

**INFRARED RADIATION EFFECTS
ON SOME FUNCTIONAL CHARACTERISTICS OF WHEAT FLOUR**

BY

MARIA EMILIA BOTERO URIBE

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfilment of the Requirements

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ABSTRACTS

High intensity infrared heat can affect rheological and functional properties of flour. Therefore, the main objective of this research was to investigate the potential of infrared radiation as an alternative method of improving bread-making characteristics. Canadian Western Red Spring (CWRS) flour of a 13.1 % moisture content and a protein content of 13.8%, was exposed to infrared radiation using a 500 W infrared lamp. The specific objectives were to determine the effect of three different infrared heating times (30, 60 and 105 s) on the consistency coefficient, flow behaviour index, Viscoamylograph peak, Falling Number, dough mixing characteristics, gluten content, starch damage, insoluble glutenin, baking performance and thermal transition recorded by a Differential Scanning Calorimeter.

The temperature distribution in a 6 mm layer of flour was measured at two infrared intensity levels controlled by a distance (100 and 70 mm) between the sample and the infrared lamp and by a rated voltage which was set at 120 and 60 V. Surface temperature differences of approximately 24 °C were observed at 120 s of infrared heating when the distance between the lamp and flour surface was changed from 100 to 70 mm. Surface temperature differences of 52 °C were recorded when the lamp rated voltage was reduced from 120 to 60 V.

For the rheological and functional tests, a 2 mm layer of flour was placed at 70 mm away from the lamp which was operated at 120 V and exposed to infrared radiation for 30, 60, and 105 s reaching an average layer temperature of 50.4 °C ± 1.4, 64.2 °C ± 1.8, 78.9 °C ± 1.5, respectively.

Infrared heating did not have a significant effect on the starch properties as shown by the Viscoamylograph peak, Falling Number, starch damage test, and the peak transitions of

the flour water mix in a Differential Scanning Calorimeter. The Falling Number did not change significantly even for the longest infrared exposure of the flour (105 s) in comparison to the control sample. The same trend was observed in the Viscoamylograph tests in which the control flour had a peak at 786.7 B.U. and the 105 s infrared treated flour had it at 753.3 B.U. The change in the percentage of damaged starch was also very small from 26.0 % for the control flour and 26.5 % for the flour exposed to infrared for 105 s. The water mixes at 80 % moisture content made with control flour, and the three infrared treated flours showed one well defined gelatinization peak between 57.8 and 59 °C and three more small endotherm peaks (70.5 to 72.9 °C, 77.6 to 85.1 °C and 89.5 to 94.3 °C). These peaks are more likely to correspond to the melting of more stable starch crystals, protein denaturation, and dissociation of the amylose-lipid complex, respectively.

Infrared radiation significantly affected the gluten properties as seen from the changes occurred in the dough mixing characteristics, and the decrease in flour water absorption, wet gluten content and loaf volume. The dough mixing characteristics, measured in a Farinograph and Mixograph, showed that the infrared flour became more resistant to mixing and over mixing, required longer time to develop to an optimum consistency, and would hold longer fermentation. As infrared exposure time increased the dough development time, and stability increased, and the mixing tolerance index and the dough weakening angle decreased. The development time increased almost 10 % in the infrared treated flour for 60 s, and increased further to 20% in the flour exposed to infrared for 105 s. The stability increased by 51.7, 58, and 100% for the dough made with the flour treated with infrared heat for 30, 60, and 105 s respectively. The mixing tolerance index decreased by 20 and 35 % in the infrared treated

flour for 60 and 105 s respectively. Also the dough weakening angle decreased by 1% and 48 % for the flour exposed to infrared radiation for 60 and 105 s, respectively.

Dough flow behaviour (flow behaviour index and consistency coefficient) was determined in a capillary rheometer. The dough was prepared in a pin mixer until the optimum peak was obtained and the amount of water was added according to the flour water absorption. The consistency coefficient (K) for the dough made with infrared treated flours increased from 40.5 ± 3.99 (control flour) to 55.3 ± 3.33 (105 s infrared treated flour). This increase in K is mainly due to the fact that dough water content decreased as infrared exposure time increased and the consistency coefficient is very sensitive to dough water levels. All doughs exhibited a non-Newtonian behaviour with a flow behaviour index between 0.43 and 0.46 which was not significantly affected by infrared radiation.

The flour wet gluten content was reduced from 35.7 % (control flour) to 31.6% (105 s infrared treated flour). All bread characteristics but loaf volume were noticeably increased for all the infrared treated flour.

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DEDICATION

To my family and Richard for being they way they are

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1 INTRODUCTION

Wheat is classified on the basis of its suitability for manufacturing yeast leavened bread, into two groups, strong and weak (Pomeranz 1988). Strong wheats form a gluten with good gas-retaining properties, and a dough with excellent handling properties. The potential bread making characteristics of flour made from weak wheat are poor. Weak wheat flours have a gluten with poor gas-retaining properties, and yield a dough with inferior handling qualities.

Flour is one of the most widely used intermediate products from wheat and the main ingredient in the manufacture of bread. The final properties of bread are highly influenced by the functional properties of flour which depends on factors such as wheat variety, environmental conditions for growing and storing, milling process, and the chemical properties of flour (Mailhot and Patton 1988). Flour quality or its suitability for bread making can be determined by measuring the rheological properties of dough. These properties give information about flowability of dough, mixing characteristics, flour strength, viscosity, and enzyme activity. Information about gluten content, starch damage, starch gelatinization and protein denaturation is also important. The above properties are determined from the Farinograph, Mixograph, capillary rheometer, Viscoamylograph peak, Falling Number, wet gluten content, starch damage test and thermal transitions of a flour-water mixture.

Micronization (infrared heating) transfers energy to the surface and subsurface layer of the material and has a deep effect on the molecular structure of the material (Ginzburg 1969). Good results were obtained using infrared radiation for roasting cocoa beans and nuts.

peeling apples, conditioning grains, drying alfalfa and beans (Ginzburg 1969). It was also found that infrared radiation speeded up the maturation process of freshly milled flour and improved its baking characteristics (Ginzburg 1969).

Because infrared radiation is known to affect textural and functional properties of the infrared treated material (Cenkowski and Sosulski 1997), this research was undertaken to investigate the potential of infrared radiation as an alternative method of improving flour bread-making characteristics. The specific objectives were:

- Determine the temperature distribution in a deep layer of flour and define three intensity levels of infrared treatment.
- Investigate the effect of the infrared treatments on the flow characteristics of dough (consistency coefficient and flow behaviour index), strength of the flour, mixing characteristics of dough, wet gluten content, viscosity, starch damage, amount of insoluble glutenin and baking characteristics.
- Study the effect of infrared heat on the thermal transitions (gelatinization and denaturation of protein)

2 LITERATURE REVIEW

2.1 The Electromagnetic Spectrum

Infrared rays make up part of the electromagnetic spectrum which is presented as an arrangement of the radiation bands by wavelength or frequency. Figure 2.1 shows the spectral distribution of the electromagnetic radiation. The audio frequency waves are located at the right end of the chart followed by the radio waves (long, medium, short and millimeter waves), and then the infrared region. At the high frequency end of the infrared region the visible light frequencies are followed by ultraviolet and then as the energy content increases, x rays, γ rays and cosmic rays (Vanzetti 1972). From this figure it is noted that there is a big difference in frequency, wavelength and energy content but all the radiation is similar in that it transports energy and travels with the same speed (the speed of light), obeying the laws of reflection, refraction, diffraction and polarization. Infrared radiation is not in any way fundamentally different from other kinds of electromagnetic radiation, but is an example of where the interaction with matter is dominated by thermal processes. It is common to refer to infrared radiation as the heat region of the spectrum owing to the fact that heated objects radiate energy in the infrared range.

The infrared region which extends from a wavelength of approximately 760 nm to 10^6 nm can be divided into three regions: near infrared (760 nm to 1350 nm wavelength), middle infrared (1350 nm to 40.000 nm), and the far infrared that extends up to 10^6 nm wavelength. These divisions and their upper and lower limits are arbitrary.

2.1.1 Infrared radiation

Infrared radiation can be generated either by gas-fired sources or by electric lamps. The gas-infrared lamps produce longer wavelengths varying from 3000 nm to 5000 nm, whereas those produced by electric lamps are between 1000 nm and 2500 nm.

The emitted energy from the source follows the radiation law as given by Planck (1959) and the Wien displacement law. Planck's law relates the amount of energy emitted from a black body to its temperature for any range of wavelengths. This law defines the spectral distribution of the radiant energy curve for a black-body at a particular temperature and when written in the following form determines emitted radiation from a source.

$$W_{\lambda} = \frac{C_1}{\lambda^5} \left[\exp(C_2 / \lambda T) - 1 \right] \quad (2.1)$$

Where W_{λ} = emitted radiation, W / (cm² μm)

$$C_1 = 3.74 \times 10^4 \text{ W}\mu\text{m}^4/\text{cm}^2$$

$$C_2 = 1.4388 \text{ }\mu\text{mK}$$

T = absolute temperature, K

λ = wavelength, μm

Equation 2.1 describes the rate of energy emitted at each wavelength. The summation of these energies over the wavelength gives the total energy radiated by the source (Mohsenin 1984). Planck's equation can be integrated to obtain total energy irradiated in a certain band

of the spectrum.

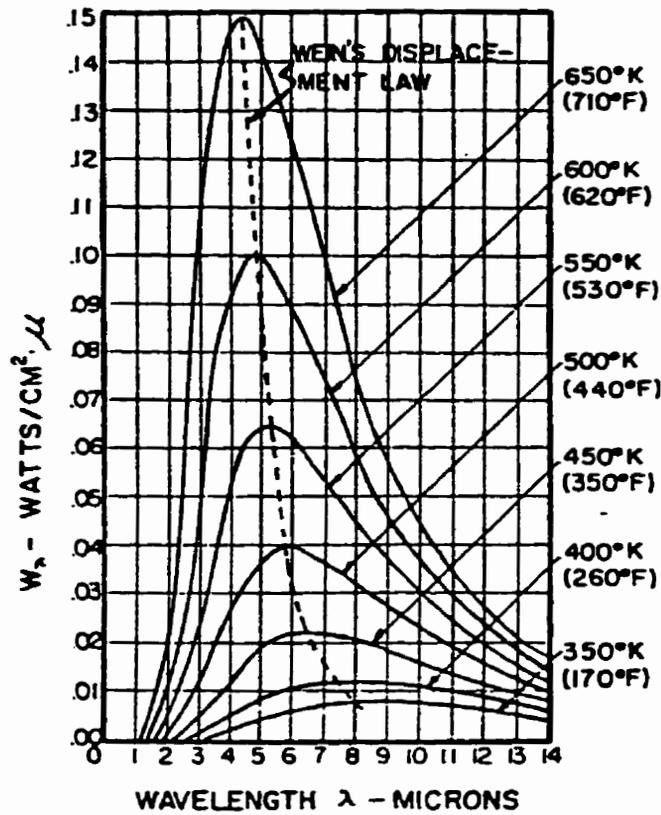


Fig. 2.2 Wien displacement law (Harrison 1960)

Fig. 2.2 represents the Wien displacement law, which shows that as the temperature of the source increases, the energy (area under the curve) increases proportionally to the power of the absolute temperature, and the peaks shift to shorter wavelength (the shorter the wavelength the higher the energy content). The Wien displacement law states that the product of the peak wavelength and temperature is equal to a constant (Todd and Ellis 1982, Mills 1992).

$$\lambda_m T = 2897.6 \mu\text{m K} \quad (2.2)$$

Where : λ_m = wavelength of maximum monochromatic emissive power, μm

T = temperature of the black body, K

Infrared energy from a source transmitted to a product must pass through a medium that in most cases is air containing carbon dioxide and water vapour. Air, similar to other diatomic gases, is characterized by such a minute absorbing capacity that, for all practical purposes in heat radiation it is transparent (Ginzburg 1969). Since CO_2 has higher peak absorption bands (2400 to 3000 nm, and 4000 to 4800 nm) than the Quartz lamp (peak maximum at 1150 nm at 100 % rated voltage) it is largely transparent to infrared radiation.

Water vapour absorbs a certain amount of radiation as its maximum peaks at 1400 nm.

When infrared energy impinges upon physical matter, the portion of it that is absorbed produces one primary effect: it increases the energy content of the atomic and subatomic particles of which physical matter is made resulting in a temperature rise.

2.1.2 Factors affecting infrared heating

Mohsenin (1984) stated that the most important factors affecting infrared heating are the penetrating properties of the infrared radiation, the variation of absorbed energy with the wavelength of the energy source, and the spectral energy of the source. The percentage of energy absorbed at different layers in a material varies according to the source of energy used.

Fig. 2.3 shows that with a 1100 K source, the absorption in the material is high and a large portion of the energy is absorbed very near the surface of the material. Almost 90% of the energy is absorbed in 1 mm of depth causing a non uniform heating over depth. As the energy of the source increases, the energy produced is less strongly absorbed by the material and therefore penetrates deeper into the material. For instance, with a 3500 K source almost 50% of the energy is absorbed over 3 mm of depth.

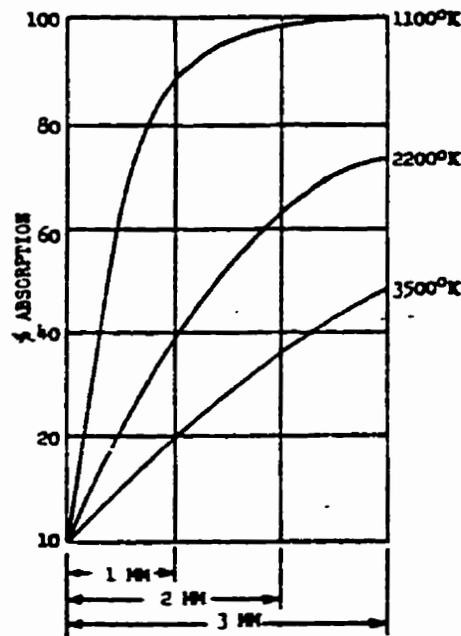


Fig. 2.3 Variation of absorption of infrared energy with depth and source of radiation (Schuman and Staley 1950)

The variation in the energy absorbed by the material, depending on the wavelength of

the infrared source, is another important concern in infrared heating. As seen in Fig. 2.4, in a 3 mm layer of water, wavelengths longer than 1400 nm are completely absorbed, while absorption drops sharply for wavelengths less than 1400 nm. Therefore, selection of an infrared source with the desirable emissive characteristics is an important factor.

