by layer in the time interval Δt . The procedure was repeated with a second, third,, and any time interval

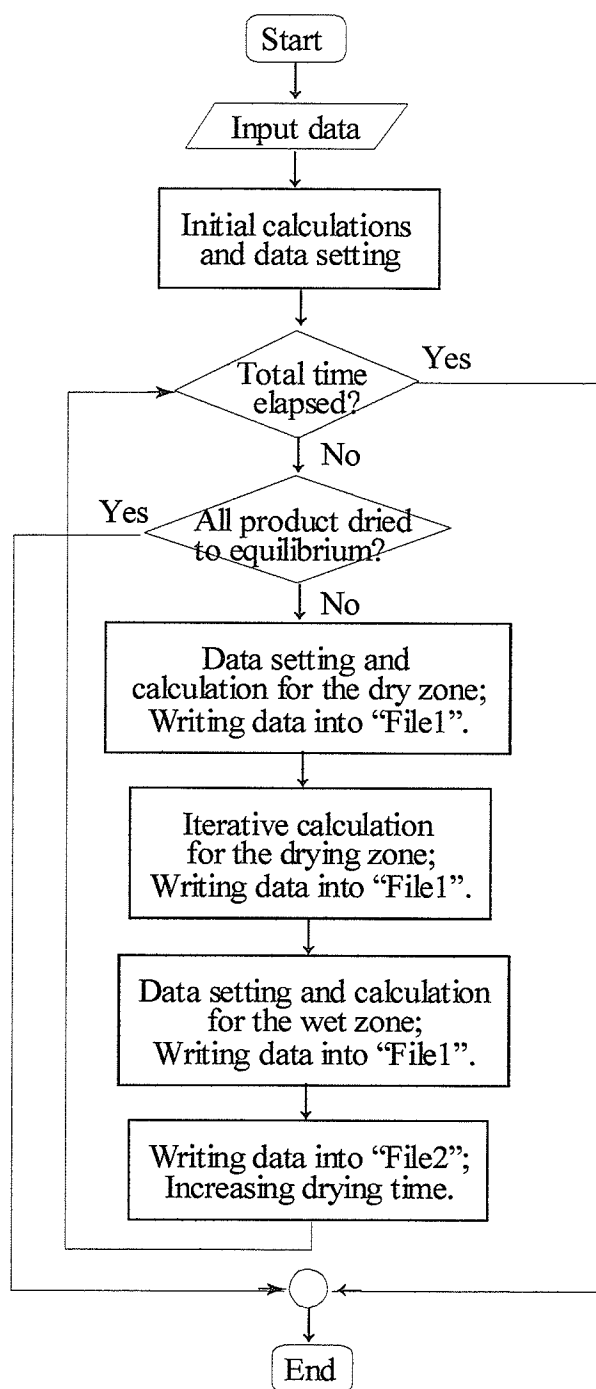


Figure 5.4 Flow chart for the computer program of simulating the drying of fixed-bed BSG in superheated steam.

until the time was up to the expected drying time or the BSG in the bed was dried to the equilibrium. When a layer was dried to the equilibrium, the layer was placed in the dry zone. When the calculated temperature of the steam passing through a layer decreased to or below 100°C, the steam had lost its drying capacity for the layer and the layer was placed in the wet zone. The following judge criterions were used for these two operations, respectively, in the program:

$$\left| M_{i,j+1} - M_{eo} \right| \leq 0.0001 \quad (5.33)$$

$$T_{s\ i+1,j} \leq 100 \quad (5.34)$$

The input data for running the program include: the mass of wet BSG in the bed, the initial moisture content of BSG, the depth of the bed, the number of distance increments in the bed, the steam flow rate and temperature at inlet, the expected drying time, and the time interval. The simulation results for a drying process can be written into two data files during the program running. "File1" records detailed calculation results including the changes of M , T , G_s , and T_s at any position in the bed at any drying time. "File2" records the changes in the average moisture content in the bed, the steam flow rate and temperature at the outlet of the bed, the positions of the dry and wet fronts, and the depth of the bed. Appendices C.3 and C.4 give an example for the two kinds of files, respectively.

5.3 Validation of the fixed-bed drying model with experimental results

5.3.1 Experiments on drying fixed beds of BSG with superheated steam

The material used in the experiments was BSG which was the same as that used in the EMC-determination and thin-layer drying experiments (Chapters 3 and 4). The initial moisture content of the tested product, determined by the vacuum-oven drying method (AACC 1995), was in a range between 3.53 and 4.11 kg/kg db (Table 5.1). Each sample, around 50 g, was

Table 5.1 Data for BSG samples tested under different drying conditions

Drying conditions		Mass of wet sample (g)	Initial moisture content (kg/kg db)	Mean residual square ^[a]	Mean deviation ^[a] (kg/kg db)
Steam temp (°C)	Steam flow rate (kg/(m ² .s))				
120.90	0.3123	50.05	3.68	0.0230	0.1517
140.87	0.3219	49.99	3.53	0.0136	0.1166
160.57	0.3186	50.02	3.66	0.0122	0.1103
140.78	0.1943	49.98	3.82	0.0234	0.1529
140.87	0.3219	49.99	3.53	0.0136	0.1166
140.71	0.4516	50.06	4.11	0.0170	0.1303

^[a] Mean residual square or mean deviation between the predicted and measured average moisture contents of the sample.

filled in the deep mesh tray to form a fixed bed of 30 mm deep. The same equipment, superheated steam drying system, as that used in the EMC-determination and thin-layer drying experiments, was used in the fixed-bed drying experiments. The drying conditions were set at three temperature levels for a medium flow rate of steam and at three levels of steam

flow rate for a medium temperature (Table 5.1). The experimental procedure and the method for determining the percentage (74.2%, Appendix C.5) of the steam passing through the sample were the same as those used for the thin-layer drying experiments (Sections 4.1.4 and 4.1.5).

5.3.2 Comparison of the predicted and experimental results

The predicted results (Appendix C.6) for the changes in the average moisture content of fixed-bed BSG samples in superheated steam under selected drying conditions listed in Table 5.1 were obtained by running the simulating program. To validate of the drying model, the comparisons of the calculated results with the experimental data (Appendix C.7) were made by plotting the curves for the changes in the average moisture content of the samples (Figs. 5.5 and 5.6). As can be seen, a reasonable agreement was obtained with the average moisture contents or drying times. The model gave a good prediction of the drying rates for $M \geq 1$ kg/kg db, but it overestimated the drying rates for $M < 1$ kg/kg db in the final stage of drying. However, the discrepancies between the predictions and experiments were small and acceptable. The small mean residual squares and mean deviations (Table 5.1) between the calculated and observed results also mean that the fixed-bed drying model described the fixed-bed drying process with an acceptable accuracy.

The small discrepancies between the calculated and observed values possibly resulted from errors in the thin-layer drying equation, the EMC equation, the values set for the parameters in the model, and the assumptions of the linear changes in the sample temperature and the layer thickness with moisture content.

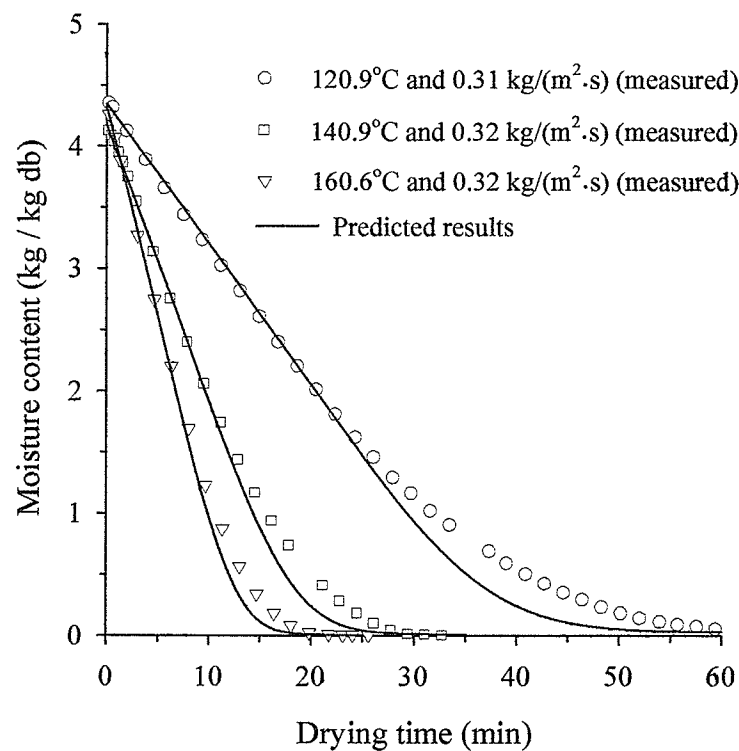


Figure 5.5 Comparison of predicted and measured average moisture contents of BSG samples (in a fixed bed of 30 mm deep initially) during drying with superheated steam at the flow rate around 0.32 kg/(m².s) and different temperatures.

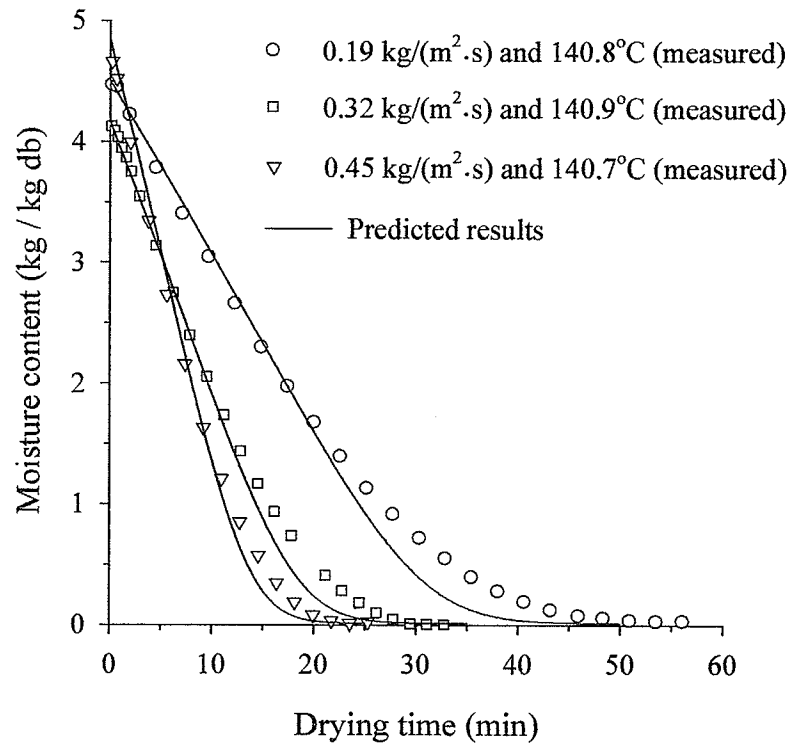


Figure 5.6 Comparison of predicted and measured average moisture contents of BSG samples (in a fixed bed of 30 mm deep initially) during drying with superheated steam at the temperature around 140°C and different flow rates.

5.3.3 Further discussion on simulation results

To study the moisture distribution inside the bed at any drying time is the most important issue for analysing drying processes, designing new drying equipment, and improving existed drying systems and their operations. In addition to the recording of the moisture distribution in the data file "File1" (Appendix C.3) generated during the computer simulation, the moisture distribution can also be roughly and visually described by plotting the wet- and dry-front history curves and the history curve for the changes of bed depth. The curves can be plotted based on the simulation results recorded in the data file "File2" (Appendix C.4). As an example, Fig. 5.7 shows the curves for the changes in the wet & dry fronts and the depth of the bed during a selected fixed-bed drying process. The wet and dry fronts moved up approximately linearly with the drying time. The depth of the bed decreased linearly from 30 to 26 mm in the first half drying process and remained unchanged in the second half drying process. Above the wet-front history curve is the wet region; between the wet- and dry-front history curves is the drying region; and below the dry-front history curve is the dry region. At any drying time, the product has the maximum moisture content in the wet region, the EMC in the dry region, and a moisture content changing with time and position in the drying region.

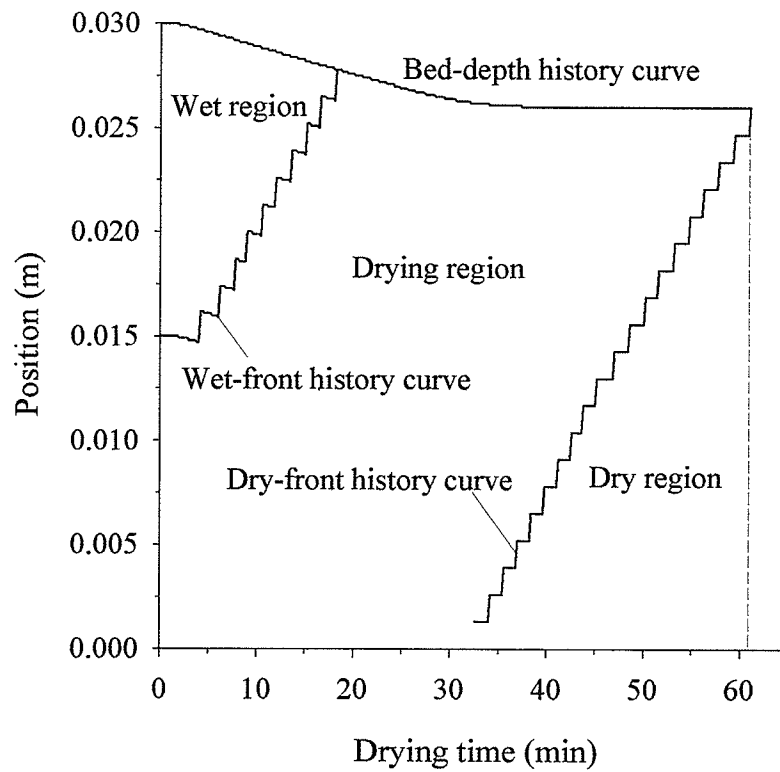


Figure 5.7 Changes of wet front, dry front, and bed depth in the process of drying the BSG sample of 30 mm deep with superheated steam at the temperature of 140.8°C and the flow rate of 0.19 kg/(m².s).

5.4 Conclusions on modelling of fixed-bed drying

During drying a deep bed of material with superheated steam, the change of steam flow rate with respect to x resulted from the evaporation of moisture from the material to be dried to the drying steam. Instead of air humidity as an important quantity in p.d.e. models for air drying, the mass flow rate of steam was considered one of the basic variables in p.d.e. models for superheated-steam drying.

A p.d.e. model for drying fixed beds of spent grains with superheated steam was developed based on the energy and mass balances using the similar manner to derivate equations for a fixed-bed model of air drying.

A finite-difference method was used to solve the simplified model for drying fixed beds of BSG with superheated steam. A computer simulation program was developed for accomplishing the numerical solution based on the finite-difference equations formed from the p.d.e. model, the initial and boundary conditions, and the division of three possible zones in the fixed bed.

The fixed-bed drying model was validated by comparing the calculated results with the experimental data. A reasonable agreement was obtained between the predicted and observed values of the average moisture content in BSG samples during the drying processes.

6 GENERAL CONCLUSIONS

The general conclusions for this thesis work were summarized as follows:

The relationships between the EMC and the temperature or relative pressure of steam were shown with the isobars described by two proposed equations. The coefficients in the equations were obtained by non-linear regressions with the SAS system based on the experimental data. The temperature or relative pressure of superheated steam had a significant effect on the EMC of spent grains exposed to superheated steam at atmospheric pressure. The EMC decreased substantially from 9.3 to 1.7 kg/100 kg dry solids for BSG (or from 6.7 to 1.4 kg/100 kg dry solids for DSG) with increasing the steam temperature from 105 to 140°C. It changed only slightly beyond 140°C and approached zero at 200°C.

Unlike hot-air drying, not only the temperature but also the velocity of steam had a significant effect on the steam drying of thin layers of spent grains. Increasing the temperature or velocity increased the drying rate near linearly and consequently decreased the drying time. An increase in steam temperature from 110 to 180°C decreased the drying time by 80% (or 85%) for drying of BSG (or DSG) at the steam velocity of 0.7 m/s. Increasing the steam velocity from 0.3 to 1.1 m/s at 145°C reduced the drying time by half for both spent grains. A model for describing the thin-layer steam drying process was developed through modifying a typical thin-layer model for air drying and conducting non-linear regression analyses with the experimental data.

A p.d.e. model for describing the drying of fixed beds of spent grains in superheated steam was developed using the similar manner to the derivation of equations for the fixed-bed

models of air drying. Instead of air humidity as an independent quantity in p.d.e. models for air drying, the mass flow rate of steam was used as one of the independent variables in the p.d.e. model for superheated-steam drying.

The simplified p.d.e. model for drying fixed beds of BSG in superheated steam was solved using a finite-difference method. A computer program for simulating the fixed-bed drying process was written in FORTRAN language. It was developed based on the finite-difference equations from the model, the known initial and boundary conditions, and the division of three possible zones in the fixed bed.

The comparisons of the predicted results with experimental data were made for validating the simplified fixed-bed drying model. There existed a good agreement between the calculated and observed average moisture contents of the fixed beds of BSG samples during the steam drying process especially for the moisture above 1 kg/kg db. There were small discrepancies between the calculated and measured data for the moisture below 1 kg/kg db.

Starch, β -glucan, pentosan, and protein are the major nutrient components in BSG and DSG. Increasing drying temperature and time caused a substantial decrease in starch content but a small or no change in β -glucan, pentosan and protein content in the dried samples. An increase in the drying temperature from 110 to 180°C caused the starch in the samples dried to the equilibrium at the steam velocity of 0.66 m/s to decrease by 14.5% for BSG and 11.5% for DSG. Increasing drying time from zero to the time when the equilibrium was reached at the steam velocity of 0.66 m/s made the starch decrease by 22% and 23% in BSG and DSG samples, respectively.

7 RECOMMENDATIONS FOR FUTURE WORK

To solve the p.d.e. drying model developed in Chapter 5 with numerical techniques more accurately, the exact values or expressions for the physical and thermodynamic properties of superheated steam and spent grains need to be obtained. The properties include: the specific heat and density of superheated steam, the heat-transfer coefficient between steam and the product to be dried, the latent heat of evaporation, as well as the porosity, specific surface area, bulk density, and specific heat of the material to be dried. The properties of superheated steam can be obtained from thermodynamic tables available in engineering handbooks. However, the heat transfer coefficients or their expressions and the properties of the spent grains need to be obtained by experimental procedures

For analysing the fixed-bed drying process, the moisture and temperature distributions inside the bed at any drying time is the most important information. It should be better to compare the predicted results with the experimental data for the moisture and temperature distributions for validating the drying model. In the current stage, the SSD system in the lab does not allow for detecting the moisture and temperature distributions. The drying system, especially the drying chamber and sample carrier of it, needs to be redesigned or modified for fulfilling the measurement of the moisture and temperature distributions.