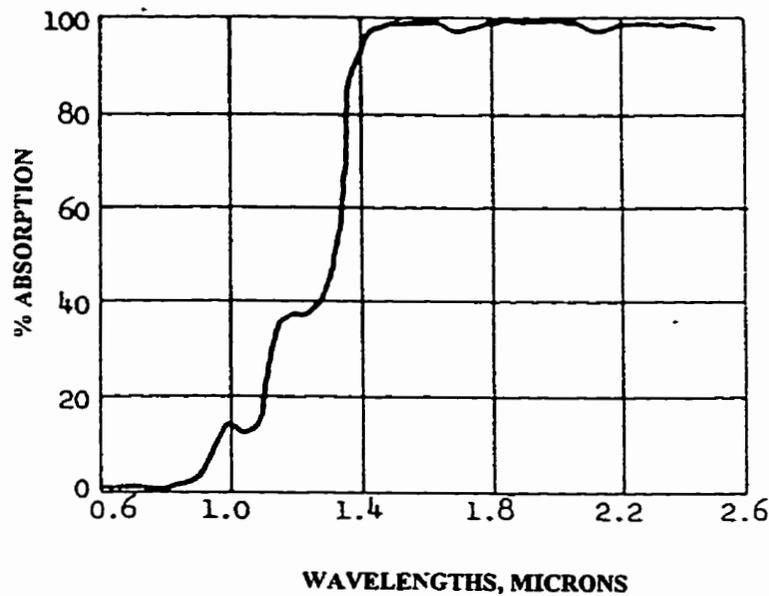


Fig. 2.4 Percent absorption of a 3-mm layer of water at different wavelengths (Schuman and Staley 1950)

The last important factor to consider in infrared heating is the spectral energy of the source. Fig. 2.5 depicts the spectral energy of three sources of infrared energy. The total energy for each source is the same. To utilize infrared energy economically, it is necessary to use a broad band of wavelengths (Mohsenin 1984).

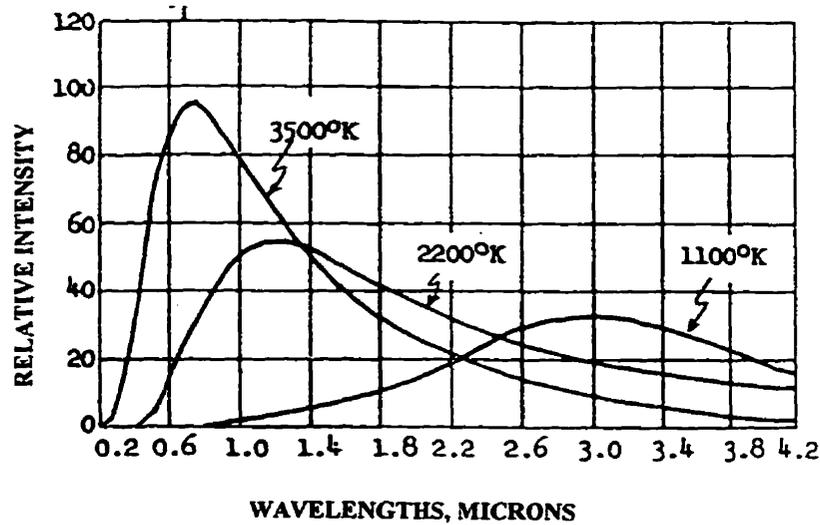


Fig. 2.5 Relative intensities of three different sources of infrared energy (Schuman and Staley 1950)

Headley (1965) and Mohsenin (1984) suggest the following steps when applying infrared radiation to drying: 1) determine the absorption spectra of the material, 2) choose a heat source most suitable for the material, and 3) superimpose the energy curve of the source over the spectral absorption of the material. Fig. 2.6 shows this process for a 3 mm water film and an infrared source of 2200 K. Notice that for wavelengths above 1400 nm water absorbs almost all the energy available from the source, which is 65 % of the total energy of the 2200 K source. The same procedure should be followed for the dry matter in the product. In doing this, the energy source should be selected such that the energy peak of the infrared source would correspond, as much as possible, to the peak absorption of water in the material and not to its dry matter.

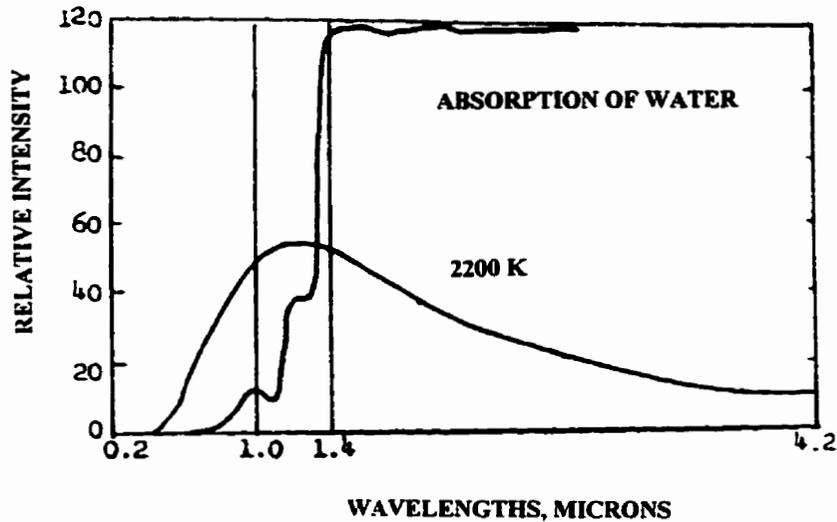


Fig. 2.6 Superposition of energy curve of the infrared source and the absorption spectra of 3-mm thick layer (Schuman and Staley 1950).

Ginzburg (1969) stated that the selection of the temperature of radiation generator depends not only on the optical properties of the material but also on its thickness. For drying thin materials, the radiation maximum of the generator should be in the range of maximum absorption of the thin layer of the material. For thick materials, the optimum range of spectrum would be one in which the material has not only the maximum transmittance but also the least reflection.

2.1.3 Advantages of infrared heating

Ginzburg (1969) has performed a great deal of research on infrared heating. From

his investigations he concluded that:

- the most important advantage of the infrared heating is the elimination of resistance to heat transfer through the convection or conduction coefficient. This improves heat transfer efficiencies, saving more time and energy, and enables better control of surface temperature.
- the density of the heat applied to the surface of the material subjected to infrared radiation is much greater (some 20 to 100 times) than in convective heating. At the same time as a result of the interaction of the electromagnetic waves with the irradiated substance, some of the imparted energy is absorbed by the substance, while some of it is radiated by the material itself in the form of secondary electromagnetic waves. It is known that the energy levels of molecules in solid bodies depends on the energy levels in the electron shells of the atoms, the oscillating and rotating movements of atoms inside the molecule. The energy, imparted to the substance by the electromagnetic waves, changes the energy condition of the molecules of the material, and becomes transformed into heat.
- infrared rays may be capable of penetrating into the depth of the material depending on the properties of the treated materials, and the temperature of the radiator.
- infrared rays have a deep effect on the molecular structure of the material. When the frequency of the incident radiation is close to the value of the frequency of the natural oscillations of the atoms in the material (resonance), then the amplitude of the imparted vibrations of the atoms is increased. At the same time the coefficient of the energy absorption (the selectivity) is also increased.

- the temperature gradients obtained when infrared radiation is applied to a thick material are much greater than in the ordinary convective drying (50 - 250 °C/cm).

It was theorized by some Russian researchers that infrared rays contribute to a change in the body structure and the directional disposition (orientation) of the molecular chains in material of plant origin, (vegetable and fruit) and in fat and water enabling an intense preheating of the body (Ginzburg 1969). Headley (1965) also stated that when a molecule is subjected to infrared radiation whose natural frequency corresponds to a particular frequency in the emitter spectrum, some of the radiant energy is absorbed. This absorbed energy reinforces the natural molecular motion of the molecules, and energy is released in form of heat.

Other advantages of infrared heating are better control over the heating surface and instant heat on and off (Ginzburg 1969).

2.1.4 Application of infrared radiation in agriculture

Ginzburg (1969) summarized some of the work done by Russian researchers on the application of infrared radiation on agricultural products. He stated that good results and some beneficial effects were obtained applying infrared rays on roasting cocoa, conditioning grains, and drying seeds and flour.

Infrared radiation improved the aroma and flavour and changed the structural and mechanical properties of the cocoa beans, making it easier to remove the capsule, and decreased the amount of energy required for their grinding by increasing their brittleness. The

application of infrared radiation also enabled a continuous roasting process which takes little time and provides a good quality product. Application of infrared rays to conditioning wheat resulted in higher yield of flour, and improved the bread baking properties. Germination capacity of seeds such as beans and alfalfa were improved by drying them with infrared radiation. Quite often these seeds acquire lower germination capacity after being dried by convective methods (Ginzburg 1969).

Infrared radiation speeded up the maturation of freshly milled flour and improved its baking characteristics. The specific volume of the bread made with the flour increased after exposure to infrared for 6 minutes. The experiment described by Ginzburg (1969) used 28 lamps of 250 W each (14 above and 14 below) placed in a tunnel. The distance of the lamps from the samples could be adjusted from 100 to 400 mm. The 5 mm thick layer of flour in the infrared treatment reached a temperature of 70 - 74 °C.

Applying infrared radiation to flour made from grain infested with eurygaster (an insect from the Pentatomidae family) improved the bread-baking properties of the flour (Ginzburg 1969). The flour used had a 19.6% moisture content and reached 70°C after 6 minutes of infrared exposure. Eight lamps of 500 W each were placed 200 mm away from the flour sample which was 5 mm thick.

Asselbergs and Powrie (1956) obtained good results using infrared radiation to peel apples, as the weight losses of the apples were about 2.5% compared to 15 to 18% lost by mechanical peeling machines. They used a heat source of around 1520 °F and exposure times of 9-30 s.

Headley and Hall (1963) used an infrared source to dry shelled corn. They used an

infrared lamp with a maximum intensity of energy between 1000 to 1150 nm, supplied by a 375 W lamp. The product was placed 30.48 cm from the centre of the lamp and was vibrated in the infrared field by an orbital sander. They concluded that vibration of the product in the infrared fields provides a means of utilizing high intensities of energy without visible damage of the product.

2.2 Rheological Measurements

Rheology is the science that deals with deformation of objects under the influence of applied forces (Lewis 1987). Deformation can be flow and hence involves the properties of viscosity or consistency or elastic or plastic. Dough rheological properties, which depend on dough structure, provide information on dough behaviour, and mechanical handling properties. From this, bakers could control the quality of the finished bread (Bloksma and Bushuk 1988).

2.2.1 Capillary rheometer

In this method, a liquid is forced through a fine bare tube and the viscosity of the liquid is determined from the measured volumetric flow rate, applied pressure and tube dimensions (Van Wazer et al. 1963).

Mackey and Ofoli (1990) used a capillary rheometer to measure the apparent viscosity of whole wheat flour-dough at 0.330, 0.337, 0.385 and 0.436 g of water per g of starch, dry basis, using length/diameter ratios ranging from 2 to 16. They found that shear rate by itself

is insufficient to accurately model the viscosity of whole wheat flour since the correlation coefficient obtained in the regression analysis was 0.46.

Santhanagopalan (1995) determined the effect of compaction on the flow properties of wheat flour-water dough. The rheological properties of the dough were determined using Farinograph, Mixograph, Alveograph, Amylograph and rheometer capillary. He found that the rheological characteristics of the compacted flour were not significantly different from the non-compacted flour in the range of shear rate of 7.8 s^{-1} to 782.5 s^{-1} .

2.2.2 Falling Number

The Falling Number is defined as the time in seconds to stir and allow the stirrer to fall a measured distance through a hot aqueous flour gel undergoing liquefaction. It is based on the rapid gelatinization of a flour suspension and subsequent measurement of the degradation of starch paste by α -amylase (Ghaly et al. 1973). The α -amylase is an endoenzyme which attacks linkages within the molecular structure of macromolecules. It appears that α -amylase hydrolyses the 1,4 α - glucosidic linkage within the starch molecules at random points (Hoseney et al. 1986).

2.2.3 Viscoamylograph

The American Association of Cereal Chemists defines the Amylograph as a recording viscometer that may be used primarily to determine the effect of α -amylase on viscosity of flour as a function of temperature. The Viscoamylograph records the viscosity changes which occur in a flour-water suspension being subjected to a uniform increase in temperature. The

viscosity tends to increase as the starch gelatinizes, while the liquefying action of α -amylase has an opposite effect (Pylar 1982). The Amylograph results are in good correlation with those of the Falling Number.

2.2.4 Farinograph

The Farinograph curve (farinogram) is obtained when a flour-water system is mixed by the action of two blades which are connected to a lever and scale system and to a pen which traces a curve. The pen records the resistance that the dough offers to the mixing blades during a prolonged and relatively gentle action (Shuey 1975, Bloksma and Bushuk 1988). As the flour-water paste is mixed, the system becomes more resistant to extension, that is, the Farinograph curve height increases. This process continues only up to a specific point, after which the dough becomes less resistant to extension giving a mixing peak (Faubion and Hosenev 1990). As the mixing action continues, the dough starts breaking down which is indicated by the point at which the curve starts to descend.

The Farinograph curve indicates two important physical dough properties, the water absorption, and a general profile of the mixing behaviour of the dough or the tolerance of the dough to mechanical mixing abuse (Shuey 1975). The water absorption of the flour, which is the amount of water required for a dough to have a definitive consistency, must be determined before the Farinograph can be performed. The dough consistency is defined as the height of the middle of the band registered in the Farinograph curve and it is expressed in instrument related units (B.U.) (Bloksma and Bushuk 1988)

The mixing characteristics of a flour are gluten quality measurements (Hlynka 1964)

and are determined through the arrival time, development time, stability and mixing tolerance index. These indices indicate the amount of work input required to develop a dough to optimum development and how much additional mixing can be imparted to the dough before it begins to break down (Kunert and D'Appolonia 1985).