Usually, a practical deep-bed dryer is a cross-flow, concurrent-flow, or counter-flow drying system. It is necessary to solve the models for the steam drying of spent grains in cross-flow, concurrent-flow, and counter-flow systems. The cross-flow and concurrent-

flow drying models may be solved by standard finite-difference methods similar to that used in the solution of the fixed-bed drying model (Bakker-Arkema et al. 1967; Brooker et al. 1974; Sharp 1982; Spencer 1969). The solution of the counter-flow drying model, which constitutes a two-point boundary system, is significantly different; it requires the application of optimization techniques (Pabis et al. 1998).

To validate the models for describing the practical drying processes, experiments on cross-flow, concurrent-flow, and counter-flow drying need to be conducted. The validation can be accomplished by comparing the predicted results with measured data or by calculating the relative standard deviations between the calculated and experimental values of selected quantities, such as moisture content in a selected layer, steam temperature in a selected position, average moisture content in the bed, and exhaust steam conditions.

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A - APPENDICES FOR CHAPTER 3

Appendix A.1

Table A.1 Experimental results for BSG in EMC determination

Temp ^[a] (°C)	Relative pressure ^[b]	Run 1			Run 2			Run 3			Mean EMC (kg/100 kg d.s.)
		Sample mass I ^[c] (g)	Sample mass II ^[d] (g)	EMC (kg/100 kg d.s. ^[e])	Sample mass I (g)	Sample mass II (g)	EMC (kg/100 kg d.s.)	Sample mass I (g)	Sample mass II (g)	EMC (kg/100 kg d.s.)	
105	0.84	2.9	2.64	9.85	2.95	2.73	8.06	2.79	2.54	9.84	9.25
110	0.71	2.74	2.62	4.58	2.71	2.58	5.04	3.03	2.84	6.69	5.44
115	0.6	2.71	2.62	3.44	3.16	3.04	3.95	2.83	2.73	3.66	3.68
120	0.51	2.63	2.56	2.73	2.98	2.9	2.76	3.16	3.07	2.93	2.81
125	0.44	2.72	2.65	2.64	3.02	2.94	2.72	2.92	2.84	2.82	2.73
130	0.38	3.01	2.94	2.38	2.75	2.69	2.23	2.7	2.64	2.27	2.29
140	0.28	3	2.93	2.39	2.48	2.45	1.22	2.68	2.64	1.52	1.71
150	0.21	2.68	2.66	0.75	2.62	2.6	0.77	2.63	2.61	0.77	0.76
160	0.16	2.5	2.48	0.81	2.32	2.32	0	2.43	2.4	1.25	0.68
170	0.13	2.82	2.79	1.08	2.54	2.54	0	2.64	2.63	0.38	0.49
180	0.1	2.76	2.74	0.73	2.51	2.51	0	2.6	2.59	0.39	0.37
190	0.08	2.01	2	0.5	2.55	2.55	0	2.54	2.53	0.4	0.3
200	0.07	2.51	2.5	0.4	2.52	2.52	0	2.49	2.5	0	0.13

[a] The temperature of steam drying the sample;

[b] Relative pressure is the ratio of the pressure of steam to the saturation pressure of the steam at the ambient temperature;

[c] The mass of the steam-dried sample;

[d] The mass of the vacuum-oven-dried sample;

[e] d.s. = dry solids.

Appendix A.2

Table A.2 Experimental results for DSG in EMC determination

Temp (°C)	Relative pressure	Run 1			Run 2			Run 3			Mean EMC (kg/100 kg d.s.)
		Sample mass I (g)	Sample mass II (g)	EMC (kg/100 kg d.s.)	Sample mass I (g)	Sample mass II (g)	EMC (kg/100 kg d.s.)	Sample mass I (g)	Sample mass II (g)	EMC (kg/100 kg d.s.)	
105	0.84	1.55	1.46	6.16	1.76	1.64	7.32	1.74	1.63	6.75	6.74
110	0.71	1.55	1.49	4.03	1.65	1.575	4.76	1.635	1.57	4.14	4.31
115	0.6	1.52	1.47	3.4	1.65	1.6	3.13	1.62	1.57	3.18	3.24
120	0.51	1.58	1.53	3.27	1.62	1.58	2.53	1.515	1.475	2.71	2.84
125	0.44	1.43	1.39	2.88	1.61	1.58	1.9	1.61	1.58	1.9	2.23
130	0.38	1.45	1.42	2.11	1.58	1.555	1.61	1.52	1.49	2.01	1.91
140	0.28	1.47	1.45	1.38	1.53	1.51	1.32	1.56	1.535	1.63	1.44
150	0.21	1.48	1.47	0.68	1.56	1.545	0.97	1.52	1.505	0.99	0.88
160	0.16	1.44	1.43	0.7	1.6	1.59	0.63	1.51	1.505	0.33	0.55
170	0.13	1.37	1.365	0.37	1.525	1.52	0.33	1.46	1.45	0.69	0.46
180	0.1	1.475	1.47	0.34	1.49	1.49	0	1.45	1.45	0	0.11
200	0.07	1.39	1.39	0	1.48	1.48	0	1.35	1.35	0	0

Appendix A.3 Example of regression-analysis program for Eq. 3.5 for BSG

```

OPTIONS LINESIZE=78;      190 0.00
DATA BSG;                 190 0.40
INPUT T EMC;              200 0.40
T1=T-100;                 200 0.00
CARDS;                    200 0.00
105 9.85                   ;
105 8.06
105 9.84                   PROC PRINT DATA=BSG;
110 4.58                   VAR T T1 EMC;
110 5.04
110 6.69                   TITLE '##### Regression for: EMC= k*EXP(n*T1**m) #####';
115 3.44                   PROC NLIN BEST=5 DATA=BSG;
115 3.95                   PARMS k=5 to 15 by 1 n=-0.1 to -1 by -0.1 m=0 to 1 by 0.1;
115 3.66                   MODEL EMC=k*EXP(n*T1**m);
120 2.73                   OUTPUT OUT=BSG1 P=P1 R=R1;
120 2.76
120 2.93                   PROC PRINT DATA=BSG1;
125 2.64                   VAR T EMC P1;
125 2.72
125 2.82                   PROC PLOT DATA=BSG1;
130 2.38                   PLOT EMC*T='M' P1*T='P'/overlay;
130 2.23                   PLOT R1*T/VREF=0;
130 2.27
140 2.39
140 1.22
140 1.52
150 0.75
150 0.77
150 0.77
160 0.81
160 0.00
160 1.25
170 1.08
170 0.00
170 0.38
180 0.73
180 0.00
180 0.39
190 0.50

```

Appendix A.4 Example of regression-analysis program for Eq. 3.13 for DSG

```

OPTIONS LINESIZE=78;      0.07 0.00
DATA DSG;                 0.07 0.00
INPUT pr EMC;             ;
CARDS;                    PROC PRINT DATA=DSG;
0.84 6.16                 VAR pr EMC;
0.84 7.32
0.84 6.75                 TITLE '#### Regression for: EMC= k*EXP(n*pr**m) ####';
0.71 4.03                 PROC NLIN BEST=5 DATA=DSG;
0.71 4.76                 PARMS k=5 to 15 by 1 n=0.1 to 1 by 0.1 m=0 to 1 by 0.1;
0.71 4.14                 MODEL EMC=k*EXP(n*Pr**m);
0.60 3.40                 OUTPUT OUT=DSG1 P=P1 R=R1;
0.60 3.13
0.60 3.18                 PROC PRINT DATA=DSG1;
0.51 3.27                 VAR pr EMC P1;
0.51 2.53
0.51 2.71                 PROC PLOT DATA=DSG1;
0.44 2.88                 PLOT EMC*pr='M' P1*pr='P'/overlay;
0.44 1.90                 PLOT R1*pr/VREF=0;
0.44 1.90
0.38 2.11
0.38 1.61
0.38 2.01
0.28 1.38
0.28 1.32
0.28 1.63
0.21 0.68
0.21 0.97
0.21 0.99
0.16 0.70
0.16 0.63
0.16 0.33
0.13 0.37
0.13 0.33
0.13 0.69
0.10 0.34
0.10 0.00
0.10 0.00
0.07 0.00

```

B - APPENDICES FOR CHAPTER 4

Appendix B.1

Table B.1 Experimental data for determining the percentage of drying medium passing through the BSG sample

No. ^[a]	Run 1							Run 2						
	$v_1^{[b]}$			$v_2^{[c]}$			$v_1 / v_2 (\%)$	v_1			v_2			$v_1 / v_2 (\%)$
1	0.85	1.09	1.5	1.15	1.06	1.8	85.79	1.3	0.85	0.75	1.4	1.1	0.9	85.29
2	1.1	1	1.1	1.3	1.08	1.12	91.43	0.75	0.85	1.35	0.87	1.35	1.5	79.3
3	1.25	1.02	1.1	1.45	1.15	1.5	82.2	0.72	1.45	1.3	0.9	1.4	1.5	91.32
4	1	0.9	1	1.35	1	1.2	81.69	0.78	0.95	1.5	0.82	1.4	1.5	86.83
5	1.1	1	1	1.35	1.08	1.25	84.24	0.75	1.05	1.3	0.88	1.15	1.35	91.72
6	1.1	1.05	1.1	1.3	1.08	1.3	88.32	0.65	0.95	1.4	0.75	1.25	1.65	82.19
7	1.25	1.05	0.95	1.4	1.2	1.3	83.33							
Average							85.29							86.11

(Continued)

No.	Run 3							Run 4						
	v_1			v_2			$v_1 / v_2 (\%)$	v_1			v_2			$v_1 / v_2 (\%)$
1	0.38	0.52	0.65	0.35	0.68	0.85	82.45	0.39	0.27	0.38	0.45	0.35	0.42	85.25
2	0.3	0.65	0.75	0.47	0.75	0.8	84.16	0.39	0.29	0.32	0.45	0.38	0.41	80.65
3	0.5	0.72	0.72	0.62	0.72	0.85	88.58	0.38	0.32	0.37	0.42	0.42	0.38	87.71
4	0.45	0.57	0.65	0.47	0.72	0.85	81.86	0.29	0.32	0.35	0.48	0.38	0.42	75
5	0.45	0.57	0.68	0.52	0.78	0.72	84.16	0.29	0.31	0.32	0.32	0.34	0.37	89.32
6	0.55	0.75	0.55	0.5	0.88	0.75	86.85	0.35	0.37	0.37	0.42	0.4	0.42	87.9
7	0.43	0.62	0.62	0.51	0.69	0.65	90.27	0.4	0.32	0.36	0.42	0.42	0.49	81.2
Average							85.47							83.86
Total average percentage	85.18%													

^[a] No. - The number of the measurement during the test.

^[b] v_1 - Air velocity at three selected points above the sample tray hung from the balance.

^[c] v_2 - Air velocity at the three selected points above the sample tray seated on the plate.

Appendix B.2

Table B.2 Experimental data for determining the percentage of drying medium passing through the DSG sample

No. ^[a]	Run 1					Run 2				
	$v_1^{[b]}$		$v_2^{[c]}$		v_1 / v_2 (%)	v_1		v_2		v_1 / v_2 (%)
1	1.02	1.14	1.25	1.28	85.38	0.8	0.64	0.88	0.76	87.8
2	1.05	1.15	1.21	1.24	89.8	0.65	0.62	0.72	0.7	89.44
3	1.05	1.13	1.25	1.25	87.2	0.84	0.7	0.96	0.78	88.51
4	1.05	1.13	1.16	1.28	89.34	0.81	0.68	0.89	0.79	88.69
Average	87.93					88.61				

(Continued)

No.	Run 3					Run 4				
	v_1		v_2		v_1 / v_2 (%)	v_1		v_2		v_1 / v_2 (%)
1	0.5	0.55	0.54	0.7	84.68	0.54	0.49	0.65	0.6	82.4
2	0.48	0.63	0.63	0.76	79.86	0.53	0.51	0.65	0.59	83.87
3	0.5	0.65	0.6	0.73	86.47	0.52	0.49	0.64	0.59	82.11
4	0.54	0.67	0.65	0.75	86.43	0.55	0.51	0.64	0.6	85.48
Average					84.36	83.47				
Total average percentage		86.09%								

^[a] No. - The number of the measurement during the test.

^[b] v_1 - Air velocity at two selected points above the sample tray hung from the balance.

^[c] v_2 - Air velocity at the two selected points above the sample tray seated on the plate.

Appendix B.3

Table B.3 Changes of moisture ratio in BSG drying

MR ^[a] (110.8°C, 0.24 m/s) ^[c]	t (min) ^[b]	MR	t (min)	MR	t (min)	MR	t (min)	MR	t (min)	MR	t (min)	MR	t (min)
		(115.9°C, 0.24 m/s)		(120.9°C, 0.24 m/s)		(130.7°C, 0.24 m/s)		(145.5°C, 0.25 m/s)		(160.3°C, 0.26 m/s)		(180.2°C, 0.27 m/s)	
1.2779	0.05	1.2375	0.05	1.2249	0.05	1.2132	0.05	1.2121	0.05	1.1746	0.05	1.1658	0.05
1.1856	0.25	1.1724	0.20	1.1686	0.10	1.1476	0.30	1.1624	0.25	1.1456	0.25	1.1417	0.30
1.1670	0.55	1.1509	0.55	1.1638	0.25	1.1235	0.50	1.1340	0.55	1.1071	0.45	1.0752	0.50
1.1293	1.10	1.1371	1.00	1.1559	0.40	1.0795	0.85	1.0971	0.80	1.0374	0.80	0.9949	0.80
1.0911	2.50	1.1153	1.20	1.1261	0.70	0.9790	1.90	1.0311	1.25	0.9433	1.25	0.9168	1.25
1.0601	3.50	1.0582	2.00	1.0991	1.25	0.8793	2.95	0.9721	1.60	0.8238	2.05	0.8104	1.70
0.9383	5.80	0.9874	3.65	1.0512	1.75	0.7040	5.25	0.8595	2.40	0.6879	2.95	0.7258	2.20
0.8452	8.85	0.8873	5.10	1.0235	1.95	0.5724	6.70	0.7569	3.40	0.5471	4.20	0.5625	3.10
0.7337	11.95	0.7929	7.45	0.9507	3.20	0.4668	8.65	0.6061	4.85	0.4338	5.25	0.4180	4.00
0.6727	13.50	0.6668	10.20	0.8900	3.75	0.3462	10.80	0.4774	6.20	0.3270	6.35	0.2946	4.80
0.6032	16.25	0.5162	14.00	0.7780	6.05	0.2593	12.60	0.3556	7.95	0.2191	7.70	0.1948	5.85
0.5212	19.45	0.4181	18.15	0.6791	7.80	0.1867	14.60	0.2493	9.50	0.1036	9.40	0.1196	6.80
0.4547	21.45	0.3104	20.80	0.5874	9.65	0.1269	16.25	0.1729	11.05	0.0614	10.60	0.0648	7.75
0.3888	25.70	0.2377	23.85	0.5038	11.85	0.0816	18.15	0.1085	12.40	0.0305	12.05	0.0334	8.70
0.3334	27.50	0.1824	26.90	0.4278	13.95	0.0480	20.00	0.0533	14.70	0.0177	12.90	0.0139	9.30
0.2822	29.85	0.1286	30.35	0.3509	15.80	0.0275	22.45	0.0239	16.55	0.0109	13.90	0.0059	10.55
0.2321	32.75	0.0945	33.10	0.2933	17.55	0.0144	24.10	0.0220	18.10	0.0038	15.00	-0.0008	11.50
0.1906	35.70	0.0607	36.30	0.2371	19.65	0.0074	25.55	0.0176	19.85	-0.0070	16.00	-0.0015	12.50
0.1498	38.90	0.0424	39.65	0.1885	21.60	0.0063	26.85	0.0086	21.55	-0.0049	16.95	0.0006	13.50
0.1252	40.55	0.0261	42.25	0.1459	23.95	0.0033	27.85	0.0087	23.30				
0.0879	43.85	0.0158	44.80	0.1108	25.65								
0.0699	46.55	0.0107	47.30	0.0819	27.65								
0.0517	48.55			0.0607	29.75								
0.0404	51.50			0.0455	31.75								
0.0314	54.45			0.0317	33.00								
0.0195	56.90			0.0262	34.55								
0.0155	59.40			0.0198	36.35								
0.0124	61.95			0.0182	38.05								
0.0014	64.45			0.0159	39.70								
0.0056	66.95												

^[a] MR - Moisture ratio.

^[b] t - Drying time.

^[c] Drying conditions: average steam temperature and velocity.