2.2.5 Mixograph

The Mixograph measures the rate of dough development, the maximum resistance of the dough to mixing, and the duration of resistance to mechanical over-mixing (Kunert and D'Appolonia 1985). The dough is mixed by four vertical pins attached to a rotating mixing head which revolves through the dough in a planetary motion around three or four other fixed pins in the wall. During the initial ascent of the curve, water is being brought into contact and absorbed by the protein and the starch, and because of the folding and stretching action of the mixing pins, the dough begins to be developed. As the dough develops, the force required to move the pins through the dough increases to a maximum elasticity or minimum mobility. This point corresponds to the top of the curve. Beyond this point, mechanical degradation of the dough causes an increase in mobility resulting in the curve sloping downward and tailing off.

Larmour et al. (1939) compared the protein content and the baking quality of hard red spring wheat using the Mixograph. It was concluded that the greatest value of the Mixograph test, knowing protein content, was to identify the type of flour. The curves established qualitative differences between flours that were or were not different in baking quality.

Johnson et al. (1943) performed a systematic and statistical analysis relating

Mixograph characteristics to baking results. Peak height, width and weakening angle were positively correlated with protein content and loaf volume. The authors found that the Mixograph characteristics tended to reflect baking strength of a flour, as a result of the above correlation.

2.3 Baking and Functional Measurements

2.3.1 Grain research laboratory (GRL) Canadian short process method

The GRL-Canadian Short Process method is used for untreated flour experimentally or commercially milled from wheat for the production of yeast raised bread (Grain Research laboratory, Canadian Grain Commission, Winnipeg, MB). It provides a test for the baking performance of flours under the conditions of high speed mixing, short fermentation and typical formulation used by Canadian bakeries.

2.3.2 Starch damage

Starch damage can be determined by the Farrand method (Farrand 1964). Farrand's method is based on the principle that damaged starch exhibits a higher water absorption capacity, and that the increase in absorption capacity is correlated with the rate of attack by the enzyme α - amylase. This method assumes that all flour contains the necessary activating level of β - amylase, so the rate of production of reducing sugars in the presence of a massive dose of α - amylase (1.500) sufficient to overshadow any naturally occurring α - amylase in the flour should correlate with the level of starch damage.

2.3.3 Wet gluten content

The wheat flour protein can be roughly divided into two fractions: the soluble fraction and the insoluble fraction. The soluble fraction contains several globulins and an abundance of albumin. The insoluble fraction, named gluten, is obtained from flour by gentle washing with a salt solution until most of the starch is removed (Knight 1965).

2.3.4 Spectrophotometric method for measuring functional glutenin

This method, developed by Sapirstein and Johnson (1996), uses spectrophotometric procedures to determine insoluble glutenin content of flour in propanol/DTT extracts by ultraviolet absorption at 214 nm. The authors found a high degree of correlation between insoluble glutenin protein absorbance and mixing development times ($R^2 = 0.78$), and work input to peak development time ($R^2 = 0.98$). There was also a high correlation with Kjeldahl protein determination ($R^2 = 0.98$).

2.4 Differential Scanning Calorimetry (DSC)

The DSC is a differential thermal system that determines the enthalpies of any process by measuring the differential heat flow required to maintain a sample of the material and an inert reference material at the same temperature. A thermogram is obtained by registering the heat that is absorbed or liberated by a material when it undergoes a change of state, such as melting from one crystalline form to another, or whenever it reacts chemically (McNaughton and Mortimer 1975).

When the starch granule is heated in the presence of water, an order-disorder phase transition occurs. When sufficient water is present, this transformation, called “gelatinization”, results in near solubilization of the starch. Gelatinization entails the loss of crystallinity of the granule as measured by the loss of birefringence, an uptake of heat as the conformation of starch is altered, hydration of the starch accompanied by swelling of the granule, and a decrease in the relaxation time of the water molecules (Donovan and Mapes 1980).

Eliasson (1980), and Wootton and Bamunuarachchi (1979) measured the effect of heating rate on gelatinization. Eliasson’s experiment was carried out on wheat starch-water mix at 50% and heating rates of 5, 10, and 20°C/min. She concluded that the ratio between the enthalpy of the first and second peak is independent of the heating rate. In Wootton and Bamunuarachchi’s experiment, wheat starch was mixed with water at a 1 to 2 ratio and heated at 8, 16, 32°C/min. They found that when the heating rate was increased, the heat of gelatinization decreased. The faster the starch was heated, the lower the enthalpy of gelatinization. Thus, the time which the starch takes to pass through the gelatinization temperature was of crucial importance. They also found that as the heating rate increases, the gelatinization temperature range becomes broader. When the heating rate was increased, the endothermic range was decreased.

Eliasson (1980), and Wootton and Bamunuarachchi (1979) also determined the influence of water content on the gelatinization of wheat starch. In Eliasson’s experiment wheat starch was mixed with water at 30, 35, 45, 45, and 60 % and heated at a scanning rate of 10°C/min. Three endotherms were observed at water contents between 35 and 60%. The

temperature of the first endotherm transition did not vary significantly with water content. The temperature for the second and third transition, however, was related to the water content. When the water content decreased, the endotherm shifted towards higher temperature. The transition enthalpy of the first endotherm and the water content were related linearly up to a water content of 70% (w/w). Extrapolation of the enthalpy to zero gave a 33% minimum water content necessary for gelatinization of wheat starch. This value is in a good agreement to Wootton and Bamunuarachchi (1979) who found that 32 % (w/w) is the minimum water content necessary for the wheat starch to gelatinize.

Wootton and Bamunuarachchi (1979) measured the effect of starch/water ratio on gelatinization on wheat, maize, waxy maize and amylose-maize starch with water to dry starch ratios of 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 and 2.0 using a heating rate of 16 °C/min. They found that the moisture content and the heat of gelatinization were linearly related ($r = 0.99$).

3 MATERIALS AND METHODS

3.1 Description of Samples

3.1.1 Flour

Flour made from Canadian Western Red Spring (CWRS) wheat with a 75% extraction rate, a moisture content of 13.1% wb., a protein content of 13.8%, and a wheat particle size index of 57.6% was used. The flour was milled at the Grain Research Laboratory, Canadian Grain Commission, Winnipeg (MB).

3.2 Experimental Apparatus

3.2.1 Lamp

The lamp used was the T3 quartz infrared lamp (Research Inc., Minneapolis, MN, Model No. 057541-001) rated at 500 W and 120 V. Lamp wattage almost triples as the voltage is doubled. The lamp has a tungsten filament wire with a peak emission wavelength of 1150 nm and 1580 nm at 120 V and 60 V, respectively. The tungsten wire is supported by a tantalum disk along its length to prevent contact with the quartz glass envelope, and is enclosed with an inert gas to prevent oxidation. Fig. 3.1 shows the infrared lamp's characteristics and response to voltage. The voltage of the lamp was varied with a variable transformer (General Electric, Toronto, ON, Model No. 9T92A86). For practical purposes, the lamp rating is described in terms of supplied voltage (120 V and 60 V). The infrared lamp radiates 80% of the available energy in less than one second after being turned on and cools down much faster than low wavelength infrared emitters (Anonymous 1994).

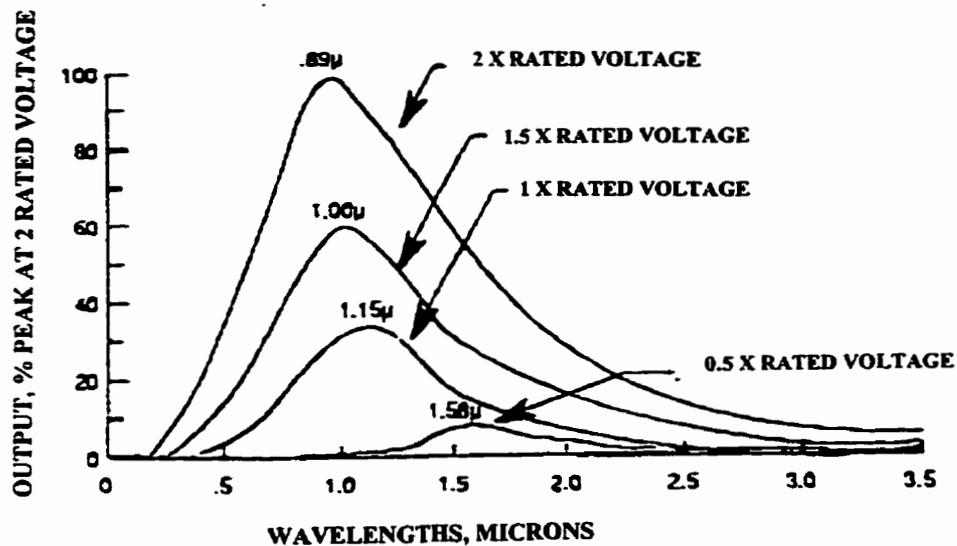


Fig. 3.1 Infrared lamp (Anonymous 1994)

Fig. 3.2 shows the experimental set up for infrared treatment. The infrared lamp was situated horizontally over the sample. A shutter made of wood and covered with aluminium foil was placed between the lamp and the flour sample and could be easily swung out. The shutter ensured that the exposure of the sample to infrared radiation was instantaneous, that the warm up time of the lamp did not need to be considered, and that the flour was rapidly shielded from the infrared radiation at the end of exposure.

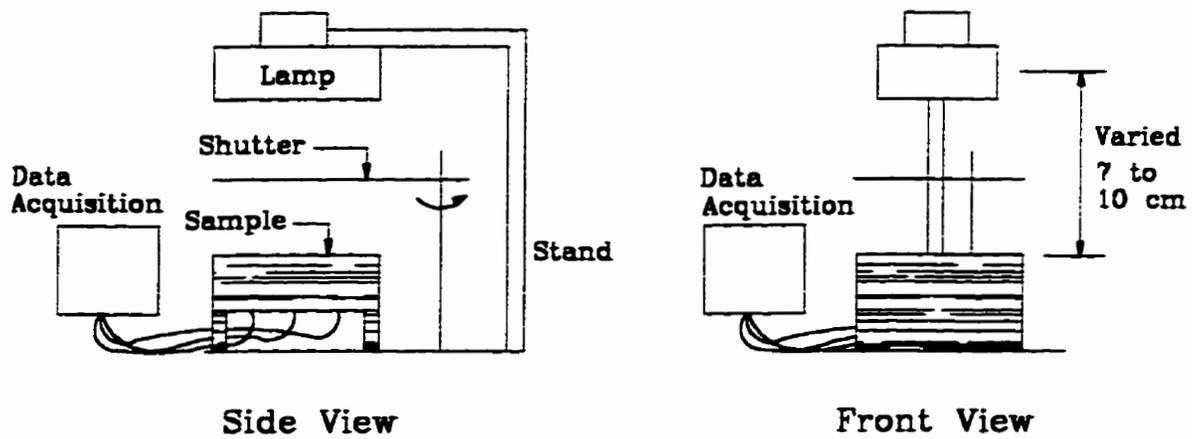


Fig. 3.2 Experimental setup for infrared treatments

3.2.2 Thermocouples

Thermocouples, type T (copper - constantan), connected to a data acquisition system (Hewlett Packard, Avondale, PA, Model No. 3421F) controlled by a computer were used to measure the temperature. The T thermocouples have a useful range of $-250\text{ }^{\circ}\text{C}$ to $340\text{ }^{\circ}\text{C}$ and good stability. The T thermocouples were checked in boiling water with a standard mercury thermometer. The thermocouples readings were very close to the mercury thermometer and had a standard deviation between $0.1\text{ }^{\circ}\text{C}$. Holes were drilled in the bottom of the wooden box, and thermocouple wires were inserted and glued at different heights (Fig. 3.3).

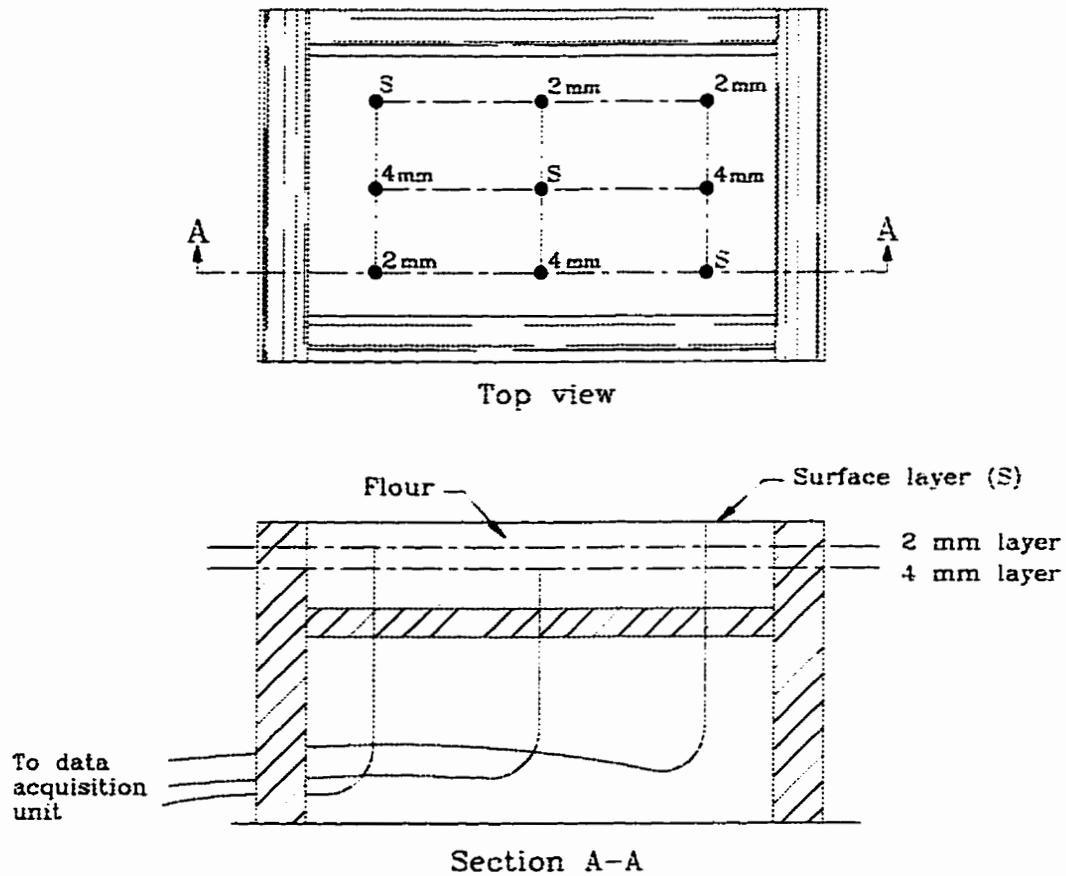


Fig. 3.3 Thermocouple assembly

3.2.3 Capillary extrusion rheometer

A capillary extrusion rheometer similar to the one used by Sharma et al. (1993) was used to measure the flow parameters of the dough made from control flour samples and the 3 infrared treated flours. The rheometer arrangement consisted of a cylinder-plunger and a capillary arrangement (Fig. 3.4).