Table B.3 Changes of moisture ratio in BSG drying (continued)

MR (110.7°C, 0.44 m/s)	t (min)	MR (115.9°C, 0.45 m/s)	t (min)	MR (120.9°C, 0.45 m/s)	t (min)	MR (130.8°C, 0.47 m/s)	t (min)	MR (145.6°C, 0.47 m/s)	t (min)	MR (160.5°C, 0.50 m/s)	t (min)	MR (179.9°C, 0.52 m/s)	t (min)
1.2820	0.10	1.2818	0.05	1.2483	0.05	1.2034	0.05	1.1815	0.05	1.1938	0.05	1.1588	0.05
1.1761	0.30	1.1829	0.25	1.1764	0.10	1.1502	0.15	1.1242	0.15	1.1198	0.30	1.0673	0.30
1.1718	0.60	1.1530	0.55	1.1663	0.25	1.1248	0.30	1.0734	0.50	1.0542	0.45	0.9904	0.50
1.1226	1.10	1.1211	1.05	1.1302	0.50	1.0635	0.65	0.9848	0.90	0.9439	0.80	0.8499	0.90
1.0806	1.65	1.0843	1.50	1.1203	0.55	0.9957	1.00	0.9043	1.25	0.8497	1.30	0.7738	1.30
1.0353	2.60	0.9980	2.45	1.0715	0.95	0.8591	1.50	0.7813	1.80	0.6444	2.15	0.6195	1.85
0.9795	3.55	0.9192	3.40	0.9735	2.05	0.7314	2.45	0.6530	2.85	0.4693	3.10	0.4779	2.45
0.8813	5.45	0.7689	5.25	0.8645	2.90	0.6089	3.80	0.4953	3.75	0.3259	3.85	0.3305	3.15
0.7609	7.35	0.6430	7.15	0.7115	4.45	0.4617	5.25	0.3800	4.65	0.2133	4.70	0.2171	3.90
0.6278	10.20	0.4819	9.95	0.5676	6.20	0.3069	7.10	0.2413	5.95	0.1358	5.60	0.1142	4.75
0.5103	13.05	0.3409	12.75	0.4395	8.30	0.2174	8.55	0.1401	7.45	0.0833	6.20	0.0499	5.75
0.4103	15.90	0.2404	15.60	0.3251	10.30	0.1486	9.75	0.0772	8.65	0.0504	7.10	0.0187	6.85
0.3164	18.75	0.1529	18.40	0.2344	12.20	0.0977	11.65	0.0401	10.05	0.0333	7.40	0.0074	7.80
0.2437	21.60	0.0991	21.25	0.1604	14.25	0.0617	12.75	0.0203	11.30	0.0172	8.10	0.0042	8.75
0.1690	25.50	0.0545	24.05	0.1025	16.65	0.0379	13.80	0.0088	12.45	0.0131	9.00	0.0044	9.65
0.1233	27.35	0.0315	26.85	0.0651	17.55	0.0177	15.40	-0.0015	13.80	0.0021	9.75	0.0001	10.65
0.0768	30.20	0.0150	29.70	0.0357	20.40	0.0085	17.10	-0.0003	15.35	0.0086	10.85		
0.0511	33.05	0.0107	32.50	0.0245	20.80	0.0076	18.95			-0.0002	11.60		
0.0353	35.90	0.0047	34.00	0.0125	22.40	0.0007	20.65			0.0011	12.90		
0.0186	38.80			0.0033	24.50								
0.0078	41.60			0.0000	26.50								
0.0010	44.90			0.0020	28.05								
				-0.0001	29.35								

Table B.3 Changes of moisture ratio in BSG drying (continued)

MR (110.8°C, 0.63 m/s)	t (min)	MR (115.8°C, 0.63 m/s)	t (min)	MR (120.8°C, 0.64 m/s)	t (min)	MR (130.8°C, 0.65 m/s)	t (min)	MR (145.6°C, 0.65 m/s)	t (min)	MR (160.5°C, 0.69 m/s)	t (min)	MR (180.3°C, 0.71 m/s)	t (min)
1.2265	0.05	1.2206	0.05	1.2135	0.05	1.1867	0.05	1.1762	0.05	1.1015	0.05	1.0814	0.05
1.1048	0.20	1.1150	0.10	1.1036	0.10	1.0383	0.15	1.0272	0.55	1.0164	0.15	1.0231	0.15
1.0828	0.45	1.0757	0.15	1.0749	0.30	0.9809	0.35	0.8987	1.05	0.9529	0.35	0.9177	0.40
1.0431	0.80	1.0344	0.40	0.9012	1.35	0.8316	1.30	0.8224	1.40	0.8950	0.55	0.8314	0.60
1.0183	1.35	0.9877	0.95	0.8224	2.00	0.7157	1.75	0.6140	2.25	0.7816	0.90	0.7008	0.95
0.9679	1.90	0.9085	1.55	0.7583	2.65	0.6319	2.40	0.4960	3.15	0.6747	1.25	0.5704	1.35
0.9162	2.35	0.8428	2.00	0.6684	3.20	0.5400	3.20	0.3857	3.55	0.5762	1.70	0.4422	1.75
0.7608	4.40	0.7780	2.90	0.5692	4.15	0.4682	3.80	0.2944	4.10	0.4752	2.15	0.3486	2.15
0.7126	5.65	0.7233	3.40	0.5215	4.60	0.3695	4.75	0.1868	5.10	0.3583	2.65	0.2313	2.70
0.6327	7.05	0.6463	4.10	0.4504	5.90	0.2853	5.85	0.1198	5.95	0.2576	3.20	0.1384	3.20
0.5099	8.55	0.5826	5.25	0.3906	6.45	0.2126	6.65	0.0631	6.90	0.1746	3.70	0.0725	3.80
0.4547	9.65	0.5031	6.10	0.3384	7.40	0.1520	7.50	0.0343	7.95	0.1168	4.40	0.0360	4.45
0.3996	12.10	0.4304	7.15	0.2709	7.95	0.1104	8.45	0.0119	8.95	0.0925	4.65	0.0141	4.90
0.3464	13.20	0.3592	8.45	0.2168	9.05	0.0755	8.85	0.0088	9.80	0.0496	5.20	0.0030	5.40
0.2963	13.95	0.2886	10.10	0.1655	9.75	0.0464	9.85	-0.0047	10.70	0.0294	6.00	-0.0079	6.00
0.2392	16.75	0.2304	11.30	0.1234	11.05	0.0360	10.75	0.0001	11.25	0.0101	6.45	-0.0073	6.55
0.1930	18.15	0.1755	12.95	0.0910	12.30	0.0267	11.70			0.0006	7.45	-0.0078	7.40
0.1509	20.10	0.1301	14.65	0.0649	12.80	0.0050	12.30			-0.0019	8.10		
0.1105	21.80	0.0980	16.20	0.0410	13.95	-0.0005	13.25						
0.0824	22.70	0.0732	17.40	0.0278	15.55	-0.0002	14.15						
0.0736	25.25	0.0448	19.70	0.0188	16.00	0.0002	14.80						
0.0643	26.55	0.0302	21.30	0.0208	16.85	-0.0003	15.95						
0.0318	28.75	0.0230	22.55	0.0009	17.65								
0.0354	29.70	0.0099	23.50	0.0028	18.55								
0.0153	30.45	0.0105	24.35	-0.0011	19.35								
0.0166	31.75	0.0104	25.45	-0.0024	20.40								
0.0009	33.50	0.0123	26.50	0.0053	21.25								
0.0106	35.60			-0.0110	22.25								
				-0.0015	23.05								

Table B.3 Changes of moisture ratio in BSG drying (continued)

MR (110.8°C, 0.81 m/s)	t (min)	MR (115.8°C, 0.83 m/s)	t (min)	MR (120.8°C, 0.83 m/s)	t (min)	MR (130.4°C, 0.85 m/s)	t (min)	MR (145.5°C, 0.89 m/s)	t (min)	MR (160.6°C, 0.91 m/s)	t (min)	MR (180.4°C, 0.93 m/s)	t (min)
1.1905	0.03	1.2062	0.03	1.2129	0.03	1.1722	0.03	1.1474	0.03	1.1435	0.03	1.1470	0.03
1.1565	0.31	1.1147	0.22	1.1252	0.24	1.0915	0.23	1.0587	0.26	1.0619	0.23	1.0915	0.07
1.1034	0.64	1.1026	0.56	1.0834	0.55	1.0384	0.52	0.9782	0.55	0.9656	0.53	1.0263	0.23
1.0724	1.28	1.0123	1.23	1.0314	0.94	0.9372	0.96	0.8440	0.95	0.7891	1.00	0.9156	0.50
1.0093	1.90	0.8878	2.13	0.9273	1.58	0.8823	1.25	0.7269	1.39	0.5958	1.63	0.6998	1.00
0.9341	2.69	0.7891	3.08	0.7510	2.58	0.7823	1.71	0.5208	2.11	0.4311	2.20	0.5363	1.40
0.8190	4.04	0.6431	4.47	0.6143	3.55	0.6619	2.29	0.3564	2.83	0.2983	2.80	0.3867	1.87
0.7118	5.66	0.5206	5.92	0.4930	4.67	0.5113	3.04	0.2295	3.55	0.1952	3.37	0.2614	2.30
0.5926	7.34	0.4282	7.25	0.3730	5.82	0.4140	3.71	0.1377	4.24	0.0890	4.20	0.1583	2.83
0.4764	9.54	0.3358	8.64	0.2966	6.38	0.2698	4.78	0.0677	5.11	0.0309	5.20	0.1001	3.20
0.3704	11.41	0.2572	10.03	0.2332	7.33	0.1761	5.76	0.0320	5.98	0.0124	5.80	0.0523	3.67
0.3004	13.24	0.1908	11.72	0.1791	8.28	0.1082	6.75	0.0209	6.73	0.0062	6.63	0.0211	4.23
0.2217	15.08	0.1376	13.17	0.1320	9.23	0.0694	7.62	0.0108	7.57	0.0032	7.50	0.0109	4.50
0.1667	16.88	0.0982	14.65	0.0957	10.21	0.0426	8.49	0.0080	8.43			0.0022	5.00
0.1183	18.71	0.0701	16.04	0.0690	11.19	0.0259	9.36	0.0087	9.50			-0.0005	5.40
0.0819	20.58	0.0429	17.43	0.0512	12.08	0.0142	10.22					-0.0011	5.77
0.0582	22.41	0.0315	18.79	0.0387	13.03	0.0081	11.09					-0.0008	6.40
0.0363	24.22	0.0215	20.21	0.0259	13.98	0.0057	11.96						
0.0270	26.08	0.0152	21.59	0.0167	14.93								
0.0149	27.89			0.0131	15.91								
				0.0098	17.08								

Table B.3 Changes of moisture ratio in BSG drying (continued)

MR (110.8°C, 1.02 m/s)	t (min)	MR (115.8°C, 1.02 m/s)	t (min)	MR (120.0°C, 1.04 m/s)	t (min)	MR (130.9°C, 1.08 m/s)	t (min)	MR (145.9°C, 1.09 m/s)	t (min)	MR (160.7°C, 1.13 m/s)	t (min)	MR (180.3°C, 1.17 m/s)	t (min)
1.0818	0.03	1.0806	0.03	1.0347	0.03	1.0959	0.03	1.0887	0.03	1.1002	0.05	1.0224	0.05
1.0797	0.24	1.0859	0.28	1.0539	0.30	1.0262	0.23	1.0233	0.23	1.0074	0.20	0.9987	0.20
1.0209	0.58	1.0045	0.59	0.9984	0.61	0.9570	0.52	0.9311	0.52	0.9567	0.30	0.8394	0.45
0.9220	1.04	0.8809	1.05	0.9492	0.94	0.8375	0.93	0.8144	0.90	0.9002	0.40	0.7970	0.60
0.9149	1.50	0.8525	1.51	0.8759	1.36	0.7712	1.25	0.7183	1.24	0.8337	0.60	0.6885	0.70
0.8580	1.93	0.7656	2.04	0.7996	1.82	0.6629	1.65	0.5929	1.70	0.7672	0.70	0.6400	0.80
0.7795	2.57	0.6719	2.65	0.6914	2.42	0.5149	2.23	0.4885	2.11	0.7146	0.80	0.6045	0.90
0.7064	3.21	0.5860	3.27	0.5998	3.03	0.3916	2.84	0.3856	2.54	0.6617	0.95	0.5548	1.05
0.6352	3.94	0.4867	4.04	0.4828	3.82	0.2750	3.53	0.3084	2.97	0.5942	1.10	0.4668	1.20
0.5685	4.71	0.4009	4.84	0.3932	4.55	0.1895	4.26	0.2042	3.58	0.5267	1.30	0.3542	1.65
0.4790	5.63	0.3090	5.74	0.2909	5.46	0.1050	5.16	0.1336	4.16	0.4632	1.45	0.2489	1.85
0.3986	6.54	0.2327	6.66	0.2111	6.36	0.0603	6.00	0.0836	4.74	0.3999	1.60	0.1496	2.20
0.3356	7.24	0.1738	7.59	0.1484	7.27	0.0335	6.86	0.0412	5.46	0.2982	2.00	0.0510	2.70
0.2300	8.44	0.1220	8.51	0.1023	8.18	0.0189	7.73	0.0173	6.24	0.1720	2.60	0.0233	3.10
0.1467	9.85	0.0854	9.44	0.0702	9.09	0.0147	8.63	0.0090	6.90	0.0868	3.30	0.0035	3.45
0.0961	11.24	0.0599	10.37	0.0451	10.00	0.0139	9.47	0.0048	7.48	0.0523	3.80	-0.0032	3.85
0.0662	12.62	0.0403	11.29	0.0304	10.91	0.0106	10.34	0.0014	8.06	0.0118	4.90	-0.0146	4.85
0.0443	14.01	0.0273	12.22	0.0213	11.85					0.0002	6.10	-0.0138	5.85
0.0255	15.39	0.0204	13.14	0.0148	12.73					-0.0031	6.70		
0.0160	16.75	0.0155	14.07										
0.0124	18.16												
0.0056	19.55												

Appendix B.4

Table B.4 Changes of moisture ratio in DSG drying

MR (110.8°C, 0.25 m/s)	t (min)	MR (116.1°C, 0.26 m/s)	t (min)	MR (121.1°C, 0.26 m/s)	t (min)	MR (130.9°C, 0.28 m/s)	t (min)	MR (145.8°C, 0.28 m/s)	t (min)	MR (160.6°C, 0.29 m/s)	t (min)	MR (180.2°C, 0.31 m/s)	t (min)
1.3149	0.03	1.2897	0.06	1.2987	0.03	1.2702	0.03	1.2632	0.03	1.2572	0.03	1.2425	0.03
1.2858	0.25	1.2687	0.24	1.2645	0.23	1.2307	0.24	1.2314	0.24	1.1923	0.29	1.1883	0.21
1.2722	0.52	1.2556	0.54	1.2070	0.93	1.1853	0.55	1.1470	0.59	1.1372	0.54	1.1043	0.48
1.2201	0.95	1.2405	0.90	1.1213	1.51	1.0908	1.03	1.0396	1.04	1.0735	0.83	0.9667	0.93
1.1617	1.48	1.0356	2.70	0.9538	2.82	1.0208	1.49	0.9449	1.48	0.9883	1.23	0.8395	1.36
1.1384	2.52	0.8709	4.59	0.7944	4.12	0.7880	2.80	0.7285	2.43	0.8871	1.69	0.6259	2.16
1.0314	4.40	0.7491	6.30	0.7169	4.99	0.6642	3.74	0.5567	3.32	0.6865	2.51	0.5380	2.53
0.9086	6.18	0.6368	8.10	0.6304	5.92	0.5614	4.69	0.4153	4.24	0.5076	3.37	0.4441	2.93
0.7983	8.03	0.5270	9.90	0.5533	6.74	0.4056	6.30	0.3123	5.10	0.3609	4.23	0.3638	3.36
0.7168	9.91	0.4351	11.73	0.4814	7.61	0.3245	7.27	0.2333	5.99	0.2500	5.09	0.3040	3.73
0.6162	11.75	0.3617	13.53	0.4232	8.48	0.2777	8.16	0.1734	6.87	0.1637	5.97	0.2380	4.13
0.5334	13.57	0.2772	15.48	0.3708	9.35	0.1846	9.92	0.1234	7.76	0.1038	6.83	0.1844	4.53
0.4675	15.42	0.2258	17.13	0.3259	10.22	0.1439	11.08	0.0922	8.68	0.0739	7.69	0.1425	4.96
0.3654	18.65	0.1922	19.05	0.2821	11.12	0.1033	12.20	0.0695	9.54	0.0528	8.54	0.0959	5.39
0.3100	20.49	0.1137	23.40	0.2488	11.96	0.0794	13.60	0.0532	10.43	0.0388	9.37	0.0553	6.16
0.2646	22.34	0.1030	25.23	0.1836	13.70	0.0624	14.49	0.0408	11.32	0.0294	10.26	0.0403	6.61
0.2168	24.34	0.0804	27.06	0.1431	15.45	0.0552	15.40	0.0289	13.19	0.0235	11.17	0.0303	7.15
0.1917	26.15	0.0773	28.83	0.1055	17.19	0.0453	17.23	0.0282	14.13	0.0204	11.97	0.0246	7.73
0.1745	27.91	0.0649	30.60	0.0877	18.93	0.0398	18.63	0.0240	14.87	0.0178	12.60	0.0220	8.19
0.1438	29.72	0.0542	32.49	0.0695	20.67	0.0341	19.97	0.0225	15.82			0.0185	8.96
0.1201	31.57	0.0564	34.20	0.0582	22.41	0.0308	21.76					0.0167	9.55
0.1113	33.17	0.0560	36.03	0.0544	24.15	0.0277	22.80						
0.0992	35.45			0.0422	25.90	0.0289	24.13						
0.0930	37.11			0.0452	27.64	0.0272	24.87						
0.0769	39.02			0.0376	29.41	0.0165	26.66						
0.0584	41.08												
0.0695	43.14												
0.0500	45.26												
0.0461	47.26												

Table B.4 Changes of moisture ratio in DSG drying (continued)

MR (110.8°C, 0.48 m/s)	t (min)	MR (116.0°C, 0.47 m/s)	t (min)	MR (121.0°C, 0.47 m/s)	t (min)	MR (130.7°C, 0.48 m/s)	t (min)	MR (145.6°C, 0.50 m/s)	t (min)	MR (160.3°C, 0.51 m/s)	t (min)	MR (179.7°C, 0.52 m/s)	t (min)
1.2741	0.03	1.2680	0.03	1.1841	0.03	1.1660	0.05	1.1313	0.06	1.1211	0.03	1.0853	0.02
1.2211	0.34	1.1950	0.24	1.1240	0.27	1.1351	0.21	1.0626	0.29	1.0448	0.26	0.9986	0.22
1.1906	0.65	1.1525	0.51	1.0904	0.55	1.0788	0.48	0.9930	0.58	0.9542	0.54	0.8955	0.49
1.1661	0.99	1.1145	0.84	1.0426	0.88	1.0245	0.75	0.9189	0.90	0.8874	0.82	0.8141	0.70
1.0712	1.42	1.0497	1.29	0.9598	1.39	0.9748	1.01	0.8147	1.31	0.7839	1.16	0.7329	0.95
1.0329	1.91	0.9919	1.77	0.8897	1.85	0.8874	1.41	0.7005	1.78	0.6575	1.59	0.5598	1.34
0.8476	3.33	0.8738	2.64	0.7408	2.82	0.8055	1.81	0.5669	2.30	0.4821	2.15	0.3948	1.73
0.6958	5.21	0.7834	3.54	0.6348	3.67	0.6212	2.61	0.4408	2.92	0.3588	2.72	0.2891	2.11
0.5652	7.37	0.5912	5.55	0.5375	4.58	0.4728	3.41	0.3396	3.50	0.2524	3.29	0.2031	2.45
0.4658	9.25	0.3998	8.07	0.4571	5.48	0.3545	4.21	0.2583	4.08	0.1581	3.94	0.1373	2.82
0.3662	11.07	0.3134	9.84	0.3723	6.42	0.2635	5.01	0.1967	4.67	0.1145	4.51	0.0843	3.21
0.3138	12.92	0.2318	11.64	0.3067	7.33	0.1885	5.81	0.1479	5.25	0.0705	5.07	0.0514	3.57
0.2380	14.77	0.1767	13.44	0.2556	8.21	0.1329	6.61	0.1059	5.83	0.0396	5.64	0.0067	4.16
0.1832	16.71	0.1317	15.27	0.2067	9.18	0.0936	7.41	0.0761	6.42	0.0217	6.18	-0.0051	4.67
0.1600	18.59	0.0820	17.94	0.1642	10.03	0.0608	8.21	0.0518	7.06	0.0071	6.77	-0.0124	5.13
0.1039	20.94	0.0547	20.73	0.1306	10.94	0.0364	9.04	0.0308	7.70	-0.0011	7.34	-0.0184	5.64
0.0889	22.79	0.0308	22.47	0.1066	11.85	0.0174	9.84	0.0149	8.25	-0.0119	7.91	-0.0195	6.00
0.0753	24.67	0.0223	24.24	0.0781	12.76	0.0106	10.61	0.0068	8.84	-0.0164	8.47		
0.0506	26.49	0.0157	26.04	0.0599	13.70	0.0015	11.41	-6.91E-05	9.42	-0.0176	9.04		
0.0486	28.34			0.0466	14.58	-0.0023	12.21			-0.0218	9.61		
0.0366	30.19			0.0417	15.48	-0.0037	13.01						
0.0278	32.04			0.0270	16.42								
0.0367	33.89			0.0196	17.33								
0.0295	35.74			0.0142	18.30								
				0.0099	19.15								
				0.0078	20.06								
				0.0048	20.97								
				0.0018	21.88								