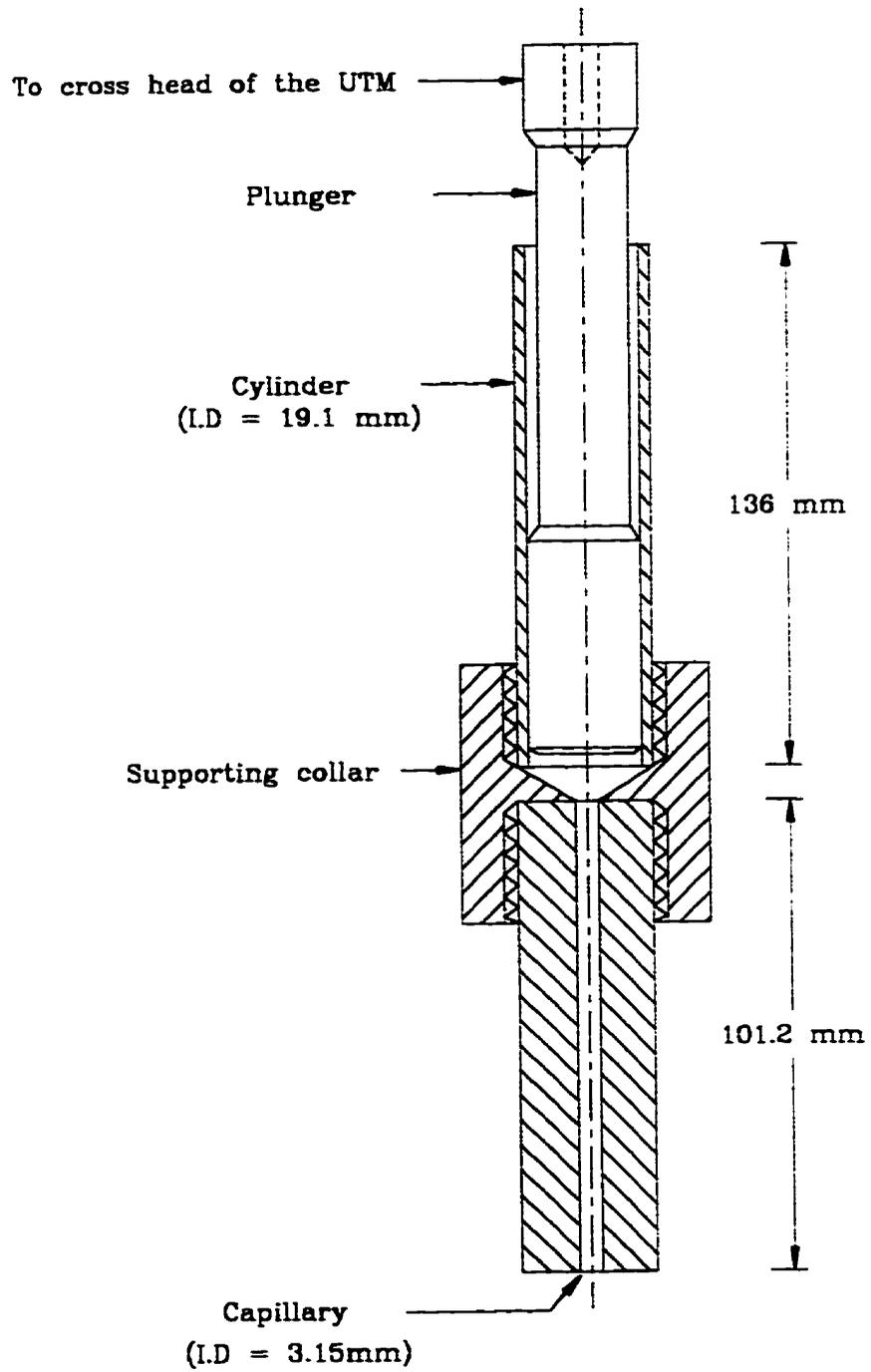


Fig. 3.4 Rheometer arrangement

The cylinder was made of brass with an inside diameter of 19.1 mm and a length of 136 mm. A hollow brass capillary tube with an inside diameter of 3.15 mm and a length of 101.2 mm was screwed into the bottom part of the cylinder. A stainless steel plunger with a close fit in the cylinder and a length of 191.5 mm was used to push the dough through the cylinder. The working length of the plunger was the same as the 136 mm height of the cylinder. One end of the plunger was screwed into the load cell of the ATS Universal Testing Machine. The cylinder was supported by a collar to avoid buckling due to excessive pressure exerted on the cylinder side walls. The supporting collar, made of channel iron, had a diameter of 27.6 mm. The supporting collar and the rheometer arrangement were placed under the crosshead of the universal testing machine so that the plunger could slide down inside of the cylinder containing the dough.

3.2.4 Differential Scanning Calorimeter (DSC)

The thermal transitions of CWRS flour were measured using a Perkin Elmer, Norwalk, CT, DSC 7 instrument. Under the control of the computer, the DSC 7 is programmed from an initial to a final temperature which embraces transitions in the sample material such as melting, glass transitions, solid-state transition, or crystallization. The DSC 7 records the heat flow to or from the sample as it is scanned over a linearly changing temperature range. It allows scanning rates of 0.1°C/min to 500°C/min in steps of 0.1°C/min. A slower scanning rate improves the peak resolution while faster scanning rates improve the sensitivity.

In the DSC 7, the reference and the sample have individual heaters which makes

possible the use of the “Null Balance “ principle (McNaughton and Mortimer 1975). The DSC is designed to keep the temperature of the sample and the reference material at the same temperature by using two control loops. One is for average temperature control, so that the temperature, T_p , of the sample and reference may be increased at a predetermined rate, which is recorded. The second loop ensures that if a temperature difference develops between the sample and the reference (because of exothermic or endothermic reaction in the sample), the power input is adjusted to remove this difference. Thus, the temperature of the sample holder is always kept the same as that of the reference holder by continuous and automatic adjustment of the heater power. A signal, proportional to the difference between the heat input to the sample and that to the reference, is fed into a recorder.

Calibration. Calibration for temperature is accomplished by running high purity standard and reference materials with known temperatures and energy transitions. The DSC calibration used was comparison of the Temperature/Area with a reference material. Indium, used as a reference material, has a melting point of 156.6 °C and is recommended when the DSC is operated in a temperature range of 50 °C to 200 °C (McNaughton and Mortimer 1975).

3.3 Experimental Methods

3.3.1 Moisture content

The moisture content of the flour was determined by method 44-15A of the American Association of Cereal Chemists (AACC 1983). In this method, 3 grams of flour are dried in a convection oven at 130 °C for 1 hour. An infrared analyser (Dickey - John, Auburn, IL,

Instalab 800) was used as well to determine the moisture content. The infrared analyzer allowed fast measurements which facilitated determination of moisture content just before any further testing of flour samples.

3.3.2 Capillary extrusion rheometer

Dough used in the capillary rheometer was prepared in a pin mixer (Model CB 1284 New Port, Muzeen and Blymthe Ltd.) (Hlynka and Anderson 1955). The amount of water added to flour was determined by the Farinograph water absorption. The dough was mixed until it reached the optimum mixing time which is the time required by the dough to reach the maximum elasticity before it starts breaking down. The rheometer test was conducted 15 minutes after the dough was prepared.

The inside wall of the cylinder was lubricated manually with oil to reduce friction between the walls of the cylinder and the dough. A visual inspection was made to ensure that the cylinder was completely coated with oil. The cylinder was filled with dough which was pushed down using a rod so that there were no air gaps in the cylinder. In some tests air gaps were still in the dough so the results were discarded. The dough was extruded at a plunger speed of 5.0 mm/min, 10.0 mm/min, 20.0 mm/min, 50.8 mm/min, 100.1 mm/min, 200.7 mm/min, 350.5 mm/min, and 500.4 mm/min. The experiments were conducted with and without the capillary set up. The force required to extrude the dough at selected plunger speeds was recorded by the ATSCCUTM software (Applied Test Systems, Inc., Butler, PA). Four runs each were conducted with and without the capillary.

3.3.3 Farinograph

The water absorption, the arrival time, the development time, the stability and mixing tolerance index were measured using a Farinograph (Brabender Instrument Inc., South Hackensack, N.J.) by following Method 54-21 recommended by the AACC (1983). The water absorption is the amount of water required to yield a dough of determined consistency (500 Brabender Units). The dough development time is the interval, to nearest 0.5 min, from first addition of water to that point in maximum consistency range immediately before first indication of weakening. The mixing tolerance index is the difference in B.U. from top of the curve at peak to the top of curve measured 5 minutes after peak is reached. The stability is the time difference, closest to 0.5 min, between the point where the top of the curve first intersects 500 B.U. line (Arrival time) and the point where the top of the curve leaves 500 B.U. line (Fig. 3.5).

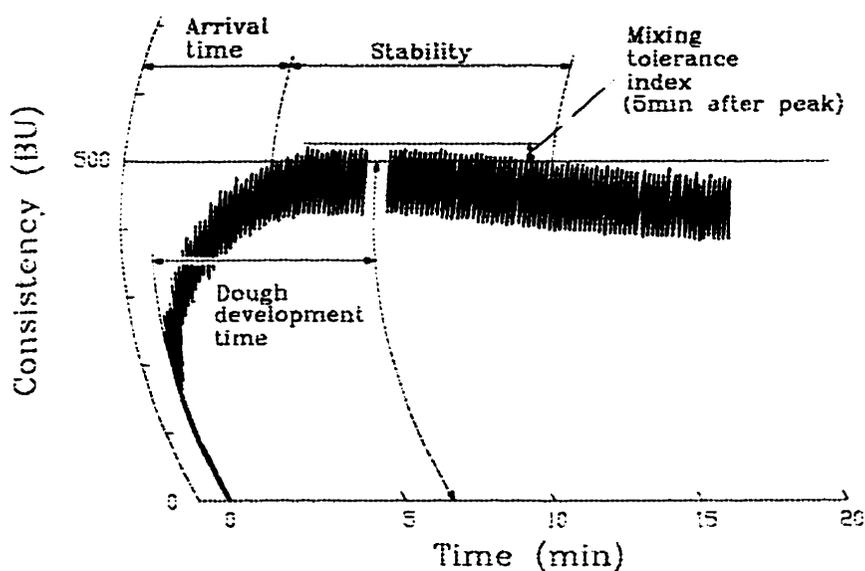


Fig. 3.5 Farinograph curve (Bloksma and Bushuk 1988).

3.3.4 Mixograph

The mixing time to peak development (MDT) or peak time, work input to peak (WIP), peak height, dough development angle (right of peak) were determined with a computerized 2-g Mixograph (National Manufacturing Division, TMCO, Lincoln, NE) following the procedure 54-40 of the AACC (1983). Those indexes were computed using Mixsmart software. The mixing time to peak development is the time required for the peak to reach the maximum height (min) or point of minimum mobility (DF) (Fig. 3.6). The peak height is the height from the base line to the centre of the curve at maximum plasticity (FO) (Mixograph units). The dough weakening angle is the angle formed with the tangent drawn (ON) at the top of the peak of the curve and the line paralleling the general slope of the curve beyond the peak (OW). Fig. 3.6 shows a typical Mixograph curve. The water absorption of the flour was adjusted to 63% at 14% moisture content w.b. for all the flour tested.

3.3.5 Wet gluten content

The wet gluten content of the control flour and the infrared treated flour was determined in the Glutomatic 2100 (Falling Number AB Huddinge/Sweden) using ICC (1980) Standard 137.

3.3.6 Starch damage

The starch damage of the control flour and the flour treated with infrared radiation for 30, 60, and 60 s was determined with the Farrand Method (Farrand 1964). In this method the starch damage is expressed in arbitrary units as a percentage of the total starch.