Table B.4 Changes of moisture ratio in DSG drying (continued)

MR (110.7°C, 0.65 m/s)	t (min)	MR (116.6°C, 0.68 m/s)	t (min)	MR (120.6°C, 0.68 m/s)	t (min)	MR (130.8°C, 0.69 m/s)	t (min)	MR (145.7°C, 0.71 m/s)	t (min)	MR (160.5°C, 0.70 m/s)	t (min)	MR (180.1°C, 0.76 m/s)	t (min)
1.1762	0.11	1.1919	0.03	1.1786	0.03	1.0999	0.11	1.1110	0.03	1.1032	0.03	0.9312	0.03
1.1552	0.37	1.1205	0.09	1.1453	0.24	1.0212	0.34	1.0756	0.22	0.9655	0.35	0.8447	0.20
1.0887	0.65	1.0671	0.30	1.0608	0.54	0.8994	0.71	0.9887	0.48	0.8586	0.61	0.7252	0.48
1.0689	0.94	1.0374	0.56	1.0146	0.84	0.8656	0.97	0.8786	0.76	0.7626	0.88	0.6211	0.73
1.0512	1.37	1.0577	0.89	0.9537	1.28	0.6935	1.71	0.7142	1.21	0.6782	1.15	0.4504	1.10
0.9486	1.88	0.9802	1.18	0.8213	1.88	0.5924	2.14	0.5749	1.63	0.5999	1.39	0.2955	1.48
0.8571	2.73	0.9282	1.60	0.7266	2.48	0.5139	2.57	0.4182	2.19	0.4544	1.81	0.1896	1.85
0.7107	4.38	0.8471	2.07	0.5585	3.52	0.4195	3.11	0.3026	2.72	0.3766	2.08	0.1083	2.23
0.5765	6.14	0.7415	2.93	0.4503	4.41	0.3356	3.71	0.2260	3.31	0.2985	2.43	0.0563	2.60
0.4408	7.85	0.5996	3.81	0.3585	5.31	0.2654	4.29	0.1109	4.15	0.2322	2.77	0.0130	2.98
0.3730	9.56	0.4919	4.73	0.2713	6.20	0.1828	5.11	0.0591	5.00	0.1087	3.41	0.0130	3.35
0.2682	11.26	0.4318	5.56	0.2170	7.10	0.1173	6.11	0.0528	5.56	0.0555	3.95	-0.0155	3.73
0.2118	12.97	0.2309	7.39	0.1457	7.99	0.0735	7.00	0.0286	5.95	0.0251	4.35	-0.0223	4.13
0.1406	15.56	0.2151	8.28	0.1138	8.92	0.0445	7.86	0.0103	6.54	-0.0203	4.85	-0.0321	4.50
0.0874	17.24	0.1619	9.16	0.0833	9.81	0.0278	8.69	0.0081	7.38	0.0117	5.15	-0.0289	4.88
0.0483	18.94	0.1110	10.05	0.0539	10.68	0.0065	10.00	-0.0054	8.22	-0.0051	5.55	-0.0271	5.25
0.0539	20.65	0.0985	10.94	0.0363	11.57	0.0019	10.86	-0.0152	8.79	-0.0164	5.97	-0.0403	5.60
0.0335	22.36	0.0746	11.82	-0.0002	12.47	-0.0049	11.86			-0.0426	6.32		
0.0122	24.92	0.0274	13.69	0.0011	13.36	0.0009	12.40			-0.0291	6.77		
-0.0081	25.77	-0.0069	14.54	-0.0060	14.29	-0.0157	13.29						
-0.0089	26.62	-0.0217	15.46	-0.0130	15.12	-0.0268	14.14						
-0.0064	27.48	-0.0025	16.32	-0.0305	16.02								
-0.0078	28.30	-0.0307	17.20	-0.0259	16.91								
-0.0047	29.47	-0.0009	18.12	-0.0223	17.81								
-0.0168	30.32	-0.0126	18.98										

Table B.4 Changes of moisture ratio in DSG drying (continued)

MR (111.2°C, 0.87 m/s)	t (min)	MR (116.0°C, 0.86 m/s)	t (min)	MR (121.0°C, 0.90 m/s)	t (min)	MR (130.7°C, 0.91 m/s)	t (min)	MR (145.6°C, 0.96 m/s)	t (min)	MR (160.3°C, 0.95 m/s)	t (min)	MR (180.5°C, 1.02 m/s)	t (min)
1.1856	0.03	1.1759	0.03	1.1485	0.29	1.1353	0.03	1.0663	0.23	0.9794	0.25	0.9054	0.21
1.1551	0.33	1.1774	0.27	1.0712	0.58	1.1152	0.22	0.9526	0.53	0.8092	0.56	0.7572	0.48
1.1320	0.69	1.1265	0.57	1.0122	0.88	1.0427	0.50	0.8350	0.82	0.6870	0.85	0.6111	0.75
1.1000	0.99	1.0756	0.87	0.8968	1.31	0.9647	0.78	0.6293	1.28	0.4671	1.30	0.3817	1.15
1.0331	1.43	0.9916	1.33	0.8009	1.75	0.8128	1.22	0.4795	1.69	0.3056	1.75	0.2303	1.55
0.9278	2.15	0.8904	1.93	0.5795	2.77	0.7028	1.64	0.3093	2.28	0.1324	2.31	0.0911	2.08
0.8410	2.93	0.5819	3.74	0.4397	3.65	0.4903	2.44	0.1898	2.86	0.0859	2.76	0.0249	2.61
0.7271	3.83	0.4688	4.64	0.3194	4.52	0.3582	3.17	0.1091	3.50	0.0469	3.19	-0.0023	3.12
0.6186	4.72	0.3703	5.73	0.2319	5.40	0.2931	3.64	0.0643	4.05	0.0211	3.61	-0.0172	3.71
0.4836	6.25	0.3122	6.45	0.1740	6.27	0.2418	4.06	0.0337	4.64	0.0060	4.03	-0.0228	4.21
0.3789	7.56	0.2464	7.36	0.1208	7.15	0.1501	4.94	0.0163	5.10	0.0011	4.43	-0.0230	4.77
0.2918	8.91	0.2032	8.29	0.0828	8.02	0.0998	5.78	0.0082	5.69	-0.0094	5.30		
0.2364	10.25	0.1665	9.17	0.0579	8.90	0.0621	6.61	-0.0013	6.30	-0.0111	5.75		
0.1798	11.60	0.1184	10.13	0.0411	9.83	0.0353	7.44	-0.0055	6.91	-0.0135	6.54		
0.1415	12.97	0.1006	10.98	0.0294	10.65	0.0192	8.33	-0.0086	7.53				
0.1172	14.29	0.0817	11.88	0.0164	11.52	0.0108	9.11	-0.0106	8.11				
0.0825	15.63	0.0670	12.79	0.0150	12.40	0.0056	9.97	-0.0126	8.84				
0.0733	17.00	0.0485	13.69	0.0139	13.27	0.0044	10.78						
0.0588	18.32	0.0412	14.60	0.0081	15.02	-0.0030	11.61						
0.0460	19.69	0.0356	15.53			-0.0080	13.89						
0.0451	21.04	0.0232	16.41			-0.0085	15.39						
0.0312	22.41	0.0183	17.31										
0.0280	23.28	0.0168	18.22										
0.0328	24.18	0.0113	19.18										
0.0306	25.07	0.0113	20.03										

Table B.4 Changes of moisture ratio in DSG drying (continued)

MR (111.0°C, 1.08 m/s)	t (min)	MR (115.7°C, 1.09 m/s)	t (min)	MR (121.1°C, 1.11 m/s)	t (min)	MR (132.0°C, 1.12 m/s)	t (min)	MR (146.1°C, 1.16 m/s)	t (min)	MR (160.6°C, 1.21 m/s)	t (min)	MR (180.5°C, 1.28 m/s)	t (min)
1.0887	0.03	1.0945	0.40	1.0845	0.33	1.0322	0.23	1.0428	0.06	1.0100	0.25	0.8285	0.23
1.0582	0.39	1.0305	0.69	1.0236	0.60	0.9192	0.51	1.0112	0.29	0.8340	0.56	0.4962	0.73
1.0450	0.80	0.9812	0.95	0.9629	0.90	0.7625	0.91	0.8574	0.61	0.7057	0.81	0.3864	0.93
0.9532	1.40	0.9377	1.26	0.8972	1.20	0.6066	1.36	0.6413	1.07	0.4927	1.22	0.1249	1.58
0.8706	2.00	0.8510	1.69	0.7671	1.70	0.4290	1.93	0.4269	1.62	0.3305	1.67	0.0566	2.07
0.7973	2.59	0.7525	2.21	0.6790	2.12	0.2988	2.49	0.2763	2.20	0.2102	2.11	0.0046	2.44
0.7310	3.19	0.6652	2.76	0.5654	2.72	0.1752	3.32	0.1274	3.09	0.1127	2.67	-0.0035	2.77
0.6798	3.78	0.5319	3.62	0.4730	3.32	0.0988	4.19	0.0617	3.96	0.0873	2.97	-0.0063	3.01
0.6141	4.38	0.4259	4.48	0.4079	3.89	0.0459	5.04	0.0151	5.66	0.0396	3.53	-0.0196	3.42
0.5535	4.97	0.3555	5.34	0.3341	4.51	0.0251	5.89	-0.0039	6.56	0.0140	4.08	-0.0258	3.68
0.4967	5.60	0.2806	6.20	0.2781	5.08	0.0173	6.72	-0.0050	7.42	-0.0084	5.03	-0.0310	4.12
0.4551	6.17	0.2199	7.06	0.2388	5.74	0.0019	7.59	-0.0114	8.26	-0.0120	6.31	-0.0298	4.41
0.4152	6.76	0.1782	7.92	0.1926	6.37	0.0001	8.44	-0.0128	9.13	-0.0088	6.86	-0.0321	4.98
0.3745	7.36	0.1357	8.87	0.1361	7.26	0.0007	9.32			-0.0221	7.83	-0.0314	5.68
0.3509	7.95	0.1051	9.64	0.1063	8.16	-0.0050	10.17						
0.3164	8.55	0.0828	10.51	0.0693	9.06	-0.0050	10.97						
0.2478	9.68	0.0582	12.23	0.0484	9.95	-0.0061	11.99						
0.2051	10.72	0.0328	13.09	0.0315	10.85								
0.1870	11.59	0.0285	13.95	0.0125	12.64								
0.1459	12.48	0.0303	14.81	0.0085	13.90								
0.1207	13.37	0.0174	15.70	-0.0018	14.49								
0.1100	14.27			-0.0074	15.42								
0.0951	16.06			-0.0127	16.02								
0.0553	17.84			-0.0028	17.15								
0.0498	19.63												
0.0520	20.52												
0.0318	21.42												

Appendix B.5

Table B.5 Regression-analysis results for Eq. 4.3 (BSG drying)

Drying conditions		Coefficients			Mean residual	Mean
Temp (°C)	Velocity (m/s)	A	K	N	square	deviation
110.9	0.24	1.1893	0.0217	1.2447	0.000653	0.0256
115.9	0.24	1.1796	0.0356	1.2021	0.000477	0.0218
120.9	0.24	1.1711	0.0485	1.1814	0.000417	0.0204
130.7	0.24	1.1632	0.0650	1.2537	0.000445	0.0211
145.5	0.25	1.1871	0.1004	1.2293	0.000260	0.0161
160.3	0.26	1.1545	0.1242	1.2893	0.000439	0.0210
180.2	0.27	1.1523	0.1586	1.3779	0.000257	0.0160
110.7	0.44	1.2001	0.0401	1.2087	0.000686	0.0262
115.9	0.45	1.2150	0.0631	1.1913	0.000469	0.0217
120.9	0.45	1.1873	0.0839	1.1983	0.000439	0.0210
130.8	0.47	1.1797	0.1679	1.0882	0.000507	0.0225
145.6	0.47	1.1526	0.1669	1.2560	0.000327	0.0181
160.5	0.50	1.1636	0.2210	1.3179	0.000337	0.0184
179.9	0.52	1.1352	0.2821	1.3066	0.000303	0.0174
110.8	0.63	1.1349	0.0703	1.1214	0.000736	0.0271
115.8	0.63	1.1267	0.1214	1.0658	0.000685	0.0262
120.8	0.64	1.1361	0.1306	1.1662	0.000707	0.0266
130.8	0.65	1.0999	0.2001	1.1348	0.000103	0.0321
145.6	0.65	1.1547	0.2137	1.3070	0.000353	0.0188
160.5	0.69	1.0602	0.3237	1.2879	0.000386	0.0196
180.3	0.71	1.0638	0.4321	1.3134	0.000249	0.0158
110.8	0.81	1.1605	0.0572	1.2439	0.000274	0.0165
115.8	0.83	1.1630	0.1017	1.1762	0.000278	0.0167
120.8	0.83	1.1734	0.1329	1.2513	0.000190	0.0138
130.4	0.85	1.1403	0.1892	1.3057	0.000147	0.0121
145.5	0.89	1.1263	0.2902	1.3495	0.000132	0.0115
160.6	0.91	1.1256	0.3359	1.3647	0.000165	0.0129
180.4	0.93	1.1141	0.4645	1.3897	0.000229	0.0151
110.8	1.02	1.0588	0.0783	1.3790	0.000394	0.0198
115.8	1.02	1.0799	0.1376	1.2764	0.000252	0.0159
121.0	1.04	1.0541	0.1166	1.4207	0.000053	0.0073
130.9	1.08	1.0783	0.2584	1.3207	0.000082	0.0091
145.9	1.09	1.0689	0.2919	1.3632	0.000135	0.0116
160.7	1.13	1.0914	0.5447	1.2625	0.000105	0.0102
180.3	1.17	1.0332	0.6049	1.4495	0.000541	0.0233

Appendix B.6

Table B.6 Regression-analysis results for Eq. 4.3 (DSG drying)

Drying conditions		Coefficients			Mean residual square	Mean deviation
Temp (°C)	Velocity (m/s)	A	K	N		
110.8	0.25	1.2925	0.0448	1.1412	0.000177	0.0133
116.1	0.26	1.3006	0.0739	1.0972	0.000143	0.0119
121.1	0.26	1.3051	0.0990	1.1315	0.000128	0.0113
130.9	0.28	1.2768	0.1514	1.1042	0.000106	0.0103
145.8	0.28	1.2720	0.1924	1.2108	0.000071	0.0084
160.6	0.29	1.2388	0.1704	1.3698	0.000102	0.0101
180.2	0.31	1.2235	0.2398	1.3575	0.000134	0.0116
110.8	0.48	1.2770	0.1138	0.9986	0.000144	0.0120
116.0	0.47	1.2400	0.1219	1.0667	0.000110	0.0105
121.0	0.47	1.1666	0.1298	1.1780	0.000059	0.0077
130.7	0.48	1.1574	0.1668	1.3618	0.000046	0.0068
145.6	0.50	1.1191	0.2213	1.3440	0.000058	0.0076
160.3	0.51	1.0982	0.2761	1.4143	0.000181	0.0135
179.7	0.52	1.0580	0.4227	1.5263	0.000250	0.0158
110.7	0.65	1.1641	0.0832	1.1931	0.000355	0.0188
116.6	0.68	1.1274	0.1022	1.3452	0.000116	0.0108
120.6	0.68	1.1586	0.1462	1.2712	0.000350	0.0187
130.8	0.69	1.0932	0.2392	1.2323	0.000178	0.0133
145.7	0.71	1.1224	0.3500	1.3109	0.000069	0.0083
160.5	0.70	1.0669	0.3713	1.4501	0.000621	0.0249
180.1	0.76	0.9095	0.6288	1.5333	0.000460	0.0214
111.2	0.87	1.2024	0.1052	1.1735	0.000114	0.0107
116.0	0.86	1.2064	0.1464	1.1887	0.000095	0.0097
121.0	0.90	1.2004	0.2072	1.2243	0.000013	0.0036
130.7	0.91	1.1520	0.2621	1.2870	0.000046	0.0068
145.6	0.96	1.1230	0.4034	1.4127	0.000034	0.0058
160.3	0.95	1.0376	0.5409	1.5216	0.000101	0.0100
180.5	1.02	0.9562	0.7262	1.6141	0.000172	0.0131
111.0	1.08	1.1065	0.1077	1.1523	0.000094	0.0097
115.7	1.09	1.1617	0.1736	1.1551	0.000083	0.0091
121.1	1.11	1.1594	0.2214	1.1475	0.000077	0.0088
132.0	1.12	1.1003	0.4125	1.2484	0.000015	0.0039
146.1	1.16	1.0720	0.4592	1.3809	0.000140	0.0118
160.6	1.21	1.1105	0.6149	1.3354	0.000079	0.0089
180.5	1.28	0.9149	0.9795	1.5587	0.000409	0.0204

Appendix B.7 SAS program for the regression analysis on Eq. 4.3

```
OPTIONS LINESIZE=78;
DATA brew;
INFILE 'data file';[a]
INPUT MR t;

PROC PRINT DATA=brew;
VAR t MR;

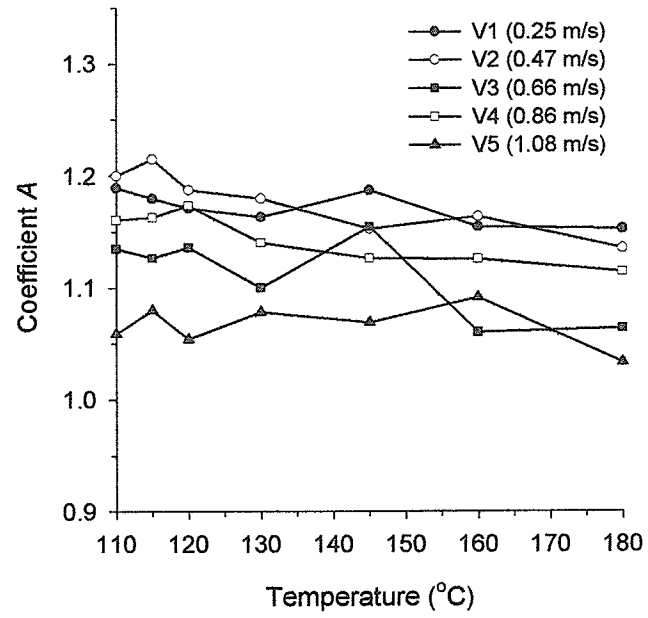
TITLE '##### Regression for  $MR=A*\exp(-K*t**N)$  #####';
PROC NLIN BEST=5 DATA=brew;
PARMS A=0 to 5 by 1 K=0 to 5 by 1 N=0 to 5 by 1;
MODEL MR=A*exp(-K*t**N);
OUTPUT OUT=brew1 P=P1 R=R1;

PROC PRINT DATA=brew1;
VAR t MR P1;

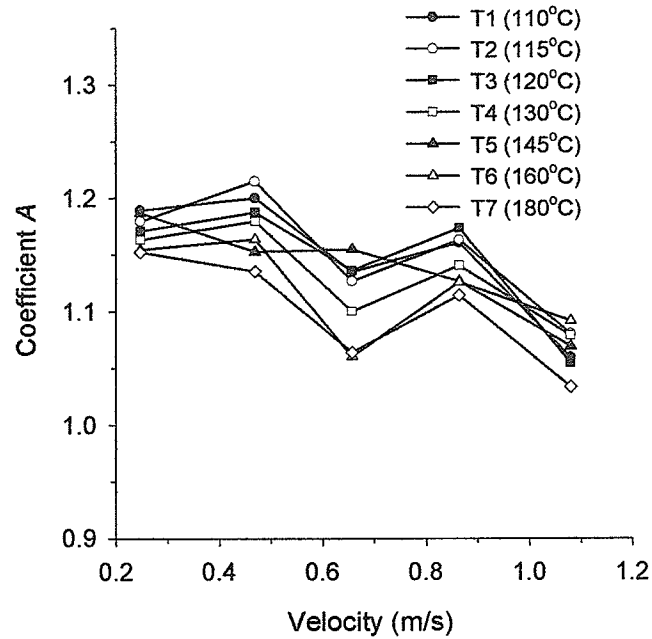
PROC PLOT DATA=brew1;
PLOT MR*t='M' P1*t='P'/overlay;
PLOT R1*t/VREF=0;
RUN;
```

^[a] The data file used in the program contains the data of changes in moisture ratio MR and drying time t in a certain drying process; all the data for different drying processes were listed in Tables B.3 and B.4.

Appendix B.8

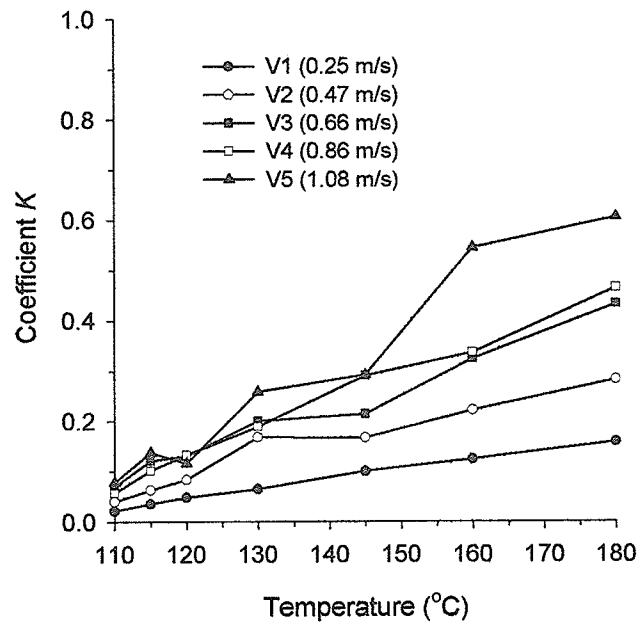


(a) Changes of coefficient A with the steam temperature for BSG-drying model.

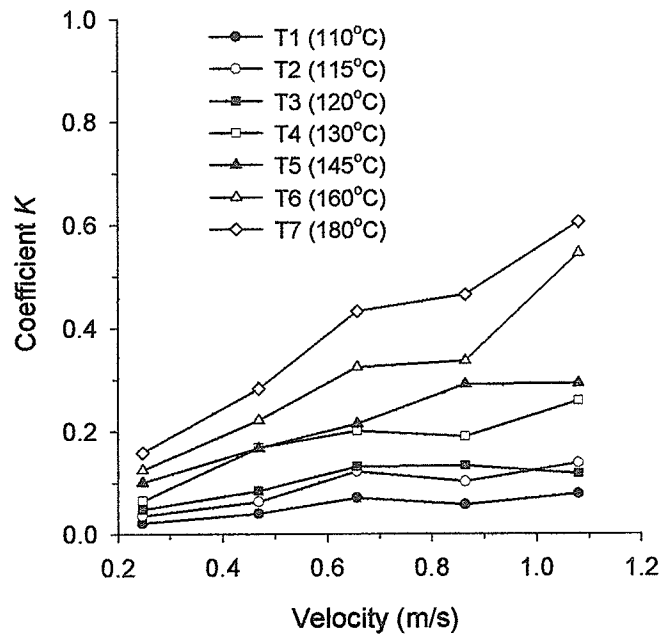


(b) Changes of coefficient A with the steam velocity for BSG-drying model.

Figure B.1 Effects of steam temperature and velocity on A , K , and N in BSG-drying model

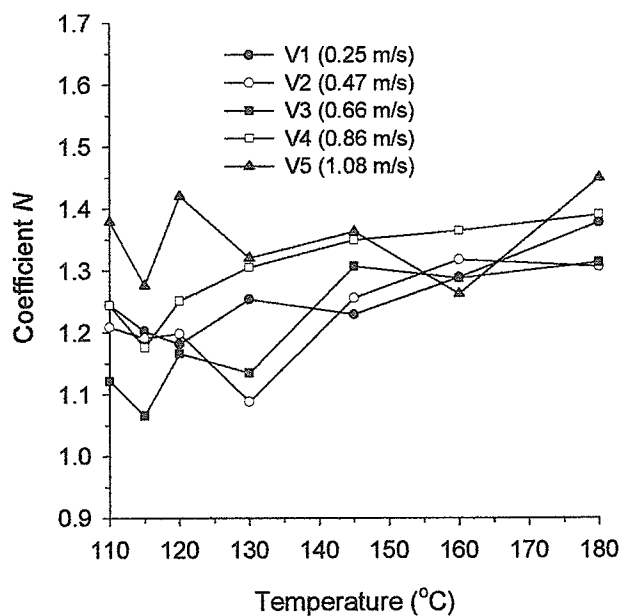


(c) Changes of coefficient K with the steam temperature for BSG-drying model.

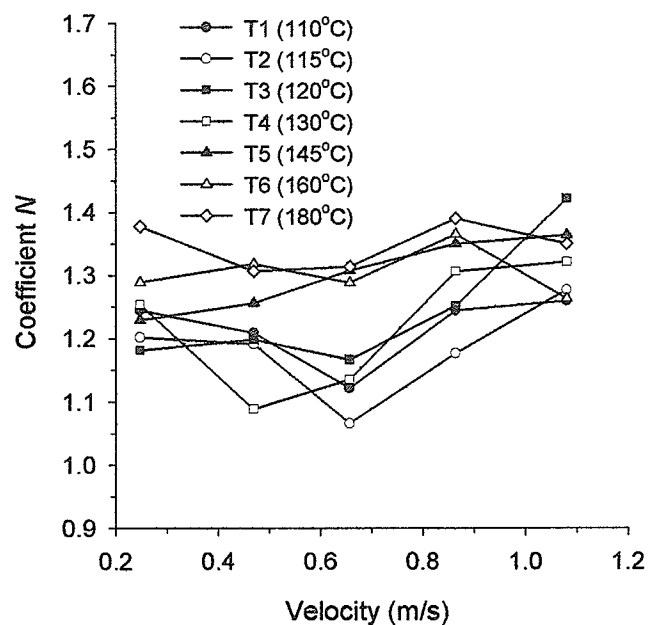


(d) Changes of coefficient K with the steam velocity for BSG-drying model.

Figure B.1 Effects of steam temperature and velocity on A , K , and N in BSG-drying model (continued)



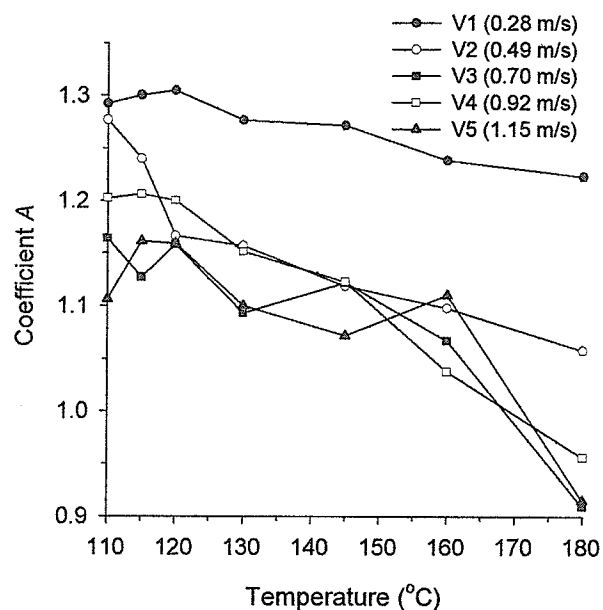
(e) Changes of coefficient N with the steam temperature for BSG-drying model.



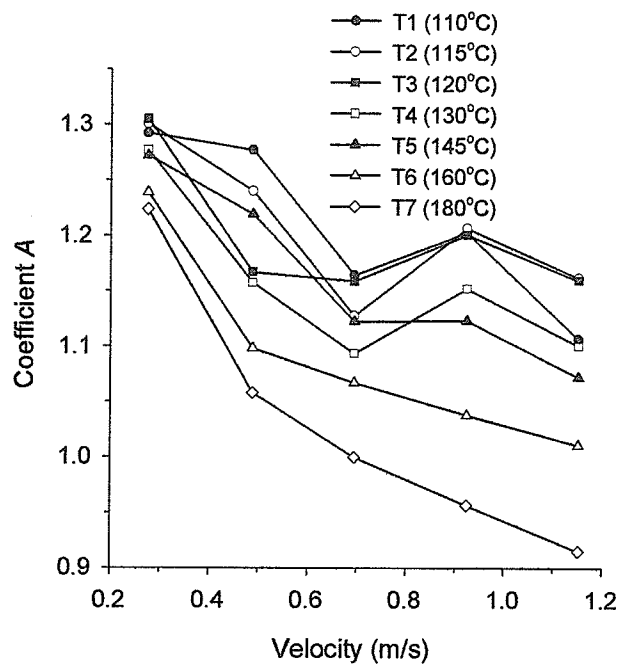
(f) Changes of coefficient N with the steam velocity for BSG-drying model.

Figure B.1 Effects of steam temperature and velocity on A , K , and N in BSG-drying model (continued)

Appendix B.9

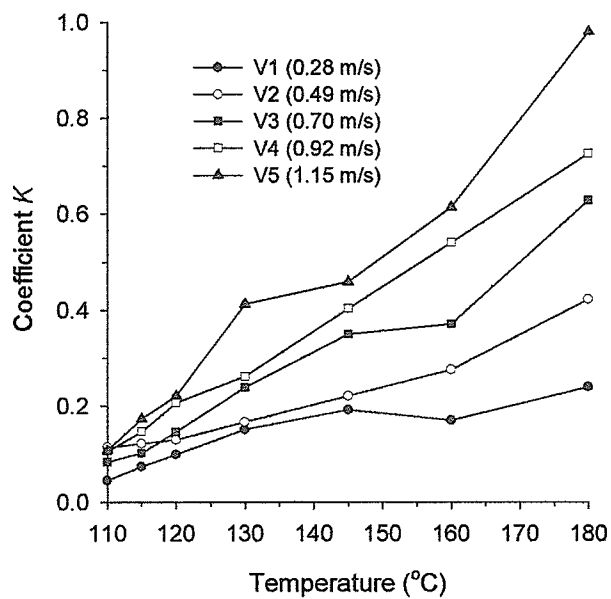


(a) Changes of coefficient A with the steam temperature for DSG-drying model.

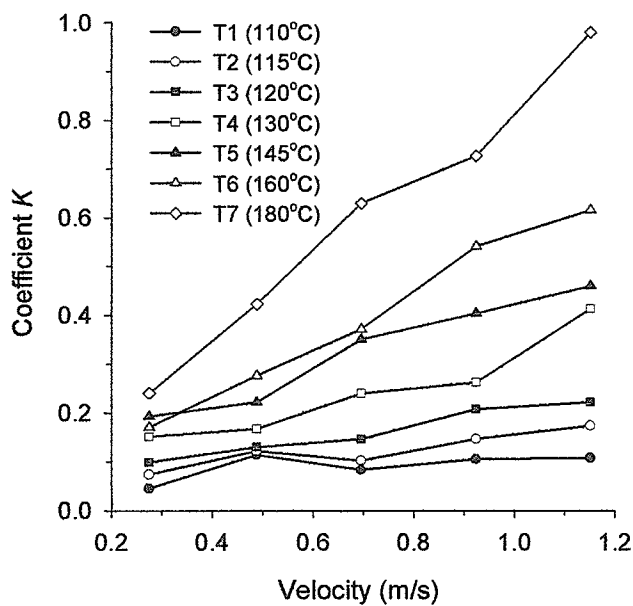


(b) Changes of coefficient A with the steam velocity for DSG-drying model.

Figure B.2 Effects of steam temperature and velocity on A , K , and N in DSG-drying model.

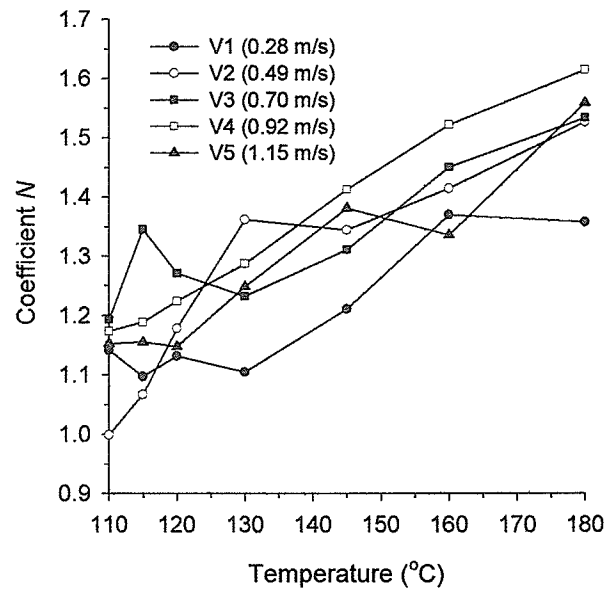


(c) Changes of coefficient K with the steam temperature for DSG-drying model.

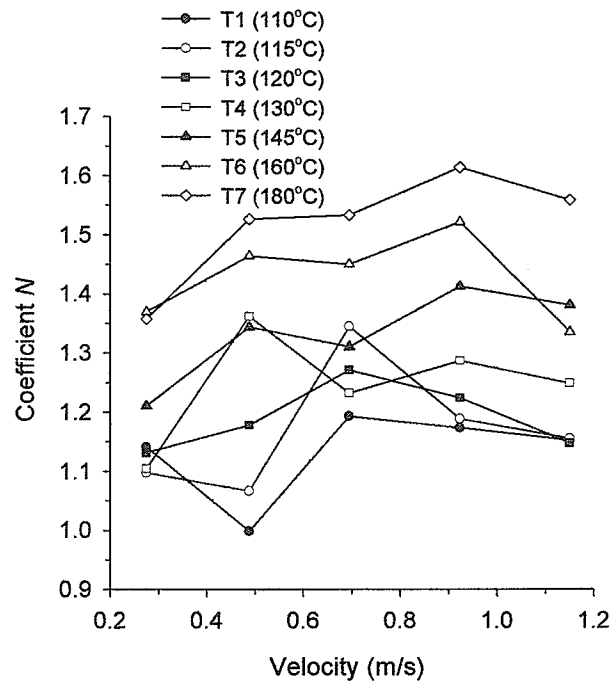


(d) Changes of coefficient K with the steam velocity for DSG-drying model.

Figure B.2 Effects of steam temperature and velocity on A , K , and N in DSG-drying model (continued).



(e) Changes of coefficient N with the steam temperature for DSG-drying model.



(f) Changes of coefficient N with the steam velocity for DSG-drying model.

Figure B.2 Effects of steam temperature and velocity on A , K , and N in DSG-drying model (continued).

Appendix B.10 SAS program for the regression analysis on Eqs. 4.6 through 4.8.

```
OPTIONS LINESIZE=78;
DATA dist;
  INFILE 'data file';[a]
INPUT A K N T V;

TITLE '##### Regression for  $A=(a_1 \cdot T + a_2) \cdot (a_3 \cdot V + a_4)$  #####';
PROC NLIN BEST=5 DATA=dist;
PARMS a1=1 to 5 by 1 a2=1 to 5 by 1 a3=1 to 5 by 1 a4=1 to 5 by 1;
MODEL A=(a1*T+a2)*(a3*V+a4);
OUTPUT OUT=dist1 P=P1 R=R1;

PROC PRINT DATA=dist1;
VAR T V A P1 R1;

TITLE '##### Regression for  $K=(k_1 \cdot T + k_2) \cdot (k_3 \cdot V + k_4)$  #####';
PROC NLIN BEST=5 DATA=dist;
PARMS k1=1 to 5 by 1 k2=1 to 5 by 1 k3=1 to 5 by 1 k4=1 to 5 by 1;
MODEL K=(k1*T+k2)*(k3*V+k4);
OUTPUT OUT=dist1 P=P1 R=R1;

PROC PRINT DATA=dist1;
VAR T V K P1 R1;

TITLE '##### Regression for  $N=n_1 \cdot T + n_2$  #####';
PROC NLIN BEST=5 DATA=dist;
PARMS n1=1 to 5 by 1 n2=1 to 5 by 1;
MODEL N=n1*T+n2;
OUTPUT OUT=dist1 P=P1 R=R1;

PROC PRINT DATA=dist1;
VAR T V N P1 R1;

RUN;
```

^[a] The data file used in the program contains all the data of changes in parameters A , K , and N with steam temperature T and velocity V for BSG or DSG drying; the data were listed in Tables B.5 and B.6.