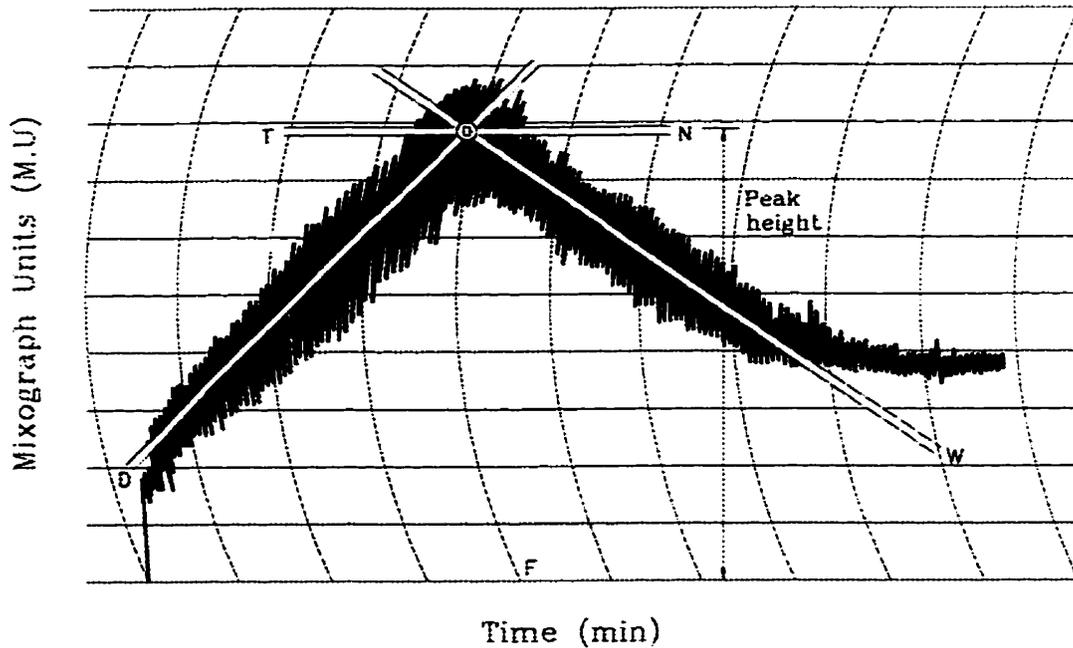


Fig 3.6 Mixograph curve (Johnson et al. 1943)

3.3.7 Falling Number

The falling Number of the control flour and the flour exposed to infrared heat was assessed in a Falling Number 1400 machine (Falling Number AB Huddinge/Sweden) following Method 107 as outlined by the ICC (1980). The falling Number is defined as the time in seconds to stir and allow the stirrer to fall a measured distance through a hot aqueous flour gel undergoing liquefaction.

3.3.8 Viscoamylograph

A rapid Amylogram test was used to determine the height of the gelatinization maximum which is obtained after running the test for 10 minutes (Fig. 3.7). The Viscoamylograph Model 3059/66 type VAV was used (C.W. Brabender Instruments, Inc., South Hackensack, N.J.).

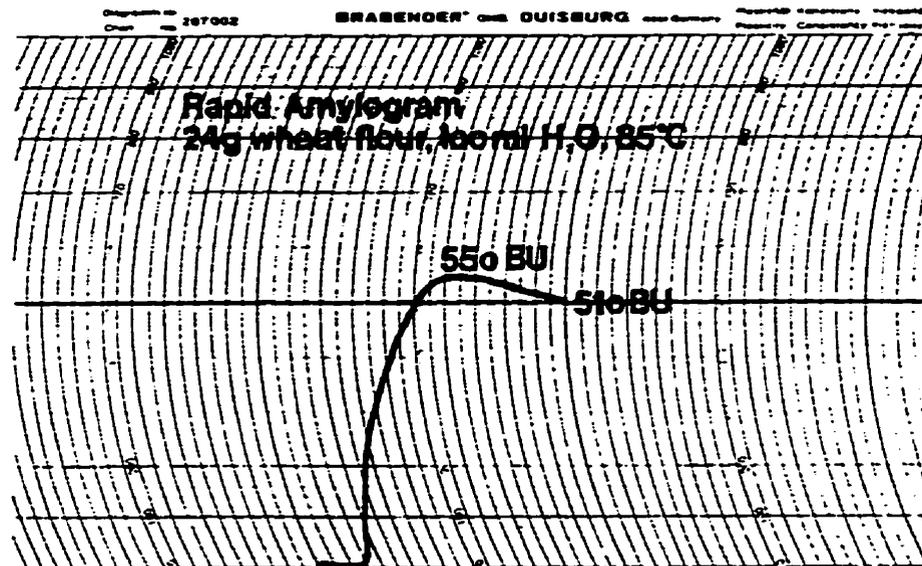


Fig. 3.7 Viscoamylograph (obtained from manual Brabender Instruments, Inc., South Hackensack, N.J.)

3.3.9 Canadian short baking process method

Canadian short process baking was conducted to determine the baking properties of

the flour (Grain Research Laboratory, Canadian Grain Commission, Winnipeg, MB). The tests were conducted at the Grain Commission Laboratory. Flour (200 g at 14% moisture basis), water (varies according to the maximum consistency according to machinability of dough), sucrose (4%), salt (2.4%), yeast (3.0%), shortening (3.0%), potassium bromate (30 ppm), ammonium phosphate (0.01%), malt (0.6%), whey (4%), and ascorbic acid (37.5 ppm) were mixed at high speed in a recording dough mixer. The dough formed was rested for 15 min, rounded seven times, rested another 7 min, and placed in a greased fermentation bowl in a cabinet at 30 °C. Then, the dough was proofed for 70 minutes according to the proofing rate of the control sample at 37.5 °C and a relative humidity of 83 %, and baked for 30 min at an oven temperature of 204 °C. The loaf volume was determined after 30 minutes of cooling. The next day, the loaf was evaluated by an expert from Grain Research Laboratory, Canadian Grain Commission, Winnipeg, MB, for appearance, crumb structure and colour.

3.3.10 Spectrophotometric method for measuring functional glutenin

The amount of insoluble glutenin in propanol / dithiothreitol (DTT) for the control flour and the three infrared treated flours was determined by ultraviolet absorption at 214 nm. Flour samples (50 mg) were extracted twice with 1 mL 50% (v/v) 1-propanol (solution 'A') for 30 min at 23°C in a microcentrifuge tube with intermittent vortexing and centrifuged for 3 min. The residue obtained was washed with the same solution for 1 min and centrifuged for 3 min at 2200 g-force. The residue, free of monomeric protein and soluble glutenin, was

reduced with 0.1 mL of the solution 'A' containing 0.08 M Tris-HCL, pH 7.5 and 1% (w/v) of DTT (reductant solution 'B') for 1 h at 60 °C. After 1 hour reduction, 0.9 mL of 50% 1-propanol was added to the mixture and centrifuged for 5 min. An aliquot (0.1 mL) of the supernatant was diluted with 0.9 mL 50% 1-propanol. Finally, 0.1 mL was taken and similarly diluted to measure absorption at 214 nm (Sapirstein and Johnson 1996).

3.3.11 Differential Scanning Calorimeter (DSC)

Flour samples of approximately 8 g each were placed and weighed in DSC aluminum caps, water was added with a syringe until the flour reached 80% (w/w) moisture content. The flour-water mixtures, weighing between 40 and 45 mg, were tightly sealed with a domed lid and placed in the left platinum-iridium sample cell. An empty sample pan and lid were placed in the reference cell. Flour-water samples were prepared at 80% moisture content because water in excess of the water binding capacity must be present if the starches are to go under gelatinization when heated (Wootton and Bamunuarachchi 1979). Collison and Chilton (1974) observed that gelatinization was completed if the starch with a moisture content of 55 % or above was heated. Whereas Wootton and Bamunuarachchi (1979) stated that even at a moisture content of 67%, the gelatinization energy was still increasing with moisture content. Samples were heated from 0 to 170 °C at a heating rate of 10 °C/min. This heating rate was chosen because higher rates increase thermal lags, giving measured temperatures that are erroneously high (Donovan and Mapes 1980). The onset (T_o), peak (T_p), and completion (T_c) temperatures were calculated for the gelatinization process. The

peak temperature was determined for the other transitions. The enthalpy of each transition was also calculated. Three tests were run for each flour.

3.4 Experimental Design

3.4.1 Specifying infrared treatment

The experiments conducted with the infrared lamp were grouped into two sections. In the first part, tests were conducted to determine the size of the micronized sample, the temperature distribution in a 6 mm layer, the distance between the lamp and the sample, the lamp rated voltage, and the sample thickness. In the second set of experiments, the CWRS flour was exposed to infrared rays for 3 different length of time. Flour from these treatments was subjected to rheological, chemical, baking and DSC analyses. All the experiments were carried out by placing the flour in a wooden box under the infrared lamp.

The size of the micronized sample was determined by measuring the surface temperature of the flour placed 100 mm from the infrared lamp which was operated at 120 V. The surface temperature of the flour was measured by inserting 9 thermocouples into the sample in a square grid formation and setting them at an equal distance. Wooden boxes with dimensions of 90 mm × 30 mm, 90 mm × 50 mm, 60 mm × 60 mm and 60 mm × 50 mm were used. These dimensions were chosen in an attempt to maximize the energy generated by the lamp and because the intensity of radiation in a quartz lamp is greatest along the axis and decreases on both sides of the axis (Ginzburg 1969). It was found that the most uniform temperature distribution along one plane was obtained for a sample of 60 mm × 50 mm. The

wooden box of such dimensions was chosen and used in further experiments.

The temperature distribution in a 6 mm flour layer was determined. Three thermocouples per layer were placed at the surface, at 1, 2, 3, and at 6 mm depth. The lamp was operated at 120 V and placed 100 mm away from the sample.

The effect of the distance between the lamp and flour on the temperature dynamics was studied. The distance between the flour and lamp was reduced to 70 mm and the temperature of the sample was measured at its surface, at 2, and at 4 mm depth by placing three thermocouples per layer. The lamp was operated at 120 V. Preliminary experiments showed that a distance less than 150 mm and larger than 50 mm should be used since at 50 mm the centre of the flour surface burnt in 75 s, and at 150 mm the flour surface only reached 100 °C after 240 s of heating. A distance of 70 mm was set for further experiments.

The effect of the lamp operating voltage on the temperature distribution was also assessed. The voltage of the lamp was changed to 50 % and the temperature distribution of the flour was determined at the surface, at 2 mm and at 4 mm depth in the sample placed 70 mm away from the lamp.

The amount of energy absorbed in a 2 mm layer was determined using the Eq. 3.1. The flour layer was exposed to infrared rays in a 50 × 60 × 2 mm wooden box which was placed at two different distances from the lamp (70 mm and 100 mm) which was operated at 60 V and 120 V. The temperature at 2 mm depth was measured after 30 s, and the mass of the 2 mm layer was calculated as the average weight of the sample before and after infrared treatment.

The CWRS flour was exposed to infrared radiation for 30, 60, and 105 s in a 50 × 60

× 2 mm wooden box. The average temperature between the surface and the bottom temperature was determined. A 2 mm layer was chosen to minimize the moisture distribution variation. Also the 2 mm layer was used because strong absorption results in high concentration of the energy at the surface or at product depth less than 3 mm (Headley 1965). The lamp voltage and the distance between the lamp and flour were set at 120 V and 70 mm, respectively. The limiting factors in selecting the infrared treatments were the possible heat damage to the flour proteins and the browning of the flour. The moisture content of the three infrared treatments were determined after irradiation. Three replicates were run for each type of flour.

3.4.2 Rheological and functional measurements

The effects of three infrared treatments (30, 60 and 105 s) on the rheological properties, baking characteristics, gluten content, starch damage and percentage of insoluble glutenin content of flour in propanol/DTT were studied on CWRS flour. The consistency coefficient and flow behaviour index was determined using a capillary extrusion rheometer. The flour water absorption and dough mixing characteristics were measured with a Farinograph and a Mixograph. The viscosity and α - amylase content was determined in an Amylograph and a Falling Number instrument, respectively. Starch damage was assessed following Farrand's method. The loaf volume, appearance, crumb structure and colour were evaluated through the GRL Canadian Short Process Method. Wet gluten content was determined in a Glutomatic machine. The percentage of functional glutenin was found by measuring the absorbance at 214 nm of a dilute aliquot of polymeric glutenin.

3.4.3 Differential Scanning Calorimeter measurements

DSC measurements of the control flour and the three infrared treated flour- water mixtures were conducted to gather some information on starch gelatinization and protein denaturation. Information on starch gelatinization was obtained by determining the process's enthalpy which indicates the amount of thermal energy involved in this process and by measuring the temperature at which starch gelatinizes. Information on denaturation temperature was obtained by recording the temperature at which protein denatured.

3.5 Calculations

3.5.1 Emitted radiation by the infrared lamp tungsten filament

The monochromatic radiation intensity of the tungsten filament emitting relatively as much energy as a black body was predicted using Planck's law (Equation 2.1). The emitted radiation by the tungsten filament at wavelengths of 1150 and 1580 nm was calculated. The peak temperature for the tungsten filament was also determined following Wien's displacement law (Equation 2.2). It is assumed that the tungsten filament emits radiation following the laws of radiation for black bodies (Headley 1965, Person and Sorenson 1962, Hall 1962).

3.5.2 Energy absorption calculations

The energy absorption in a 2 mm layer over 30 s of infrared heating was calculated

for the flour samples placed at two different distances from the lamp (70 mm and 100 mm) and at two different lamp rated voltage (50% and 100%). The effect of two variables, the distance between the lamp and the flour, and the lamp rated voltage on the infrared energy absorption was determined under these conditions. The energy absorption was calculated at 30 s of infrared heating because of the smallest moisture content change and the highest increase in temperature.

The energy absorption was calculated:

$$Q = m C_p \Delta T \quad (3.1)$$

Where Q = energy, kJ

m = mass of the 2 mm flour layer, kg

C_p = specific heat of flour, kJ/kg K

ΔT = temperature gradient ($T_{30} - T_0$), K

T_0 = initial temperature of flour

T_{30} = temperature of flour at 30 s of infrared heating

The specific heat coefficient of the flour was taken as 1.8 kJ/kg K (Rahman 1995) and assumed to be constant over the infrared heating period.

3.5.3 Rheometer calculations

For the rheometer calculations the follow assumptions were made (Heldman 1975):

- (1) The dough exhibits no slippage at the wall, and is incompressible. The lubrication

used on the wall of the cylinder did not influence the capillary performance as the capillary was not lubricated.

- (2) The dough velocity has no radial or tangential components, and the dough viscosity is not influenced by pressure.
- (3) The flow is laminar (the dough was made to flow through the cylindrical tube at sufficiently low value of Reynolds number), and is steady.
- (4) The measurement is conducted under isothermal conditions.
- (5) The cylinder is sufficiently long that end effects are negligible.

For the capillary rheometer test, the assumption that the properties of the dough are independent of time has to be also made. However, the dough is an unstable complex colloidal system that changes its physical characteristics continuously (Pylar 1982). Therefore, this assumption may not apply completely. However, the tests were always performed in the same time frame (15 minutes after the dough was made) and lasted the same time. Therefore, the error generated was the same size.

To measure the flow behaviour of a liquid using the capillary rheometer the equation of motion of a dough was used. This equation is an expression of stress in terms of velocity gradients (Van Wazer et al. 1963). When a shearing force is applied to the surface of a fluid (Fig.3.8), a force tending to resist the flow is generated and is equal to the force tending to move the cylindrical column in the direction of flow, as follows:

$$\tau (2 \pi rL) = \Delta p (\pi r^2) \quad (3.2)$$

Where : τ = shear stress, k Pa

Δp = applied pressure resulting in the movement of the fluid through the tube
(pressure difference between the ends of the capillary), kPa

r = variable distance from the centre of the tube at which the shear stress (τ)
results, m

L = length of the capillary, m

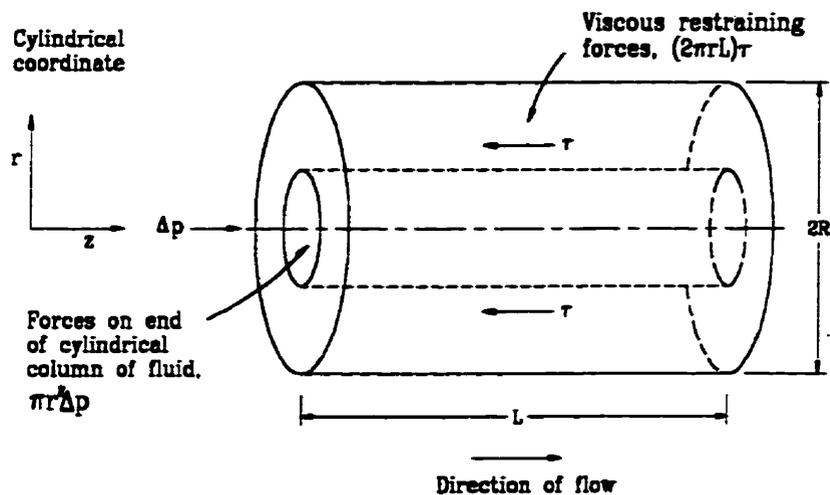


Fig. 3.8 Shear forces in a rheometer capillary (Van Wazer et al. 1963)

A shearing force is defined as one which would allow molecules to slip past one another along a given plane. The shear force per unit area of the plane on which it acts is the shear stress. Because the shear stress and the shear rate vary with radius, it was necessary to calculate both of them at the same point in the capillary. The shear stress at the centre of the capillary is zero and becomes maximum at the wall (Van Wazer et al. 1963). Therefore, the most convenient location for measuring shear stress is at the wall. The shear stress at the capillary wall is:

$$\tau_w = \Delta p R / 2L \quad (3.3)$$

Where : τ_w = shear stress at the wall, kPa

R = radius of the capillary, m

L = length of the capillary, m

Shear rate is a measure of the extent to which fluid molecules slip past one another during flow. The shear rate varies with radius and the mode of variation depends on the velocity distribution, which in turn is determined by the nature of the fluid (Van Wazer et al. 1963). A true rate of shear at the capillary wall is possible using the assumptions mentioned above. The shear rate at the wall is a more difficult quantity to determine from the experimental data. Therefore, to calculate the true shear rate at the wall, the Rabinowitsch - Mooney coefficient was applied (Van Wazer et al. 1963). The true shear rate is calculated from the volumetric flow rate of the fluid and then multiplied by the Rabinowitsch - Mooney

factor.

The volumetric flow is calculated: (Sharma and Hanna 1992)

$$Q = A V \quad (3.4)$$

Where Q = volumetric flow rate, m^3/s

A = cross sectional area of plunger, m^2

V = speed of plunger, m/s

The apparent shear rate for Newtonian fluids is calculated as (Toledo 1991):

$$\gamma = 4Q / \pi R^3 \quad (3.5)$$

Where γ = shear rate, s^{-1}

R = radius of the capillary, m

The Rabinowitsch - Mooney coefficient was calculated:

$$CF = (3 / 4) + (1 / 4n) \quad (3.6)$$

Where: CF = Rabinowitsch - Mooney coefficient

n = is the slope of the plot of log shear stress vs log shear rate (flow behaviour index)

The corrected (at the wall) shear rate was calculated as:

$$\gamma_w = \gamma CF \quad (3.7)$$

The flow behaviour index (n) and the consistency coefficient (K) can be calculated using the power law model (Toledo 1991).

$$\tau = K \gamma_w^n \quad (3.8)$$

Where: τ = shear stress, kPa

γ_w = shear rate at the wall, s^{-1}

K = consistency coefficient, $Pa s^{-n}$

3.6 Analysis of Data

A Completely Randomized Design was chosen since flour can be considered a homogenous material. The flour was divided into samples or batches to which the infrared treatment was applied.

Analysis of variance (ANOVA) and Duncan's Multiple Range Test (DMRT) were conducted for all tests using SAS version 6.11 (SAS Institute Inc., Cary, NC).

4 RESULTS

4.1 Specifying Infrared Treatment

The sample size (area of exposure) was determined by measuring temperature distribution at the surface of the sample. Sample sizes of 90 mm × 30 mm , 90 mm × 50 mm, and 60 mm × 60 mm, showed surface temperature differences of up to 23% between the hottest and coldest points of the flour sample. Highest temperatures were recorded at the center whereas lowest temperatures were observed at the edge of the sample. A sample size of 60 × 50 mm showed temperature differences less than 10%, and this size was chosen for further testing.

Following the methodology developed for this test, a 6 mm deep layer of flour was placed in the 60 × 50 mm box and exposed to infrared heat. The lamp was operated at 120 V and placed 100 mm away from the sample. Fig. 4.1 shows the temperature distribution for the sample exposed to infrared at various locations from the surface of the flour. The data points are averages of three readings and the vertical bars indicate standard deviations. Symbols without the standard deviation bars indicate that the size of the symbol is greater than the size of the vertical bar (standard deviation). Temperature differences between the surface and 1, 2 , 3, and 6 mm depth after 180 s were in the order of 13, 26, 27, and 38 °C, respectively.

Tests to determine the effect of distance between the flour and the lamp on temperature dynamics were conducted. The flour was placed 70 mm away from the lamp

(120 V). Reducing the distance between the lamp and the sample from 100 mm to 70 mm, increased the rate of temperature change at different depths. Particularly, the dynamics in surface temperature changes were greatly affected. For instance, after 120 s of infrared exposure, surface temperatures reached $74.1^{\circ}\text{C} \pm 3.9$ and $98.8^{\circ}\text{C} \pm 3.7$ for flour placed at 100 mm and 70 mm, respectively from the lamp. Temperatures at the 2 mm depth were $48.8^{\circ}\text{C} \pm 1.4$ and $65.1^{\circ}\text{C} \pm 1.1$ for flour placed at 100 mm and 70 mm, respectively, from the lamp. This is observed by comparing Fig. 4.1 and 4.2. Because of the low thermoconductivity of the flour the original depth of flour (4 or 6 mm) did not have a significant effect on temperature distribution in the 2 mm layer. There were significant differences between the temperature at the surface and at 2 mm depth for either lamp placement distance (70 mm and 100 mm) (DMRT $p = 0.05$).

The effect of changes in the rated voltage on temperature dynamics in the flour sample was also tested. The lamp was rated at 50% (60 V) and placed 70 mm away from the flour. Fig. 4.2 compares flour temperature in the samples where the infrared lamp was operated at 100 % (120 V) and 50 % (60 V) of rated voltage.

Decreasing the voltage of the lamp to 60 V not only decreased intensity of the lamp but also shifted the peak emission wavelength from 1150 nm to 1580 nm (Fig. 3.1). This resulted in a reduction in severity of the treatment of the surface layer, and a decrease in the rate of temperature change at different depths, in which the surface temperature particularly was greatly affected (Fig. 4.2). Surface temperature after 120 s of infrared heating in the

sample where the lamp was rated at 60 V was $46.1^{\circ}\text{C} \pm 2.9$ whereas this temperature reached $98.8^{\circ}\text{C} \pm 3.2$ in the sample in which the lamp was rated at 120 V. The voltage effect, determined by measuring the temperature at surface and at 2 mm depth, was significantly different (DMRT $p = 0.05$).

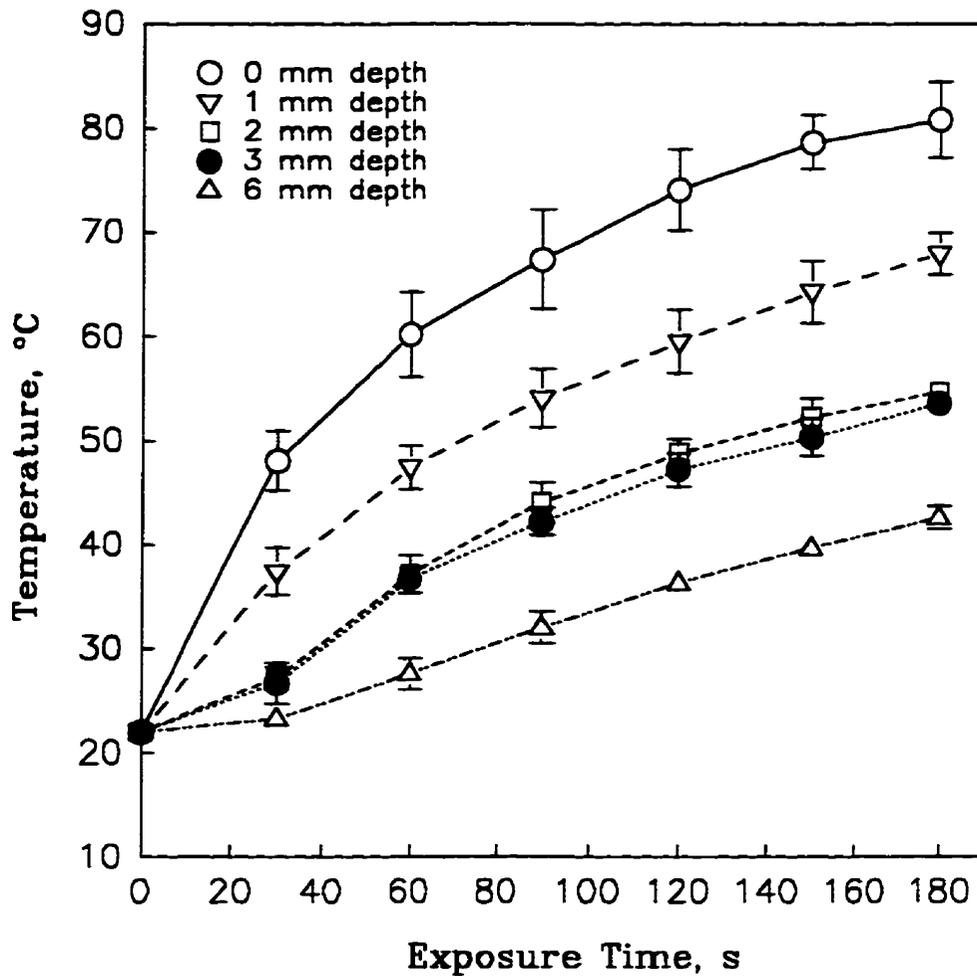


Fig. 4.1 Temperature distribution at various depths in a 6 mm layer of CWRS flour placed 100 mm away from infrared lamp which was operated at 120 V.

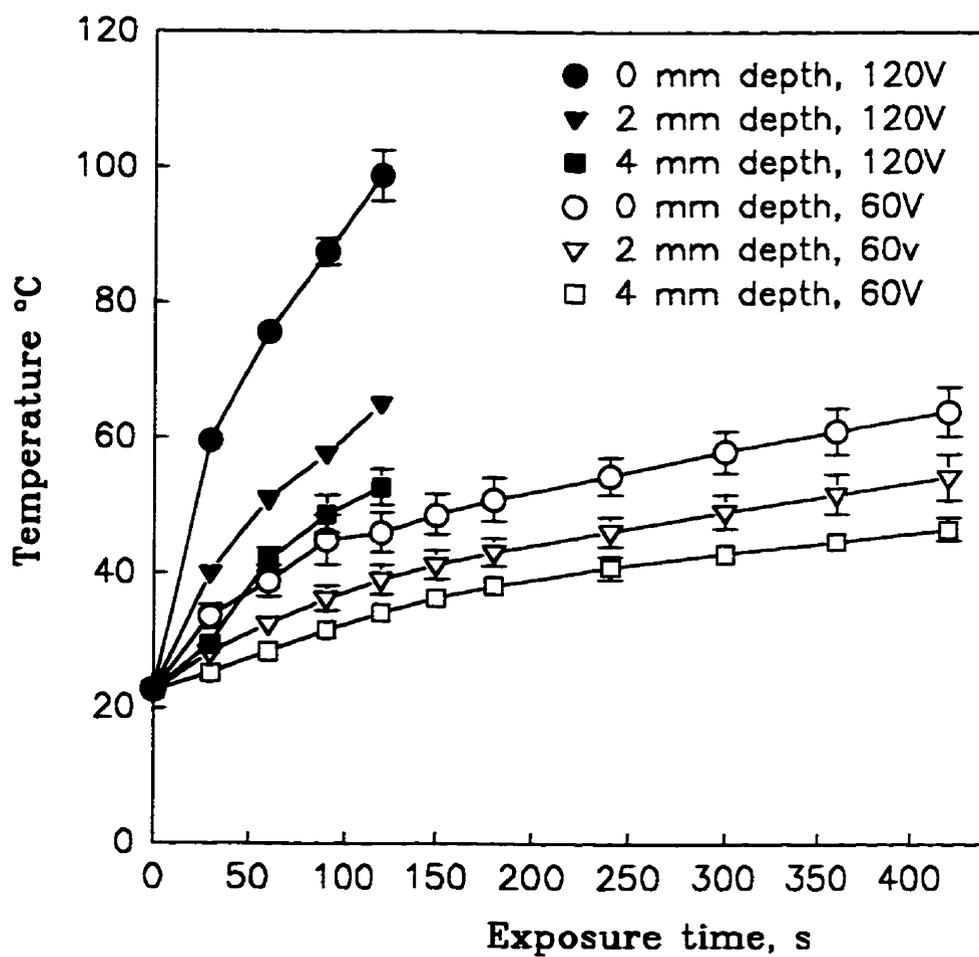


Fig. 4.2 Comparison of the temperature distribution in a 4 mm thick layer of flour exposed to IR radiation. The infrared lamp was operated at 120 V and 60 V and was placed 70 mm away from flour surface.