C - APPENDICES FOR CHAPTER 5

Appendix C.1 Models for continuous deep-bed drying

C.1.1 Cross-flow drying model

In a cross-flow drying system, steam flows in the x direction and spent grain in the y direction. The drying time t depends on the distance spent grain moves in the y direction and the velocity of the spent-grain movement v . By replacing the term t with y/v in equations 5.8, 5.14, 5.16, and 5.17 and introducing $G = \rho v$, the model for steady-state drying in a cross-flow system is obtained as:

$$\frac{\partial T_s}{\partial x} = -\frac{h a}{G_s c_s} (T_s - T) - \frac{\varepsilon \rho_s G}{\rho G_s} \frac{\partial T_s}{\partial y} \quad (\text{C.1a})$$

$$\frac{\partial T}{\partial y} = \frac{h a (T_s - T)}{G (c + c_w M)} + \frac{h_v + c_s (T_s - T)}{c + c_w M} \frac{\partial M}{\partial y} \quad (\text{C.1b})$$

$$\frac{\partial G_s}{\partial x} = -G \frac{\partial M}{\partial y} \quad (\text{C.1c})$$

$$\frac{\partial M}{\partial y} = -\frac{\rho K N}{60 G} (M - M_e) \left[\frac{1}{K} \text{Ln} \left(\frac{A (M_o - M_e)}{M - M_e} \right) \right]^{\frac{N-1}{N}} \quad (\text{C.1d})$$

Boundary and initial conditions are

$$\begin{aligned} T_s(0, y) &= T_{so}; \quad G_s(0, y) = G_{so} \\ T(x, 0) &= 100; \quad M(x, 0) = M_o + \frac{(c + c_w M_o) (100 - T_o)}{c_s (T_{so} - 100) + h_v} \end{aligned} \quad (\text{C.1e})$$

C.1.2 Concurrent-flow drying model

In a concurrent-flow drying system, both steam and spent grain flow in the same direction x , but the steam velocity V_s is greater than the spent-grain velocity v . The drying time t depends on the distance spent grain moves in the x direction and the velocity of the movement v . By replacing the variable y with x and replacing the partial-differential symbol ∂ with total-differential symbol d in the cross-flow drying model, the model for steady-state drying in a concurrent-flow system is written as:

$$\frac{dT_s}{dx} = -\frac{h a}{G_s c_s} (T_s - T) - \frac{\varepsilon \rho_s G}{\rho G_s} \frac{dT_s}{dx} \quad (\text{C.2a})$$

$$\frac{dT}{dx} = \frac{h a (T_s - T)}{G (c + c_w M)} + \frac{h_v + c_v (T_s - T)}{c + c_w M} \frac{dM}{dx} \quad (\text{C.2b})$$

$$\frac{dG_s}{dx} = -G \frac{dM}{dx} \quad (\text{C.2c})$$

$$\frac{dM}{dx} = -\frac{\rho K N}{60 G} (M - M_e) \left[\frac{1}{K} \ln \left(\frac{A (M_o - M_e)}{M - M_e} \right) \right]^{\frac{N-1}{N}} \quad (\text{C.2d})$$

Boundary and initial conditions are

$$\begin{aligned} T_s(0) &= T_{so}; \quad G_s(0) = G_{so} \\ T(0) &= 100; \quad M(0) = M_o + \frac{(c + c_w M_o) (100 - T_o)}{c_s (T_{so} - 100) + h_v} \end{aligned} \quad (\text{C.2e})$$

C.1.3 Counter-flow drying model

In a counter-flow drying system, steam and spent grain flow in opposite directions. It is assumed that spent grain moves in the positive direction x . By replacing the term x with $-x$, the term y with x , and the mathematic symbol ∂ with d in the cross-flow drying model, the model for steady-state drying in a counter-flow system is presented as:

$$\frac{dT_s}{dx} = \frac{h a}{G_s c_s} (T_s - T) + \frac{\varepsilon \rho_s G}{\rho G_s} \frac{dT_s}{dx} \quad (\text{C.3a})$$

$$\frac{dT}{dx} = \frac{h a (T_s - T)}{G (c + c_w M)} + \frac{h_v + c_s (T_s - T)}{c + c_w M} \frac{dM}{dx} \quad (\text{C.3b})$$

$$\frac{dG_s}{dx} = G \frac{dM}{dx} \quad (\text{C.3c})$$

$$\frac{dM}{dx} = -\frac{\rho K N}{60 G} (M - M_e) \left[\frac{1}{K} \text{Ln} \left(\frac{A (M_o - M_e)}{M - M_e} \right) \right]^{\frac{N-1}{N}} \quad (\text{C.3d})$$

Boundary and initial conditions are

$$\begin{aligned} T_s(L) &= T_{so}; \quad G_s(L) = G_{so} \\ T(0) &= 100; \quad M(0) = M_o + \frac{(c + c_w M_o) (100 - T_o)}{c_s (T_{se} - 100) + h_v} \end{aligned} \quad (\text{C.3e})$$

If it is assumed that steam flows in the positive direction x , the variable y in the cross-flow drying model should be replaced by $-x$ and symbol ∂ by d to obtain the counter-flow drying model as:

$$\frac{dT_s}{dx} = - \frac{h a}{G_s c_s} (T_s - T) + \frac{\varepsilon \rho_s G}{\rho G_s} \frac{dT_s}{dx} \quad (\text{C.4a})$$

$$\frac{dT}{dx} = - \frac{h a (T_s - T)}{G (c + c_w M)} + \frac{h_v + c_s (T_s - T)}{c + c_w M} \frac{dM}{dx} \quad (\text{C.4b})$$

$$\frac{dG_s}{dx} = G \frac{dM}{dx} \quad (\text{C.4c})$$

$$\frac{dM}{dx} = \frac{\rho K N}{60 G} (M - M_e) \left[\frac{1}{K} \text{Ln} \left(\frac{A (M_o - M_e)}{M - M_e} \right) \right]^{\frac{N-1}{N}} \quad (\text{C.4d})$$

Boundary and initial conditions are

$$\begin{aligned} T_s(0) &= T_{so}; \quad G_s(0) = G_{so} \\ T(L) &= 100; \quad M(L) = M_o + \frac{(c + c_w M_o) (100 - T_o)}{c_s (T_{se} - 100) + h_v} \end{aligned} \quad (\text{C.4e})$$

Appendix C.2 Program for simulating the drying of fixed-bed BSG in superheated steam

```

C PROGRAM TO SOLVE DEEP-BED DRYING MODEL
C
C BASIC STATEMENTS
C
    CHARACTER*20 File1, File2
    COMMON AMo
    COMMON /DENS/ Pmo, Pme
    COMMON /THICK/ Dxo, Dxe
    DIMENSION AM1(50), AM2(50), T(50), Gs(51), Vs(51),
+Ts(51), Dx(50), X(50)
C
C To define a number of statement functions
AME(Ts)=0.62*EXP(-1.1166*(Ts-100)**0.3339)
A(Ts, Vs)=(1.2925-0.00058*Ts)*(0.9991-0.0963*Vs)
AK(Ts, Vs)=(0.00273*Ts-0.2609)*(2.0984*Vs+0.2174)
AN(Ts)=0.00222*Ts+0.9599
Ps(Ts)=0.7401-0.001505*Ts
C
C INPUT SECTION OF THE PROGRAM
C
    PRINT*, 'Input the mass of the sample (g):'
    READ*, Wo
    PRINT*, 'Input the initial moisture content (db):'
    READ*, AMo
    PRINT*, 'Input the depth of the sample bed (mm):'
    READ*, Xo
    PRINT*, 'Input the number of layers in the bed:'
    READ*, Nx
    PRINT*, 'Input the steam temperature at inlet (oC):'
    READ*, Tso
    PRINT*, 'Input the steam flow rate at inlet (kg/(m2.s)):'
    READ*, Gso
    PRINT*, 'Input the expected drying time (min):'
    READ*, Timeo
    PRINT*, 'Input the time interval (min):'
    READ*, Dt
C
C TO DEFINE AND OPEN DATA FILES
C
    PRINT*, 'Name for the file recording the simulation
+process:'
    READ*, File1
    OPEN (1, FILE=File1)
    PRINT*, 'Name for the file recording major data:'
    READ*, File2
    OPEN (2, FILE=File2)
C
C TO WRITE INPUTTED PARAMETERS IN THE DATA FILES

```

```

C
WRITE (1, *) 'Mass of sample:', Wo, ' g'
WRITE (1, *) 'Initial moisture content:', AMo, ' kg/kg'
WRITE (1, *) 'Depth of sample bed:', Xo, ' mm'
WRITE (1, *) 'Number of layers in sample bed:', Nx
WRITE (1, *) 'Steam temperature at inlet:', Tso, ' oC'
WRITE (1, *) 'Steam flow rate at inlet:', Gso,
+' kg/(m2.s)'
WRITE (1, *) 'Expected drying time:', Timeo, ' min'
WRITE (1, *) 'Time interval:', Dt, ' min'

C
WRITE (2, *) 'Mass of sample:', Wo, ' g'
WRITE (2, *) 'Initial moisture content:', AMo, ' kg/kg'
WRITE (2, *) 'Depth of sample bed:', Xo, ' mm'
WRITE (2, *) 'Number of layers in sample bed:', Nx
WRITE (2, *) 'Steam temperature at inlet:', Tso, ' oC'
WRITE (2, *) 'Steam flow rate at inlet:', Gso, ' kg/(m2.s)'
WRITE (2, *) 'Expected drying time:', Timeo, ' min'
WRITE (2, *) 'Time interval:', Dt, ' min'

C
C BASIC CALCULATION BASED ON THE INPUT DATA
C
Dxo=Xo/1000/Nx
Dxe=0.867*Dxo
D1=0.066
Pmo=4*(Wo/1000)/(3.14159*D1**2*(Xo/1000)*(1+AMo))
Pme=Pmo/0.867
AMEo=AME(Tso)
Nt=NINT(Timeo/Dt)
Pso=Ps(Tso)
Vso=Gso/Pso

C
C TO SET VALUES FOR SOME PHYSICAL AND THERMODYNAMIC PROPERTIES
C
Cs=2000
Cw1=4193
Cw=4313
C=1245

C
C TO CALCULATE THE INITIAL MOISTURE CONTENT CONSIDERING
C STEAM CONDENSATION
C
AMo1=AMo+(C+Cw1*AMo)/(2257000+Cs*(Tso-100))*(100-10)

C
C TO SET JUDGE CRITERION FOR TERMINATING THE DRYING OF A LAYER
C (A small difference between moisture content and equilibrium
C moisture content)
C
DM=0.0001

C
C MAJOR DERIVATION FOR DRYING SIMULATION
C

```

```

        J=0
        Time=0
        m=1
        WRITE(2, 100)
100    FORMAT(/4H J, 9H T(min), 8H M(db), 7H Gs ,
+10H Ts(C) ,9H Front1, 5H L1, 9H Front2,
+5H L2, 9H Depth)
C
200    m5=m-1
        IF (J .GT. Nt) GO TO 800
C
        PRINT*, ' '
        PRINT*, ' '
        PRINT*, 'Time interval:', J, '      Drying time:',
+Time, ' min'
        WRITE(1, *) ' '
        WRITE(1, *) 'Time interval:', J, '      Drying time:',
+Time, ' min'
        WRITE(*, 300)
        WRITE(1, 300)
300    FORMAT(1X, 3H I, 7H X(i), 8H M(i), 10H T(i),
+10H Gs(i), 8H Ts(i))
C
        AveM=0
C
C For dried region
C
        IF (m .GT. 1) THEN
            DO 500 i=1, m-1
                Dx(i)=Dxe
                X(i)=(i-0.5)*Dxe
                AM1(i)=AM2(i)
                T(i)=Tso
                Gs(i)=Gso
                Vs(i)=Vso
                Ts(i)=Tso
                AveM=AveM+AM1(i)
                WRITE(*, 400) i, X(i), AM1(i), T(i), Gs(i), Ts(i)
                WRITE(1, 400) i, X(i), AM1(i), T(i), Gs(i), Ts(i)
400            FORMAT(1X, I3, 2X, F6.4, 2X, F6.4, 2X, F8.3, 2X,
+ F7.3, 2X, F7.3)
500            CONTINUE
            ENDIF
C Calculation of dry front position
        IF (m .EQ. 1) THEN
            X1=-1
            No1=-1
        ELSE
            X1=X(m-1)+Dx(m-1)/2
            No1=m-1
        ENDIF
C

```

```

      IF (m .GT. Nx) GO TO 900
C
      Ts(m)=Tso
      Vs(m)=Vso
      L=0
      DO 600 i=m, Nx
        IF(L .NE.0) GO TO 510
C
C   For drying region
C
        IF (J .EQ. 0) THEN
          Am1(i)=AMo1
        ELSE
          AM1(i)=AM2(i)
        ENDIF
        Dx(i)=Dxx(AM1(i))
        IF (i .EQ. 1) THEN
          X(i)=Dx(i)/2
        ELSE
          X(i)=X(i-1)+Dx(i-1)/2+Dx(i)/2
        ENDIF
C
C   To define transition variables
C
        AMe5=AMe(Ts(i))
        A5=A(Ts(i), Vs(i))
        AK5=AK(Ts(i), Vs(i))
        AN5=AN(Ts(i))
        Ps5=Ps(Ts(i))
        P5=P(AM1(i))
        Dt5=Dt*60
C
C   Derivation
C
        AMmax=A5*(AMo-AMe5)/EXP((AN5-1)/AN5)+AMe5
        IF (AM1(i) .GE. AMmax) THEN
          AM2(i)=AM1(i)-Dt5*AK5*AN5*(AMmax-AMe5)*(ALOG(A5*
+          (AMo-AMe5)/(AMmax-AMe5))/AK5)**((AN5-1)/AN5)/60
        ELSE
          AM2(i)=AM1(i)-Dt5*AK5*AN5*(AM1(i)-AMe5)*(ALOG(A5*
+          (AMo-AMe5)/(AM1(i)-AMe5))/AK5)**((AN5-1)/AN5)/60
        ENDIF
        DR=(AM2(i)-AM1(i))/Dt5
C
        IF (AM1(i) .GE. AMo) THEN
          T(i)=100
          DerT=0
        ELSE
          T(i)=Tso-(Tso-100)*(AM1(i)-AMeo)/(AMo-AMeo)
          DerT=-(Tso-100)/(AMo-AMeo)*DR
        ENDIF
C

```

```

      Gs(i)=Vs(i)*Ps5
      Gs(i+1)=Gs(i)-Dx(i)*P5*DR
      Vs(i+1)=Gs(i+1)/Ps5
      Hv5=Hv(AM1(i), T(i))
      Ts(i+1)=Ts(i)+Dx(i)*P5*(Hv5+Cs*(Ts(i)-T(i)))/(Gs(i)*Cs)
+    *DR-Dx(i)*P5*(C+Cw*AM1(i))/(Gs(i)*Cs)*DerT
C
C   To find the first layer in wet region
C
      IF (Ts(i+1) .LE. 100) THEN
        Ts(i+1)=100
        L=i
      ENDIF
C
C   To check if the layer has been dried to equilibrium
C
      IF ((AM2(i)-AMeo) .LE. DM) THEN
        m5=i
        AM2(i)=AMeo
      ENDIF
      GO TO 520
C
C   For wet region
C
510    AM1(i)=AMo1
      AM2(i)=AMo1
      T(i)=100
      Gs(i+1)=Gs(i)
      Vs(i+1)=Vs(i)
      Ts(i+1)=100
C
      Dx(i)=Dxx(AM1(i))
      IF (i .EQ. 1) THEN
        X(i)=Dx(i)/2
      ELSE
        X(i)=X(i-1)+Dx(i-1)/2+Dx(i)/2
      ENDIF
C
520    AveM=AveM+AM1(i)
      WRITE(*, 400) i, X(i), AM1(i), T(i), Gs(i), Ts(i)
      WRITE(1, 400) i, X(i), AM1(i), T(i), Gs(i), Ts(i)

600    CONTINUE
C
C   Calculation of wet front position
      IF (L .EQ. 0) THEN
        X2=-1
        No2=-1
      ELSE
        X2=X(L)+Dx(L)/2
        No2=L+1
      ENDIF

```

```

C      AveM=AveM/Nx
      Depth=X(Nx)+Dx(Nx)/2
C
      WRITE(*, 100)
      WRITE(*, 700) J, Time, AveM, Gs(Nx+1), Ts(Nx+1), X1, No1,
+X2, No2, Depth
      WRITE(2, 700) J, Time, AveM, Gs(Nx+1), Ts(Nx+1), X1, No1,
+X2, No2, Depth
700   FORMAT(I4, 2X, F7.3, 2X, F6.4, 2X, F6.4, 2X, F7.3,
+2X, F7.4, 2X, I3, 2X, F7.4, 2X, I3, 2X, F7.4)
C
      J=J+1
      Time=Time+Dt
      m=m5+1
      GO TO 200
C
800   PRINT*, ' '
      PRINT*, 'The drying time was up to the specified time.'
      PRINT*, 'The drying simulation was stopped.'
      PRINT*, 'The sample was not dried to equilibrium.'
      WRITE(1,*) ' '
      WRITE(1,*) 'The drying time was up to the specified time.'
      WRITE(1,*) 'The drying simulation was stopped.'
      WRITE(1,*) 'The sample was not dried to equilibrium.'
      WRITE(2,*) ' '
      WRITE(2,*) 'The drying time was up to the specified time.'
      WRITE(2,*) 'The drying simulation was stopped.'
      WRITE(2,*) 'The sample was not dried to equilibrium.'
      GO TO 910
C
900   No2=-1
      X2=-1
      AveM=AveM/Nx
      WRITE(*, 100)
      WRITE(*, 700) J, Time, AveM, Gs(Nx+1), Ts(Nx+1), X1, No1,
+X2, No2, Depth
      WRITE(2, 700) J, Time, AveM, Gs(Nx+1), Ts(Nx+1), X1, No1,
+X2, No2, Depth
C
      PRINT*, ' '
      PRINT*, 'The sample was dried to equilibrium.'
      PRINT*, 'The drying simulation was stopped.'
      WRITE(1,*) ' '
      WRITE(1,*) 'The sample was dried to equilibrium.'
      WRITE(1,*) 'The drying simulation was stopped.'
      WRITE(2,*) ' '
      WRITE(2,*) 'The sample was dried to equilibrium.'
      WRITE(2,*) 'The drying simulation was stopped.'
C
910   CLOSE(1)
      CLOSE(2)

```

```

      END
C
C *****
C
C EXTERNAL FUNCTION FOR LATENT HEAT OF EVAPORATION
C
      FUNCTION Hv(AM, T)
      Hfg=2257000-2916.7*(T-100)
      IF (AM .GE. 0.2) THEN
        Hv=Hfg
      ELSE
        Hv=Hfg*(1+EXP(-19.9*AM))
      ENDIF
      RETURN
      END
C
C EXTERNAL FUNCTION FOR BULK DENSITY
C
      FUNCTION P(AM)
      COMMON AMo /DENS/ Pmo, Pme
      IF (AM .GE. AMo) THEN
        P=Pmo
      ELSE IF (AM .LT. 0.11) THEN
        P=Pme
      ELSE
        P=Pmo-(Pmo-Pme)*(AMo-AM)/(AMo-0.11)
      ENDIF
      RETURN
      END
C
C EXTERNAL FUNCTION FOR LAYER THICKNESS
C
      FUNCTION Dxx(AM)
      COMMON AMo /THICK/ Dxo, Dxe
      IF (AM .GE. AMo) THEN
        Dxx=Dxo
      ELSE IF (AM .LT. 0.11) THEN
        Dxx=Dxe
      ELSE
        Dxx=Dxo-(Dxo-Dxe)*(AMo-AM)/(AMo-0.11)
      ENDIF
      RETURN
      END
C
C *****

```

Appendix C.3 An example of "File1" recording detailed simulating results for drying fixed-bed BSG in the steam of 140.8°C and 0.19 kg/(m² · s)

Mass of sample: 49.9800 g
 Initial moisture content: 3.82000 kg/ kg
 Depth of sample bed: 30.0000 mm
 Number of layers in sample bed: 20
 Steam temperature at inlet: 140.780°C
 Steam flow rate at inlet: 0.194300 kg/(m² · s)
 Expected drying time: 80.0000 min
 Time interval: 0.200000 min