The temperature of the tungsten filament when the lamp was rated at 120 V ($\lambda = 1150$ nm) and 60 V ($\lambda = 1580$ nm) were 2520 K and 1834 K respectively. These temperatures were calculated using Eq. 2.2. The monochromatic emissive power of the tungsten filament

when the lamp was rated at 120 V and 60 V was 9.24 Watt/ $\mu\text{m cm}^2$ and 1.88 Watt/ $\mu\text{m cm}^2$ respectively. The emissive power was determined for the two peak temperatures using Eq. 2.1.

In an attempt to determine the effect of distance between the lamp and the flour, and lamp operated voltage on energy absorption, the energy absorbed into the 2 mm flour layer was determined using (Eq. 3.1) in flour samples placed at two different distances from the lamp (70 mm and 100 mm) which was operated at two different rated voltages (60 V and 120 V) as indicated in Table 4.1. The energy absorption values are the average of three readings. Energy absorbed into the 2 mm layer increased approximately three times when the distance between the flour and lamp was reduced from 100 mm to 70 mm. Changing the lamp rated voltage to 60 V reduced the energy generated by the lamp, so the energy absorbed into the 2 mm layer decreased from 124.3 J \pm 16.3 to 40.7 J \pm 1.24. A closer comparison in terms of radiation energy reaching the surface would be to compare the energy absorption when the lamp was at 100 mm and operated at 120 V versus the experiment when the lamp was at 70 mm and operated at 60 V.

Table 4.1 Energy absorption (J) and its standard deviation in a 2 mm layer of flour placed at 70 mm and 100 mm away from the infrared lamp which was operated at 60 V and 120 V for 30 s.

Experimental conditions (Distance between lamp and flour and lamp operated voltage)		
100 mm - 120 V	70 mm - 60 V	70 mm - 120 V
37.7 J \pm 4.89	40.7 J \pm 1.24	124.3 J \pm 16.38

Analysis of variance for the three experiments (70 mm-120 V, 70 mm-60 V, and 100 mm-120 V) showed that distance between the lamp and sample surface was the variable that affected flour temperature the most. It was also found that the 70 mm - 120 V experiment conditions had the major effect on the temperature of the flour followed by the 100 mm -120 V, and 70 mm - 60 V.

Flour samples (60 mm × 50 mm × 2 mm), placed at 70 mm from the lamp, were exposed to infrared radiation for 30, 60, and 105 s. The infrared lamp was operated at 120 V in an attempt to use infrared energy efficiently. Headley (1965) suggested that infrared utilization energy could be improved substantially if the infrared emitter used has a peak intensity wavelength that corresponds with the wavelength at peak water absorption and low dry matter absorptivity of the sample. Infrared absorption by water is almost 100% at wavelengths longer than 1400 nm, and only 10% at wavelengths less than 1000 nm. Starch and protein, the flour dry matter, have the lowest peak absorption at 8000 nm and 5800 nm respectively. At wavelengths less than 2000 nm, the energy absorption is less than 45% and 30% for dry starch and dry gluten respectively (Headley 1965). According to this, the T3 quartz lamp should be operated at 50% of the rated voltage because the lamp peak wavelength is 1580 nm and infrared absorption by water is almost 100%. However, at this peak wavelength, the energy under the curve is very low as the energy under the curve decreases as the rated voltage decreases. Therefore, the best alternative was to use the lamp rated at 100%. Increasing the voltage to 200 % would not be a good choice because the lamp peak wavelength is 890 nm. At this peak wavelength, the flour surface layers would be overheated and infrared absorption by water would be less than 10%.

Infrared exposure time determined the temperature reached by the sample. Average temperature between the surface and 2 mm depth was calculated for each treatment. In the most severe infrared treatment, flour was exposed to infrared rays for 105 s and reached an average temperature of $78.9\text{ }^{\circ}\text{C} \pm 1.5$. For the intermediate infrared treatment, flour was exposed for 60 s and reached an average temperature of $64.2\text{ }^{\circ}\text{C} \pm 1.8$. For the mild treatment, the exposure time was 30 s and the flour reached an average temperature of $50.4\text{ }^{\circ}\text{C} \pm 1.4$.

These infrared treatments caused losses of moisture in the flour. Fig. 4.3 shows moisture contents of the flour after 30, 60, and 105 s exposure to infrared treatment. Moisture content of the flour exposed to infrared heat for 105 s was reduced from 13.1% to 1.3 %. The measured moisture content of the flour and infrared exposure time were essentially linearly related during the first 105 s that the flour was exposed to infrared heating ($R^2 = 0.99$). Generally, drying characteristics follow an exponential function (Jayas et al. 1991); but because the flour exposure time was short, this relationship was assumed to be linear. The effect of infrared heat on rheological properties and thermal transitions of the CWRS flour was determined in the infrared treatments defined above.

Infrared heating had a significant effect on average temperature and moisture content of the flour (ANOVA, $p \leq 0.001$). Average temperature means obtained at 30, 60, and 105s of infrared treatment were significantly different from each other and from the average temperature of control (DMRT, $p < 0.05$). Moisture content obtained after 30, and 60 s of

infrared treatment were significantly different from each other and from the control. (DMRT, $p = 0.05$).

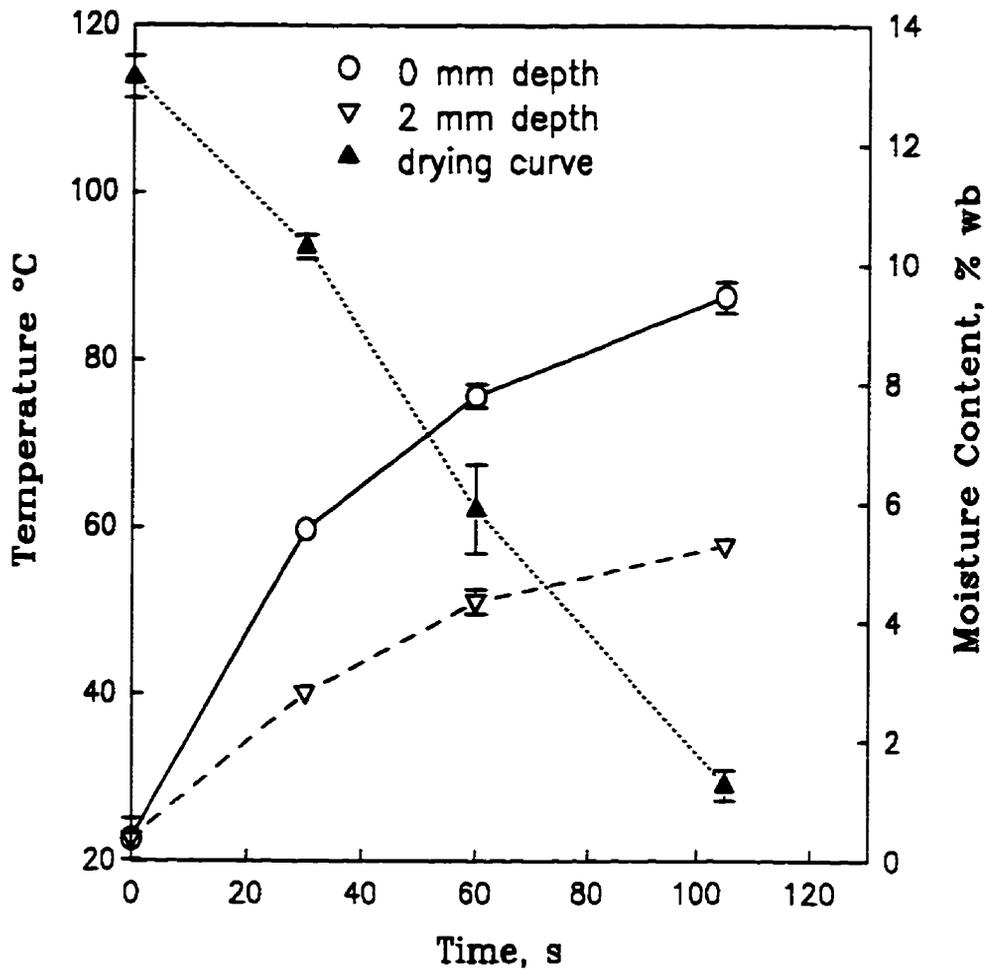


Fig. 4.3 Moisture loss in a 2 mm layer of flour exposed to IR heating with reference to the temperature history at the bottom and surface of the 2 mm layer of flour. The lamp was operated at 120 V and placed 70 mm away from the flour surface.

4.2 Rheological and Functional Measurements

4.2.1 Capillary rheometer test

Flow properties, flow behaviour index and consistency coefficient of dough made with control flour, and 30, 60 and 105 s infrared treated flour, were determined in a capillary rheometer. Final water contents of the dough made with the control flour, and the flour exposed 30, 60 and 105 s to infrared were 47.2, 46.9, 46.4 and 45.3 % respectively. Each dough had different water content because infrared treatment reduced flour water absorption from 63.1% (control flour) to 57.2% for the 105 s infrared treated flour. Doughs were prepared following the Farinograph water absorption because this value is close to the amount of water added to make bread and affects the dough mechanical development and the gas retention properties of dough (Hlynka 1964). Dough could have been prepared at the same water content but this was not the choice since CWRS flour is mainly used for bread.

Results of the extrusion tests for doughs prepared from control flour and flour exposed to three infrared radiation times (30, 60, and 105 s) are shown in Table 4.2. The corresponding forces with their standard deviations required to extrude the dough through the capillary are shown in columns 3 to 6. Each force is an average of four readings. Dough made with the 105 s infrared treated flour required the highest force to push it through the capillary.

Based on data shown in Table 4.2, shear rates, pressures drop and shear stress were

calculated (Table 4.3). As the cross head speed increased, volumetric flow rate and pressure drop increased for all doughs tested. With increases in volumetric flow rate, shear rate also increased. In the shear rate range analyzed (7.8 to 782.5 s⁻¹), dough made with flour exposed to infrared for 105 s exhibited the largest shear stress. This indicated that this flour dough required higher shear stresses to enable the molecules to slip past one another at the shear rate analyzed. The 60 s infrared treated flour exhibited the second highest values.

Table 4.2 Extrusion Force (N), and its standard deviation at different flow values (Q), of CWRS flour-dough made from flour exposed to different infrared treatment times using a capillary rheometer of 3.15 mm diameter and 101.2 mm length.

Cross head Speed (mm/min)	Flow rate (Q) 10 ⁻⁴ m ³ /s	Force (N)			
		Control Flour	30 s IR exposure	60 s IR exposure	105 s IR exposure
1	2	3	4	5	6
5.0	2.4	103.8 ± 11.31	114.7 ± 10.61	116.3 ± 18.14	137.5 ± 3.84
10.0	4.7	158.9 ± 18.95	158.0 ± 8.95	168.0 ± 7.16	185.3 ± 13.71
20.0	9.4	230.4 ± 20.82	222.7 ± 17.63	252.6 ± 14.82	284.6 ± 30.23
50.8	23.8	373.5 ± 27.52	374.2 ± 19.11	407.0 ± 23.86	463.3 ± 39.40
100.1	46.9	510.9 ± 29.46	523.8 ± 14.50	555.4 ± 23.73	614.1 ± 46.52
200.7	94.1	661.7 ± 31.83	639.7 ± 11.81	683.3 ± 27.34	758.8 ± 44.65
350.5	164.0	780.1 ± 18.65	748.3 ± 16.46	786.4 ± 19.61	868.3 ± 45.31
500.4	235.0	833.0 ± 27.05	786.1 ± 20.86	823.3 ± 8.43	920.7 ± 48.88

Table 4.3 Pressure drop (ΔP) and Shear Stress (τ) during extrusion of control sample of CWRS flour-dough and three samples prepared from flour exposed to infrared for three different times (30, 60 and 105 s) using a rheometer capillary of 3.15 mm diameter and 101.2 mm length.

Shear Rate (1/s) γ	Water-Flour dough							
	Control		30 s exposure		60 s exposure		105 s exposure	
	ΔP (kPa)	τ (kPa)						
7.8	13.3	103.6	14.7	114.6	14.9	116.2	17.6	137.3
15.6	20.4	158.7	20.3	157.9	21.6	167.8	23.8	185.1
31.3	29.6	230.1	28.6	222.5	32.4	252.3	36.5	284.2
79.4	47.9	373.1	48.0	373.7	52.2	406.6	59.5	462.8
156.5	65.6	510.3	67.2	523.2	71.4	554.8	78.8	613.4
313.8	84.9	660.9	82.1	639.0	87.7	682.5	97.4	756.0
548.1	100.1	779.3	96.1	747.5	100.9	785.6	111.5	867.3
782.5	106.9	831.8	100.9	785.2	105.7	822.4	118.2	919.7

Table 4.4 shows Rabinowitsch - Mooney correction factor (CF), flow behaviour index (n) and consistency coefficient (K) for dough made with the control flour and flour exposed to different infrared heating periods. The Rabinowitsch-Mooney correction factor (Eq. 3.6) was calculated from the log-log plot of shear rate and shear stress and was used to calculate the corrected shear rate. The log-log shear rate-shear stress was highly correlated ($R^2 = 0.98$).

Flow behaviour index and consistency coefficient were determined from the log-log plot of corrected shear rate vs shear stress. Flow behaviour index is the gradient of the straight line, whereas the consistency coefficient is the antilog of the intercept value.

Table 4.4 Rabinowitsch-Mooney correction factor (CF), flow behaviour index (n), and consistency coefficient (K), with their standard deviations for water-dough prepared from CWRS flour exposed to infrared radiation for different times.