Time interval: 0 Drying time: 0. min

I	X(i)	M(i)	T(i)	Gs(i)	Ts(i)
1	0.0008	4.5083	100.000	0.194	140.780
2	0.0022	4.5083	100.000	0.201	131.230
3	0.0038	4.5083	100.000	0.207	123.782
4	0.0053	4.5083	100.000	0.211	117.913
5	0.0068	4.5083	100.000	0.215	113.257
6	0.0083	4.5083	100.000	0.217	109.548
7	0.0098	4.5083	100.000	0.220	106.588
8	0.0112	4.5083	100.000	0.221	104.227
9	0.0127	4.5083	100.000	0.223	102.346
10	0.0142	4.5083	100.000	0.224	100.855
11	0.0157	4.5083	100.000	0.224	100.000
12	0.0172	4.5083	100.000	0.224	100.000
13	0.0187	4.5083	100.000	0.224	100.000
14	0.0202	4.5083	100.000	0.224	100.000
15	0.0217	4.5083	100.000	0.224	100.000
16	0.0232	4.5083	100.000	0.224	100.000
17	0.0247	4.5083	100.000	0.224	100.000
18	0.0262	4.5083	100.000	0.224	100.000
19	0.0277	4.5083	100.000	0.224	100.000
20	0.0292	4.5083	100.000	0.224	100.000

Time interval: 1 Drying time: 0.200000 min

I	X(i)	M(i)	T(i)	Gs(i)	Ts(i)
1	0.0008	4.3827	100.000	0.194	140.780
2	0.0022	4.4060	100.000	0.201	131.230
3	0.0038	4.4250	100.000	0.207	123.782
4	0.0053	4.4405	100.000	0.211	117.913
5	0.0068	4.4532	100.000	0.215	113.257

6	0.0083	4.4636	100.000	0.217	109.548
7	0.0098	4.4722	100.000	0.220	106.588
8	0.0112	4.4792	100.000	0.221	104.227
9	0.0127	4.4851	100.000	0.223	102.346
10	0.0142	4.4900	100.000	0.224	100.855
11	0.0157	4.5083	100.000	0.224	100.000
12	0.0172	4.5083	100.000	0.224	100.000
13	0.0187	4.5083	100.000	0.224	100.000
14	0.0202	4.5083	100.000	0.224	100.000
15	0.0217	4.5083	100.000	0.224	100.000
16	0.0232	4.5083	100.000	0.224	100.000
17	0.0247	4.5083	100.000	0.224	100.000
18	0.0262	4.5083	100.000	0.224	100.000
19	0.0277	4.5083	100.000	0.224	100.000
20	0.0292	4.5083	100.000	0.224	100.000

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Time interval: 151 Drying time: 30.2000 min

I	X(i)	M(i)	T(i)	Gs(i)	Ts(i)
1	0.0007	0.0134	140.777	0.194	140.780
2	0.0020	0.0137	140.775	0.194	140.777
3	0.0033	0.0141	140.771	0.194	140.773
4	0.0046	0.0147	140.764	0.194	140.764
5	0.0059	0.0158	140.752	0.194	140.750
6	0.0072	0.0176	140.732	0.194	140.727
7	0.0085	0.0207	140.700	0.194	140.688
8	0.0098	0.0256	140.647	0.194	140.625
9	0.0111	0.0336	140.561	0.194	140.527
10	0.0124	0.0464	140.424	0.195	140.379
11	0.0137	0.0751	140.117	0.195	140.160
12	0.0150	0.1176	139.661	0.195	139.814
13	0.0163	0.1837	138.953	0.195	139.310
14	0.0176	0.2819	137.901	0.196	138.569
15	0.0189	0.4309	136.305	0.197	137.485
16	0.0202	0.6394	134.071	0.198	135.896
17	0.0215	0.9238	131.025	0.199	133.687
18	0.0229	1.2848	127.158	0.202	130.770
19	0.0243	1.7020	122.689	0.204	127.166
20	0.0257	2.1652	117.727	0.207	123.056

Time interval: 152 Drying time: 30.4000 min

I	X(i)	M(i)	T(i)	Gs(i)	Ts(i)
1	0.0007	0.0134	140.777	0.194	140.780
2	0.0020	0.0136	140.775	0.194	140.778
3	0.0033	0.0140	140.771	0.194	140.773
4	0.0046	0.0146	140.765	0.194	140.766
5	0.0059	0.0156	140.754	0.194	140.753
6	0.0072	0.0173	140.736	0.194	140.731
7	0.0085	0.0201	140.706	0.194	140.694
8	0.0098	0.0247	140.656	0.194	140.636
9	0.0111	0.0322	140.576	0.194	140.544
10	0.0124	0.0442	140.448	0.195	140.404
11	0.0137	0.0711	140.160	0.195	140.196
12	0.0150	0.1110	139.732	0.195	139.867
13	0.0163	0.1734	139.063	0.195	139.386
14	0.0176	0.2665	138.066	0.196	138.683
15	0.0189	0.4083	136.547	0.197	137.653
16	0.0202	0.6081	134.407	0.198	136.138
17	0.0215	0.8826	131.467	0.199	134.016
18	0.0229	1.2340	127.702	0.201	131.192
19	0.0243	1.6442	123.307	0.204	127.670
20	0.0257	2.1042	118.380	0.207	123.613

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Time interval: 304 Drying time: 60.8002 min

I	X(i)	M(i)	T(i)	Gs(i)	Ts(i)
1	0.0007	0.0132	140.780	0.194	140.780
2	0.0020	0.0132	140.780	0.194	140.780
3	0.0033	0.0132	140.780	0.194	140.780
4	0.0046	0.0132	140.780	0.194	140.780
5	0.0059	0.0132	140.780	0.194	140.780
6	0.0072	0.0132	140.780	0.194	140.780
7	0.0085	0.0132	140.780	0.194	140.780
8	0.0098	0.0132	140.780	0.194	140.780
9	0.0111	0.0132	140.780	0.194	140.780
10	0.0124	0.0132	140.780	0.194	140.780
11	0.0137	0.0132	140.780	0.194	140.780
12	0.0150	0.0132	140.780	0.194	140.780
13	0.0163	0.0132	140.780	0.194	140.780
14	0.0176	0.0132	140.780	0.194	140.780

15	0.0189	0.0132	140.780	0.194	140.780
16	0.0202	0.0132	140.780	0.194	140.780
17	0.0215	0.0132	140.780	0.194	140.780
18	0.0228	0.0132	140.780	0.194	140.780
19	0.0241	0.0132	140.780	0.194	140.780
20	0.0254	0.0133	140.779	0.194	140.780

Time interval: 305 Drying time: 61.0002 min

I	X(i)	M(i)	T(i)	Gs(i)	Ts(i)
1	0.0007	0.0132	140.780	0.194	140.780
2	0.0020	0.0132	140.780	0.194	140.780
3	0.0033	0.0132	140.780	0.194	140.780
4	0.0046	0.0132	140.780	0.194	140.780
5	0.0059	0.0132	140.780	0.194	140.780
6	0.0072	0.0132	140.780	0.194	140.780
7	0.0085	0.0132	140.780	0.194	140.780
8	0.0098	0.0132	140.780	0.194	140.780
9	0.0111	0.0132	140.780	0.194	140.780
10	0.0124	0.0132	140.780	0.194	140.780
11	0.0137	0.0132	140.780	0.194	140.780
12	0.0150	0.0132	140.780	0.194	140.780
13	0.0163	0.0132	140.780	0.194	140.780
14	0.0176	0.0132	140.780	0.194	140.780
15	0.0189	0.0132	140.780	0.194	140.780
16	0.0202	0.0132	140.780	0.194	140.780
17	0.0215	0.0132	140.780	0.194	140.780
18	0.0228	0.0132	140.780	0.194	140.780
19	0.0241	0.0132	140.780	0.194	140.780
20	0.0254	0.0132	140.780	0.194	140.780

The sample was dried to equilibrium.
The drying simulation was stopped.

Appendix C.4 An example of "File2" recording some simulating results for drying fixed-bed BSG in the steam of 140.8°C and 0.19 kg/(m² · s)¹

Mass of sample: 49.9800 g
 Initial moisture content: 3.82000 kg/ kg
 Depth of sample bed: 30.0000 mm
 Number of layers in sample bed: 20
 Steam temperature at inlet: 140.780°C
 Steam flow rate at inlet: 0.194300 kg/(m² · s)
 Expected drying time: 80.0000 min
 Time interval: 0.200000 min

J	T(min)	M(db)	Gs	Ts(C)	Front1	L1	Front2	L2	Depth
0	0.000	4.5083	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
1	0.200	4.4790	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
2	0.400	4.4497	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
3	0.600	4.4204	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
4	0.800	4.3911	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
5	1.000	4.3618	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
6	1.200	4.3325	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
7	1.400	4.3037	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
8	1.600	4.2751	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
9	1.800	4.2466	0.2242	100.000	-1.0000	-1	0.0150	11	0.0300
10	2.000	4.2182	0.2242	100.000	-1.0000	-1	0.0149	11	0.0299
11	2.200	4.1898	0.2242	100.000	-1.0000	-1	0.0149	11	0.0299
12	2.400	4.1616	0.2241	100.000	-1.0000	-1	0.0149	11	0.0299
13	2.600	4.1333	0.2241	100.000	-1.0000	-1	0.0149	11	0.0299
14	2.800	4.1052	0.2241	100.000	-1.0000	-1	0.0149	11	0.0299
15	3.000	4.0770	0.2240	100.000	-1.0000	-1	0.0148	11	0.0298
16	3.200	4.0488	0.2240	100.000	-1.0000	-1	0.0148	11	0.0298
17	3.400	4.0207	0.2240	100.000	-1.0000	-1	0.0148	11	0.0298
18	3.600	3.9926	0.2239	100.000	-1.0000	-1	0.0148	11	0.0298
19	3.800	3.9644	0.2238	100.000	-1.0000	-1	0.0147	11	0.0297
20	4.000	3.9363	0.2238	100.000	-1.0000	-1	0.0147	11	0.0297
21	4.200	3.9083	0.2246	100.000	-1.0000	-1	0.0162	12	0.0297
22	4.400	3.8796	0.2245	100.000	-1.0000	-1	0.0162	12	0.0297
23	4.600	3.8508	0.2244	100.000	-1.0000	-1	0.0161	12	0.0296
24	4.800	3.8221	0.2244	100.000	-1.0000	-1	0.0161	12	0.0296
25	5.000	3.7934	0.2243	100.000	-1.0000	-1	0.0161	12	0.0296

¹ The negative value (-1.0000 or -1) in the data file means the data is not available for the front position or layer number.

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81	16.200	2.1537	0.2242	100.000	-1.0000	-1	0.0251	19	0.0281
82	16.400	2.1245	0.2241	100.000	-1.0000	-1	0.0250	19	0.0280
83	16.600	2.0955	0.2248	100.000	-1.0000	-1	0.0265	20	0.0280
84	16.800	2.0657	0.2247	100.000	-1.0000	-1	0.0265	20	0.0280
85	17.000	2.0361	0.2246	100.000	-1.0000	-1	0.0265	20	0.0280
86	17.200	2.0065	0.2245	100.000	-1.0000	-1	0.0264	20	0.0279
87	17.400	1.9770	0.2243	100.000	-1.0000	-1	0.0264	20	0.0279
88	17.600	1.9476	0.2242	100.000	-1.0000	-1	0.0264	20	0.0279
89	17.800	1.9183	0.2241	100.000	-1.0000	-1	0.0264	20	0.0279
90	18.000	1.8892	0.2240	100.000	-1.0000	-1	0.0263	20	0.0278
91	18.200	1.8602	0.2248	100.000	-1.0000	-1	0.0278	21	0.0278
92	18.400	1.8306	0.2247	100.000	-1.0000	-1	0.0278	21	0.0278
93	18.600	1.8010	0.2245	100.000	-1.0000	-1	0.0278	21	0.0278
94	18.800	1.7715	0.2244	100.000	-1.0000	-1	0.0277	21	0.0277
95	19.000	1.7421	0.2243	100.000	-1.0000	-1	0.0277	21	0.0277
96	19.200	1.7128	0.2242	100.000	-1.0000	-1	0.0277	21	0.0277
97	19.400	1.6837	0.2241	100.000	-1.0000	-1	0.0276	21	0.0276
98	19.600	1.6546	0.2239	100.000	-1.0000	-1	0.0276	21	0.0276
99	19.800	1.6257	0.2238	100.129	-1.0000	-1	-1.0000	-1	0.0276
100	20.000	1.5969	0.2236	100.295	-1.0000	-1	-1.0000	-1	0.0276
101	20.200	1.5682	0.2235	100.467	-1.0000	-1	-1.0000	-1	0.0275
102	20.400	1.5396	0.2233	100.644	-1.0000	-1	-1.0000	-1	0.0275
103	20.600	1.5112	0.2232	100.828	-1.0000	-1	-1.0000	-1	0.0275
104	20.800	1.4828	0.2231	100.890	-1.0000	-1	-1.0000	-1	0.0275
105	21.000	1.4547	0.2229	101.081	-1.0000	-1	-1.0000	-1	0.0274

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155	31.000	0.3420	0.2064	120.985	-1.0000	-1	-1.0000	-1	0.0263
156	31.200	0.3283	0.2060	121.555	-1.0000	-1	-1.0000	-1	0.0263
157	31.400	0.3149	0.2056	122.122	-1.0000	-1	-1.0000	-1	0.0263
158	31.600	0.3020	0.2053	122.678	-1.0000	-1	-1.0000	-1	0.0263
159	31.800	0.2894	0.2049	123.238	-1.0000	-1	-1.0000	-1	0.0263
160	32.000	0.2772	0.2045	123.794	-1.0000	-1	-1.0000	-1	0.0262
161	32.200	0.2655	0.2041	124.345	-1.0000	-1	-1.0000	-1	0.0262
162	32.400	0.2541	0.2038	124.890	-1.0000	-1	-1.0000	-1	0.0262
163	32.600	0.2431	0.2034	125.431	0.0013	1	-1.0000	-1	0.0262

164	32.800	0.2324	0.2030	125.963	0.0013	1	-1.0000	-1	0.0262
165	33.000	0.2222	0.2027	126.479	0.0013	1	-1.0000	-1	0.0262
166	33.200	0.2123	0.2024	126.994	0.0013	1	-1.0000	-1	0.0262
167	33.400	0.2027	0.2020	127.501	0.0013	1	-1.0000	-1	0.0262
168	33.600	0.1936	0.2017	127.999	0.0013	1	-1.0000	-1	0.0262
169	33.800	0.1847	0.2014	128.488	0.0013	1	-1.0000	-1	0.0262
170	34.000	0.1763	0.2011	128.966	0.0013	1	-1.0000	-1	0.0261
171	34.200	0.1681	0.2008	129.435	0.0026	2	-1.0000	-1	0.0261
172	34.400	0.1603	0.2005	129.893	0.0026	2	-1.0000	-1	0.0261
173	34.600	0.1528	0.2003	130.327	0.0026	2	-1.0000	-1	0.0261
174	34.800	0.1456	0.2000	130.760	0.0026	2	-1.0000	-1	0.0261
175	35.000	0.1387	0.1997	131.182	0.0026	2	-1.0000	-1	0.0261
176	35.200	0.1322	0.1995	131.592	0.0026	2	-1.0000	-1	0.0261
177	35.400	0.1259	0.1992	131.990	0.0026	2	-1.0000	-1	0.0261
178	35.600	0.1198	0.1990	132.377	0.0039	3	-1.0000	-1	0.0261
179	35.800	0.1141	0.1988	132.752	0.0039	3	-1.0000	-1	0.0261
180	36.000	0.1086	0.1986	133.115	0.0039	3	-1.0000	-1	0.0261

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291	58.200	0.0132	0.1943	140.776	0.0234	18	-1.0000	-1	0.0260
292	58.400	0.0132	0.1943	140.776	0.0234	18	-1.0000	-1	0.0260
293	58.600	0.0132	0.1943	140.776	0.0234	18	-1.0000	-1	0.0260
294	58.800	0.0132	0.1943	140.777	0.0234	18	-1.0000	-1	0.0260
295	59.000	0.0132	0.1943	140.777	0.0234	18	-1.0000	-1	0.0260
296	59.200	0.0132	0.1943	140.777	0.0234	18	-1.0000	-1	0.0260
297	59.400	0.0132	0.1943	140.778	0.0247	19	-1.0000	-1	0.0260
298	59.600	0.0132	0.1943	140.778	0.0247	19	-1.0000	-1	0.0260
299	59.800	0.0132	0.1943	140.779	0.0247	19	-1.0000	-1	0.0260
300	60.000	0.0132	0.1943	140.779	0.0247	19	-1.0000	-1	0.0260
301	60.200	0.0132	0.1943	140.779	0.0247	19	-1.0000	-1	0.0260
302	60.400	0.0132	0.1943	140.779	0.0247	19	-1.0000	-1	0.0260
303	60.600	0.0132	0.1943	140.779	0.0247	19	-1.0000	-1	0.0260
304	60.800	0.0132	0.1943	140.779	0.0247	19	-1.0000	-1	0.0260
305	61.000	0.0132	0.1943	140.779	0.0260	20	-1.0000	-1	0.0260

The sample was dried to equilibrium.

The drying simulation was stopped.

Appendix C.5

Table C.1 Experimental data for determining the percentage of drying medium passing through the BSG sample in the fixed bed of 30 mm

No. ^[a]	Run 1			Run 2			Run 3		
	v_1 ^[b]	v_2 ^[c]	v_1 / v_2 (%)	v_1	v_2	v_1 / v_2 (%)	v_1	v_2	v_1 / v_2 (%)
1	0.62	0.83	74.7	0.65	0.83	78.31	0.65	0.93	69.89
2	0.6	0.86	69.77	0.67	0.92	72.82	0.57	0.75	76
3	0.6	0.82	73.17	0.6	0.76	78.95	0.6	0.76	78.95
4	0.65	0.85	76.47	0.59	0.77	76.62	0.47	0.61	77.05
5	0.65	0.85	76.47	0.55	0.72	76.39	0.42	0.62	67.74
6	0.29	0.37	78.38	0.5	0.68	73.53	0.3	0.45	66.67
7	0.25	0.39	64.1	0.4	0.54	74.07	0.38	0.53	71.7
8	0.3	0.39	76.92	0.64	0.83	77.1			
9				0.8	1.02	78.43			
10				0.68	0.9	75.55			
Average			73.75			76.18			72.57
Total average percentage			74.17%						

^[a] No. - The number of the measurement during the test.

^[b] v_1 - Air velocity at a selected point above the sample tray hung from the balance.

^[c] v_2 - Air velocity at the selected point above the sample tray seated on the plate.

Appendix C.6

Table C.2 Predicted results for the changes of average moisture content in fixed-bed BSG samples during superheated-steam drying

t (min) ^[a]	M (kg/kg db) ^[b]				
	120.9°C ^[c]	140.9°C	160.6°C	140.8°C	140.7°C
	0.31 kg/(m ² .s) ^[c]	0.32 kg/(m ² .s)	0.32 kg/(m ² .s)	0.19 kg/(m ² .s)	0.45 kg/(m ² .s)
0.0000	4.3449	4.1699	4.3216	4.5083	4.8468
0.2000	4.3219	4.1236	4.2504	4.4790	4.7743
0.4000	4.2988	4.0774	4.1792	4.4497	4.7018
0.6000	4.2757	4.0312	4.1080	4.4204	4.6292
0.8000	4.2526	3.9849	4.0426	4.3911	4.5567
1.0000	4.2295	3.9387	3.9756	4.3618	4.4856
1.2000	4.2065	3.8995	3.9089	4.3325	4.4240
1.4000	4.1834	3.8556	3.8424	4.3037	4.3555
1.6000	4.1603	3.8119	3.7760	4.2751	4.2870
1.8000	4.1374	3.7683	3.7096	4.2466	4.2186
2.0000	4.1146	3.7246	3.6433	4.2182	4.1487
2.2000	4.0917	3.6811	3.5756	4.1898	4.0789
2.4000	4.0690	3.6377	3.5080	4.1616	4.0092
2.6000	4.0464	3.5932	3.4401	4.1333	3.9395
2.8000	4.0237	3.5489	3.3724	4.1052	3.8699
3.0000	4.0011	3.5045	3.3035	4.0770	3.8004
3.2000	3.9785	3.4602	3.2347	4.0488	3.7297
3.4000	3.9559	3.4159	3.1659	4.0207	3.6591
3.6000	3.9334	3.3717	3.0972	3.9926	3.5888
3.8000	3.9109	3.3276	3.0276	3.9644	3.5186
4.0000	3.8885	3.2826	2.9580	3.9363	3.4473
4.2000	3.8661	3.2376	2.8886	3.9083	3.3762
4.4000	3.8438	3.1928	2.8183	3.8796	3.3053
4.6000	3.8215	3.1481	2.7483	3.8508	3.2334
4.8000	3.7993	3.1035	2.6784	3.8221	3.1617
5.0000	3.7762	3.0580	2.6077	3.7934	3.0902
5.2000	3.7532	3.0128	2.5372	3.7647	3.0178
5.4000	3.7302	2.9676	2.4668	3.7361	2.9455
5.6000	3.7073	2.9225	2.3956	3.7075	2.8737
5.8000	3.6844	2.8776	2.3246	3.6790	2.8023
6.0000	3.6616	2.8319	2.2540	3.6505	2.7297
6.2000	3.6388	2.7863	2.1837	3.6222	2.6576
6.4000	3.6161	2.7408	2.1138	3.5931	2.5857
6.6000	3.5935	2.6955	2.0443	3.5640	2.5130
6.8000	3.5710	2.6494	1.9753	3.5350	2.4406

^[a] t - Drying time.

^[b] M - Average moisture content.

^[c] Drying conditions: average steam temperature and steam flow rate.

7.0000	3.5486	2.6035	1.9069	3.5060	2.3686
7.2000	3.5262	2.5578	1.8389	3.4771	2.2970
7.4000	3.5030	2.5122	1.7717	3.4483	2.2260
7.6000	3.4799	2.4660	1.7051	3.4196	2.1555
7.8000	3.4568	2.4198	1.6391	3.3909	2.0855
8.0000	3.4338	2.3738	1.5739	3.3616	2.0163
8.2000	3.4109	2.3281	1.5094	3.3323	1.9476
8.4000	3.3881	2.2826	1.4457	3.3030	1.8796
8.6000	3.3654	2.2363	1.3829	3.2738	1.8123
8.8000	3.3428	2.1902	1.3210	3.2447	1.7458
9.0000	3.3202	2.1443	1.2600	3.2157	1.6800
9.2000	3.2969	2.0986	1.2000	3.1861	1.6151
9.4000	3.2735	2.0522	1.1411	3.1564	1.5510
9.6000	3.2503	2.0060	1.0832	3.1269	1.4878
9.8000	3.2272	1.9600	1.0265	3.0974	1.4256
10.0000	3.2041	1.9142	0.9711	3.0680	1.3643
10.2000	3.1812	1.8687	0.9169	3.0386	1.3041
10.4000	3.1583	1.8234	0.8641	3.0094	1.2449
10.6000	3.1356	1.7784	0.8127	2.9804	1.1868
10.8000	3.1130	1.7336	0.7628	2.9506	1.1300
11.0000	3.0895	1.6893	0.7144	2.9209	1.0744
11.2000	3.0661	1.6451	0.6677	2.8913	1.0200
11.4000	3.0428	1.6013	0.6226	2.8618	0.9670
11.6000	3.0195	1.5578	0.5792	2.8323	0.9154
11.8000	2.9964	1.5147	0.5376	2.8029	0.8652
12.0000	2.9734	1.4720	0.4978	2.7738	0.8165
12.2000	2.9504	1.4296	0.4599	2.7439	0.7694
12.4000	2.9276	1.3876	0.4238	2.7142	0.7238
12.6000	2.9049	1.3459	0.3896	2.6845	0.6798
12.8000	2.8814	1.3047	0.3572	2.6548	0.6374
13.0000	2.8579	1.2639	0.3268	2.6253	0.5967
13.2000	2.8345	1.2236	0.2982	2.5959	0.5577
13.4000	2.8113	1.1837	0.2715	2.5666	0.5203
13.6000	2.7881	1.1443	0.2466	2.5374	0.4847
13.8000	2.7650	1.1054	0.2235	2.5076	0.4508
14.0000	2.7420	1.0669	0.2021	2.4779	0.4185
14.2000	2.7191	1.0291	0.1823	2.4482	0.3880
14.4000	2.6963	0.9917	0.1642	2.4187	0.3591
14.6000	2.6728	0.9549	0.1476	2.3892	0.3319
14.8000	2.6493	0.9188	0.1324	2.3598	0.3063
15.0000	2.6259	0.8832	0.1186	2.3306	0.2822
15.2000	2.6025	0.8483	0.1061	2.3016	0.2597
15.4000	2.5793	0.8140	0.0948	2.2718	0.2387
15.6000	2.5562	0.7804	0.0846	2.2422	0.2191
15.8000	2.5331	0.7475	0.0755	2.2126	0.2009
16.0000	2.5102	0.7154	0.0673	2.1831	0.1841
16.2000	2.4874	0.6839	0.0600	2.1537	0.1685
16.4000	2.4647	0.6532	0.0535	2.1245	0.1541
16.6000	2.4412	0.6233	0.0477	2.0955	0.1408
16.8000	2.4177	0.5942	0.0426	2.0657	0.1286

17.0000	2.3944	0.5658	0.0381	2.0361	0.1174
17.2000	2.3711	0.5383	0.0341	2.0065	0.1072
17.4000	2.3479	0.5116	0.0306	1.9770	0.0978
17.6000	2.3249	0.4858	0.0275	1.9476	0.0893
17.8000	2.3019	0.4607	0.0248	1.9183	0.0816
18.0000	2.2791	0.4366	0.0225	1.8892	0.0745
18.2000	2.2563	0.4133	0.0204	1.8602	0.0681
18.4000	2.2328	0.3908	0.0186	1.8306	0.0624
18.6000	2.2093	0.3692	0.0171	1.8010	0.0571
18.8000	2.1860	0.3484	0.0158	1.7715	0.0524
19.0000	2.1627	0.3285	0.0146	1.7421	0.0482
19.2000	2.1395	0.3095	0.0136	1.7128	0.0444
19.4000	2.1164	0.2912	0.0127	1.6837	0.0409
19.6000	2.0935	0.2738	0.0120	1.6546	0.0379
19.8000	2.0706	0.2573	0.0113	1.6257	0.0351
20.0000	2.0478	0.2415	0.0108	1.5969	0.0326
20.2000	2.0243	0.2265	0.0103	1.5682	0.0304
20.4000	2.0009	0.2122	0.0099	1.5396	0.0284
20.6000	1.9775	0.1988	0.0096	1.5112	0.0267
20.8000	1.9542	0.1860	0.0093	1.4828	0.0251
21.0000	1.9310	0.1740	0.0090	1.4547	0.0237
21.2000	1.9079	0.1626	0.0088	1.4267	0.0225
21.4000	1.8850	0.1519	0.0086	1.3988	0.0214
21.6000	1.8621	0.1418	0.0085	1.3711	0.0204
21.8000	1.8393	0.1324	0.0083	1.3435	0.0196
22.0000	1.8167	0.1235	0.0082	1.3161	0.0188
22.2000	1.7932	0.1152	0.0081	1.2888	0.0181
22.4000	1.7699	0.1074	0.0081	1.2617	0.0175
22.6000	1.7466	0.1002	0.0080	1.2348	0.0170
22.8000	1.7234	0.0934	0.0079	1.2081	0.0165
23.0000	1.7003	0.0871	0.0079	1.1816	0.0161
23.2000	1.6773	0.0812	0.0078	1.1552	0.0157
23.4000	1.6544	0.0758	0.0078	1.1290	0.0154
23.6000	1.6317	0.0707	0.0078	1.1031	0.0151
23.8000	1.6090	0.0660	0.0078	1.0773	0.0149
24.0000	1.5856	0.0617	0.0077	1.0517	0.0147
24.2000	1.5622	0.0576	0.0077	1.0264	0.0145
24.4000	1.5389	0.0539	0.0077	1.0013	0.0143
24.6000	1.5157	0.0505	0.0077	0.9764	0.0142
24.8000	1.4926	0.0473	0.0077	0.9517	0.0141
25.0000	1.4696	0.0444	0.0077	0.9273	0.0139
25.2000	1.4467	0.0417		0.9032	
25.4000	1.4239	0.0392		0.8793	
25.6000	1.4012	0.0369		0.8556	
25.8000	1.3787	0.0348		0.8323	
26.0000	1.3562	0.0329		0.8092	
26.2000	1.3339	0.0312		0.7864	
26.4000	1.3117	0.0295		0.7639	
26.6000	1.2896	0.0281		0.7417	
26.8000	1.2677	0.0267		0.7198	
27.0000	1.2459	0.0255		0.6983	

27.2000	1.2242	0.0243	0.6770
27.4000	1.2026	0.0233	0.6561
27.6000	1.1812	0.0224	0.6355
27.8000	1.1600	0.0215	0.6153
28.0000	1.1388	0.0207	0.5954
28.2000	1.1179	0.0200	0.5758
28.4000	1.0970	0.0194	0.5566
28.6000	1.0764	0.0188	0.5378
28.8000	1.0558	0.0182	0.5194
29.0000	1.0355	0.0177	0.5013
29.2000	1.0153	0.0173	0.4836
29.4000	0.9952	0.0169	0.4663
29.6000	0.9754	0.0165	0.4494
29.8000	0.9557	0.0162	0.4329
30.0000	0.9362	0.0159	0.4167
30.2000	0.9168	0.0156	0.4010
30.4000	0.8977	0.0154	0.3857
30.6000	0.8787	0.0151	0.3707
30.8000	0.8599	0.0149	0.3562
31.0000	0.8413	0.0148	0.3420
31.2000	0.8229	0.0146	0.3283
31.4000	0.8048	0.0145	0.3149
31.6000	0.7868	0.0143	0.3020
31.8000	0.7690	0.0142	0.2894
32.0000	0.7515	0.0141	0.2772
32.2000	0.7341	0.0140	0.2655
32.4000	0.7170	0.0139	0.2541
32.6000	0.7001	0.0138	0.2431
32.8000	0.6834	0.0138	0.2324
33.0000	0.6670	0.0137	0.2222
33.2000	0.6507	0.0136	0.2123
33.4000	0.6347	0.0136	0.2027
33.6000	0.6190	0.0135	0.1936
33.8000	0.6035	0.0135	0.1847
34.0000	0.5882	0.0135	0.1763
34.2000	0.5732	0.0134	0.1681
34.4000	0.5584	0.0134	0.1603
34.6000	0.5438	0.0134	0.1528
34.8000	0.5295	0.0133	0.1456
35.0000	0.5155	0.0133	0.1387
35.2000	0.5017		0.1322
35.4000	0.4881		0.1259
35.6000	0.4748		0.1198
35.8000	0.4618		0.1141
36.0000	0.4490		0.1086
36.2000	0.4364		0.1034
36.4000	0.4241		0.0984
36.6000	0.4121		0.0937
36.8000	0.4003		0.0892
37.0000	0.3888		0.0849
37.2000	0.3775		0.0808

37.4000	0.3664	0.0769
37.6000	0.3557	0.0733
37.8000	0.3451	0.0698
38.0000	0.3348	0.0665
38.2000	0.3248	0.0633
38.4000	0.3150	0.0604
38.6000	0.3054	0.0576
38.8000	0.2961	0.0549
39.0000	0.2870	0.0524
39.2000	0.2782	0.0500
39.4000	0.2696	0.0478
39.6000	0.2612	0.0456
39.8000	0.2531	0.0436
40.0000	0.2451	0.0418
40.2000	0.2374	0.0400
40.4000	0.2299	0.0383
40.6000	0.2227	0.0367
40.8000	0.2156	0.0352
41.0000	0.2088	0.0338
41.2000	0.2021	0.0325
41.4000	0.1957	0.0313
41.6000	0.1894	0.0301
41.8000	0.1834	0.0290
42.0000	0.1775	0.0280
42.2000	0.1718	0.0270
42.4000	0.1663	0.0261
42.6000	0.1610	0.0253
42.8000	0.1558	0.0245
43.0000	0.1509	0.0237
43.2000	0.1461	0.0230
43.4000	0.1414	0.0224
43.6000	0.1369	0.0218
43.8000	0.1326	0.0212
44.0000	0.1284	0.0206
44.2000	0.1244	0.0201
44.4000	0.1205	0.0197
44.6000	0.1167	0.0192
44.8000	0.1131	0.0188
45.0000	0.1096	0.0184
45.2000	0.1063	0.0181
45.4000	0.1030	0.0177
45.6000	0.0999	0.0174
45.8000	0.0969	0.0171
46.0000	0.0940	0.0168
46.2000	0.0913	0.0166
46.4000	0.0886	0.0163
46.6000	0.0860	0.0161
46.8000	0.0836	0.0159
47.0000	0.0812	0.0157
47.2000	0.0789	0.0155
47.4000	0.0767	0.0154

47.6000	0.0746	0.0152
47.8000	0.0726	0.0151
48.0000	0.0707	0.0149
48.2000	0.0688	0.0148
48.4000	0.0670	0.0147
48.6000	0.0653	0.0146
48.8000	0.0637	0.0145
49.0000	0.0621	0.0144
49.2000	0.0606	0.0143
49.4000	0.0592	0.0142
49.6000	0.0578	0.0141
49.8000	0.0565	0.0141
50.0000	0.0552	0.0140
50.2000	0.0540	
50.4000	0.0528	
50.6000	0.0517	
50.8000	0.0506	
51.0000	0.0496	
51.2000	0.0486	
51.4000	0.0477	
51.6000	0.0468	
51.8000	0.0459	
52.0000	0.0451	
52.2000	0.0444	
52.4000	0.0436	
52.6000	0.0429	
52.8000	0.0422	
53.0000	0.0416	
53.2000	0.0409	
53.4000	0.0403	
53.6000	0.0398	
53.8000	0.0392	
54.0000	0.0387	
54.2000	0.0382	
54.4000	0.0378	
54.6000	0.0373	
54.8000	0.0369	
55.0000	0.0365	
55.2000	0.0361	
55.4000	0.0357	
55.6000	0.0354	
55.8000	0.0350	
56.0000	0.0347	
56.2000	0.0344	
56.4000	0.0341	
56.6000	0.0338	
56.8000	0.0336	
57.0000	0.0333	
57.2000	0.0331	
57.4000	0.0329	
57.6000	0.0326	

57.8000	0.0324
58.0000	0.0322
58.2000	0.0320
58.4000	0.0319
58.6000	0.0317
58.8000	0.0315
59.0000	0.0314
59.2000	0.0312
59.4000	0.0311
59.6000	0.0310
59.8000	0.0308
60.0000	0.0307

Appendix C.7

Table C.3 Experimental data for the changes of average moisture content in fixed-bed BSG samples during superheated-steam drying

t (min) ^[a]	M ^[b]	t (min)	M	t (min)	M	t (min)	M	t (min)	M
120.9°C ^[c]		140.9°C		160.6°C		140.8°C		140.7°C	
0.31 kg/(m ² .s) ^[c]		0.32 kg/(m ² .s)		0.32 kg/(m ² .s)		0.19 kg/(m ² .s)		0.45 kg/(m ² .s)	
0.2164	4.3555	0.1659	4.1262	0.1952	4.2584	0.1719	4.4703	0.2092	4.6614
0.5565	4.3176	0.4423	4.0890	0.7527	4.0685	0.6302	4.4552	0.6575	4.5215
1.9169	4.1234	0.7463	4.0371	1.3382	3.8826	1.8906	4.2211	2.0023	3.9935
3.7720	3.8886	1.1333	3.9487	3.0109	3.2685	4.4974	3.7814	3.7954	3.3418
5.6271	3.6561	1.5480	3.8668	4.6558	2.7460	7.0755	3.4042	5.5885	2.7321
7.5130	3.4390	2.0455	3.7524	6.3285	2.2017	9.6536	3.0473	7.3816	2.1598
9.3372	3.2340	2.8748	3.5480	8.0291	1.6930	12.2318	2.6610	9.2046	1.6342
11.1923	3.0267	4.5333	3.1382	9.6739	1.2300	14.8099	2.3002	10.9678	1.2107
13.0473	2.8204	6.1919	2.7537	11.3467	0.8728	17.3880	1.9761	12.7609	0.8518
14.9333	2.6108	7.8504	2.4000	13.0194	0.5650	19.9661	1.6789	14.5540	0.5750
16.7575	2.3990	9.5089	2.0578	14.6921	0.3389	22.5443	1.3957	16.3770	0.3480
18.6435	2.2035	11.1675	1.7393	16.3927	0.1844	25.1224	1.1330	18.1402	0.1891
20.4676	2.0133	12.8260	1.4390	18.0376	0.0841	27.7005	0.9173	19.9333	0.0814
22.3227	1.8123	14.4846	1.1680	19.8218	0.0288	30.3073	0.7206	21.7264	0.0353
24.2705	1.6225	16.1431	0.9389	21.7176	0.0115	32.8281	0.5517	23.5195	0.0152
26.0638	1.4584	17.8016	0.7386	23.0836	0.0086	35.4063	0.3964	25.2828	0.0247
27.9498	1.2948	21.1187	0.4102	24.0315	0.0073	37.9844	0.2807		
29.7739	1.1655	22.7772	0.2846	25.5927	0.0056	40.5625	0.1933		
31.6290	1.0235	24.4358	0.1844			43.1406	0.1247		
33.4841	0.9074	26.0943	0.1012			45.8620	0.0758		
37.3488	0.6912	27.7528	0.0466			48.2969	0.0557		
39.0493	0.5944	29.4114	0.0133			50.8750	0.0386		
40.9044	0.5061	31.0699	0.0093			53.4531	0.0296		
42.7594	0.4269	32.7285	0.0033			56.0313	0.0301		
44.6145	0.3534								
46.4696	0.2978								
48.3246	0.2353								
50.1797	0.1840								
52.0348	0.1448								
54.0135	0.1148								
55.7449	0.0939								
57.6000	0.0750								
59.4551	0.0554								
61.3101	0.0493								

^[a] t - Drying time.

^[b] M - Average moisture content (kg/kg db).

^[c] Drying conditions: average steam temperature and steam flow rate.