	CF	n	K(kPa s ⁻ⁿ)
Control	1.30	0.46 ^B ± 0.010	40.5 ^B ± 3.99
30 s	1.33	0.44 ^{AB} ± 0.020	44.4 ^B ± 5.05
60 s	1.32	0.44 ^{AB} ± 0.020	47.4 ^B ± 5.21
105 s	1.33	0.43 ^A ± 0.010	55.3 ^A ± 3.33

Means with the same letter for a column are not significantly different (DMRT, p<0.05)
n=4

Infrared heating produced an overall effect on the consistency coefficient means (ANOVA $p \leq 0.010$). But only the exposure of 105 s was significantly different from the control flour (DMRT, $p = 0.05$). Consistency coefficient of the flour increased as infrared exposure time increased. This increase was 9.6, 17.0 and 36.6 % for the 30, 60, and 105 s of infrared exposure, respectively (Table 4.4).

Infrared heating did not have a significant effect on the flow behaviour index. Only the exposure time of 105 s was significantly different from the control flour, and the three exposure times were not significantly different from each other (DMRT, $p = 0.05$).

Shear stress and shear rate data were correlated by a two parameter power law model (Eq. 3.8) (Fig. 4.4). The classical approach in describing mathematically the relationship between shear stress and shear rate as indicated by equation 3.8 was not perfectly correlated. The simulation results over predicted the shear stress in all experiments for the shear rate

above 30 s⁻¹. To correct this inefficiency, Eq. 3.8 was modified to the following form:

$$\tau = K_1 \left[C_{FI} \gamma \exp \left(-\frac{\gamma}{C_T} \right) \right]^{n_1} \quad (4.1)$$

Where:

K₁ = modified consistency coefficient,

n₁ = modified flow behaviour index,

C_{FI} = modified Rabinowitsch-Mooney correction factor, and

C_T = correction factor

The modified correction factors are obtained using a “best fit” approach (Cenkowski et al. 1996). The verification of this approach is shown in Fig. 4.5. The modified coefficients used are shown in Table 4.5.

Table 4.5 Values for the modified coefficients in Eq. 4.1 for dough prepared from the control and flour exposed to infrared radiation for three different times (30, 60, and 105s).

Coefficients	Infrared treated flour for			
	Control	30 s	60 s	105 s
K ₁	40.0	40.0	45.0	45.0
n ₁	0.521	0.516	0.502	0.495
C _{FI}	0.95	0.95	1.00	1.35
C _T	1000	940	900	900

Means with the same letter for a column are not significantly different (DMRT, p < 0.05), n=4

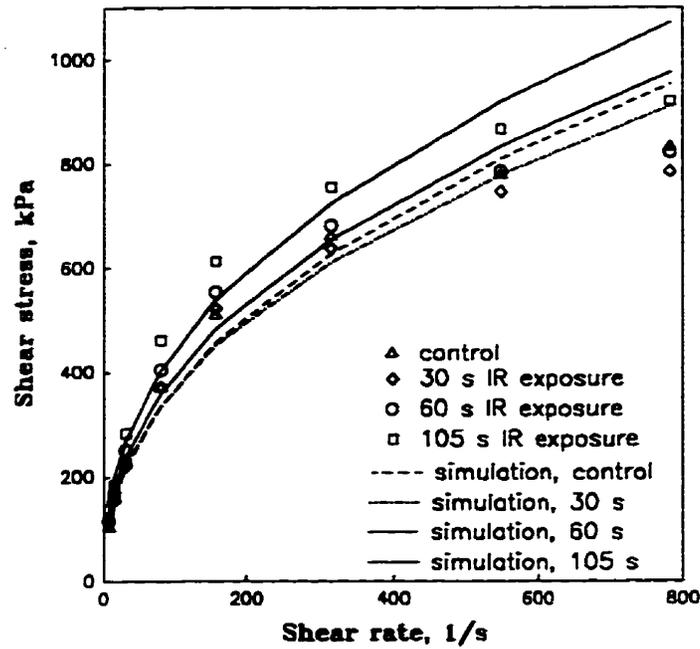


Fig.4.4 Shear stress vs. shear rate in capillary flour-water dough extrusion for the control sample and the dough prepared from flour exposed to infrared radiation for 30, 60, and 105 s.

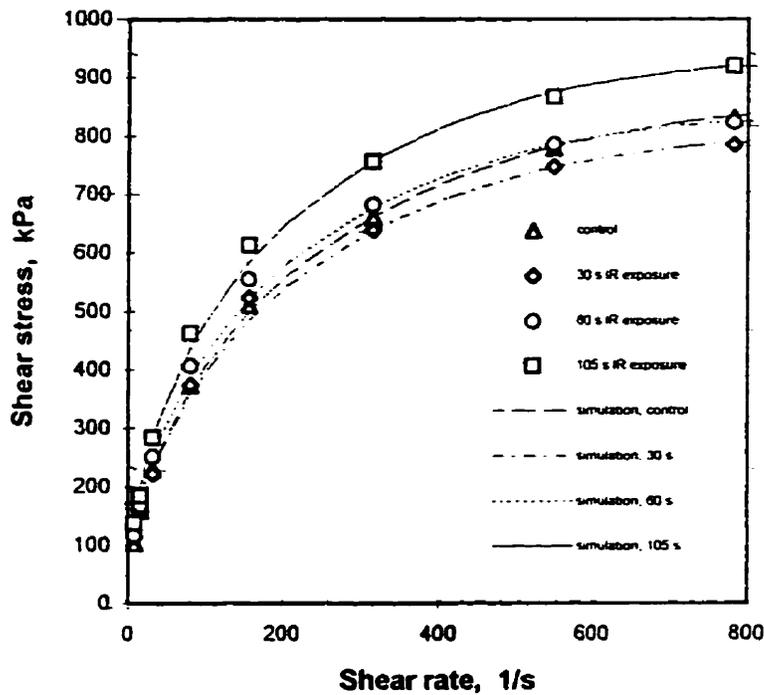


Fig. 4.5 Verification of the modified equation 4.1 against the results obtained at the conditions indicated in Fig. 4.4.

4.2.2 Farinograph

Water absorption, development time, arrival time, stability, and mixing tolerance index (M.T.I.) of the control flour and the three infrared treated flours are shown in Table 4.6.

The farinograms of control flour and three infrared treated flours, organized in order of increasing infrared exposure time from top to bottom, are shown in Fig. 4.6.

Infrared exposure time significantly affected the water absorption of the flour. (ANOVA, $p \leq 0.0001$). The three infrared treatments produced effects on the water absorption that differed significantly from each other and from the control flour (DMRT, $p = 0.05$). Reduction in water absorption capacity due to infrared treatment was 1.5, 3.7, and 9.3% for the flour treated at 30, 60 and 105 s, respectively.

Infrared treatments did not have any effect on the Farinograph arrival time. The control flour had an arrival time of 3 minutes, similar to that of the infrared treated flours.

Infrared exposure time had a significant effect on development time of the dough (ANOVA, $p \leq 0.0001$). However, only exposure time of 60 s or longer were significantly different from the control flour (DMRT, $p = 0.05$). Development time was increased by 7 % in flour exposed to infrared for 60 s and 20% for flour exposed for 105 s.

Infrared radiation had a highly significant effect on stability of the dough (ANOVA, $p \leq 0.0001$). The effect of the 30 s treatment on stability was not significantly different from the effect of the 60 s treatment (DMRT $p < 0.05$). Infrared radiation increased stability of the dough by 51.7% and 58% for the 30 and 60 s treatments and by 100% for the 105 s treatment.

Infrared heating decreased significantly the mixing tolerance index of the dough

(ANOVA, $p < 0.0015$). However, this effect was not significantly different from the control flour for exposure time less than 60 s (DMRT, $p = 0.05$). The M.T.I. decreased by 20% in flour treated for 60 s and 35% in flour treated for 105 s.

Table 4.6 Farinograph indices for CWRS flour exposed to different infrared radiation times (30, 60, and 105s) when the lamp was rated at 120 V and placed 70 mm away from the sample.

Properties	Control	Infrared Treated		
		30 s	60 s	105 s
Water absorption (%)	63.1 ^A	62.1 ^B	60.8 ^C	57.2 ^D
Arrival Time (min)	3.0 ^A	3.0 ^A	3.0 ^A	3.0 ^A
Development Time (min)	7.5 ^C	7.5 ^C	8.0 ^B	9.0 ^A
Stability (min)	14.5 ^C	22.0 ^B	23.0 ^B	29.0 ^A
Mixing Tolerance Index (B.U)	29.0 ^A	29.0 ^A	23.0 ^B	19.0 ^C

B.U : Brabender Units

Means with the same letter for a row are not significantly different (DMRT, $p=0.05$), $n=2$

4.2.3 Mixograph

Table 4.7 shows the mixing time to peak development (MDT), work input to peak (WIP), peak height, right of peak (dough weakening angle) for the control flour doughs and for three doughs made with flour exposed to infrared rays for 30, 60, and 105 s.

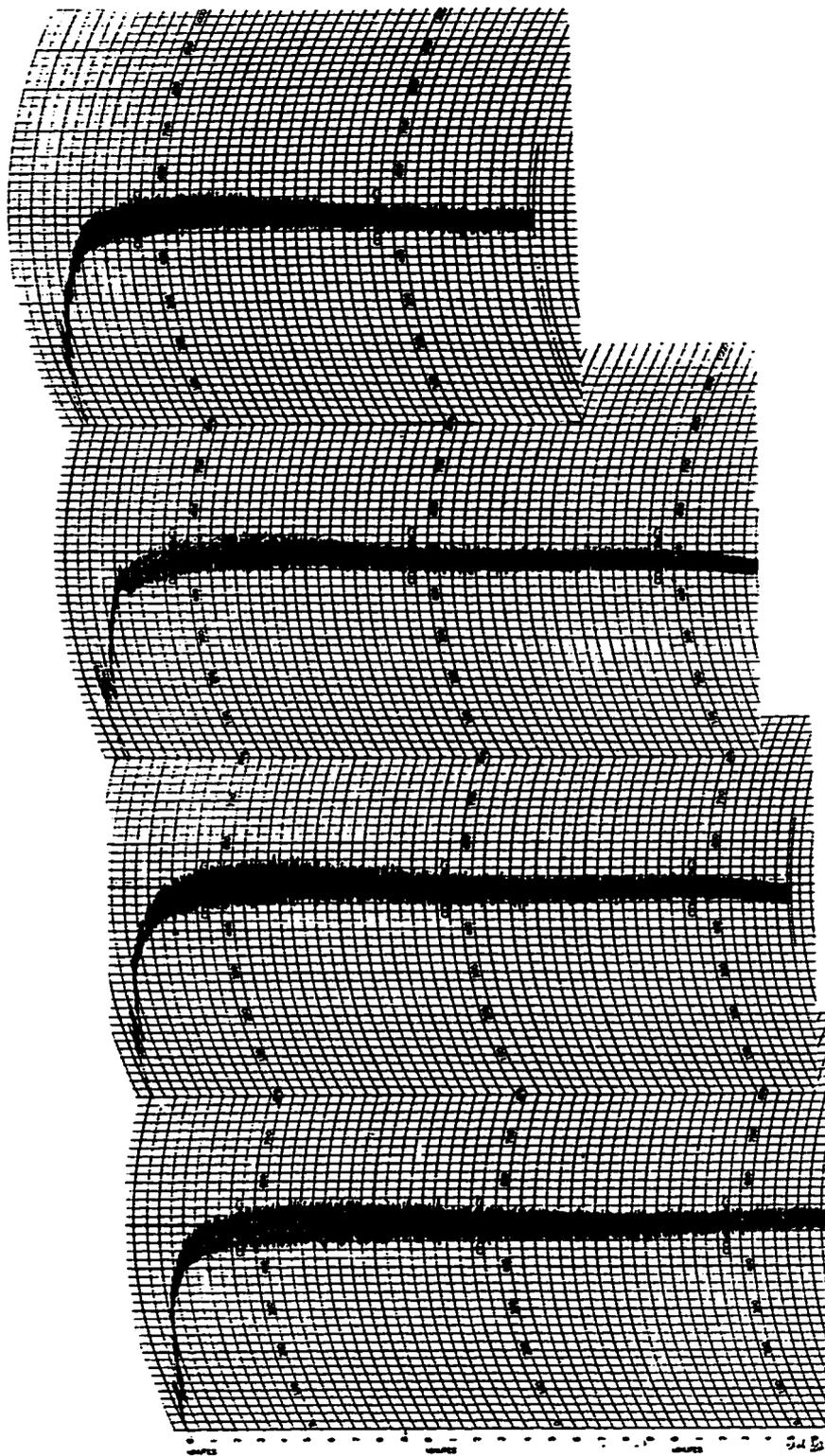


Fig. 4.6 Farinographs of CWRS flour arranged from top to bottom of increasing infrared exposure time (Control flour, 30, 60, and 105 s)

Fig. 4.7 shows the Mixograph curves of flour arranged in order of increasing infrared treatment time from top to bottom. Flour water absorption was adjusted to 63 % at 14% moisture content for all flour tested.

Infrared heating produced significant effects on the mixing time to peak development of the flour doughs tested (ANOVA, $p \leq 0.0001$), but exposure time of 30 s was not significantly different from the control flour (DMRT, $p = 0.05$). Peak times of the flour heated with infrared increased by 1.8, 6.6 and 51.8% for the 30, 60 and 105 s infrared exposure time respectively.

Infrared treatment did not have a significant effect on the peak height (ANOVA, $p \leq 0.139$). Infrared rays had a significant effect on work input to peak (ANOVA, $p \leq 0.0001$). All the exposure time means with the exception of 30 s were significantly different from the control (DMRT, $p = 0.05$).

Table 4.7 Mixograph results for CWRS flour exposed to infrared for 30, 60 and 105 s when the lamp was rated at 120 V and placed at 70 mm away from the flour surface.

Properties	Infrared Treated flour			
	Control	30 s	60 s	105 s
Mixing time to peak development (min)	4.42 ^C	4.50 ^{BC}	4.71 ^B	6.71 ^A
Work input to peak (% Tq * min)	138 ^C	136 ^C	161 ^B	244 ^A
Peak height (MU)	47.4 ^B	47.7 ^{AB}	50.5 ^A	48.5 ^{AB}
Right of peak	3.74 ^A	3.57 ^A	3.57 ^A	1.94 ^B

MU: Mixograph Units.

Means with the same letter for a row are not significantly different (DMRT, $p \leq 0.05$), $n=3$.

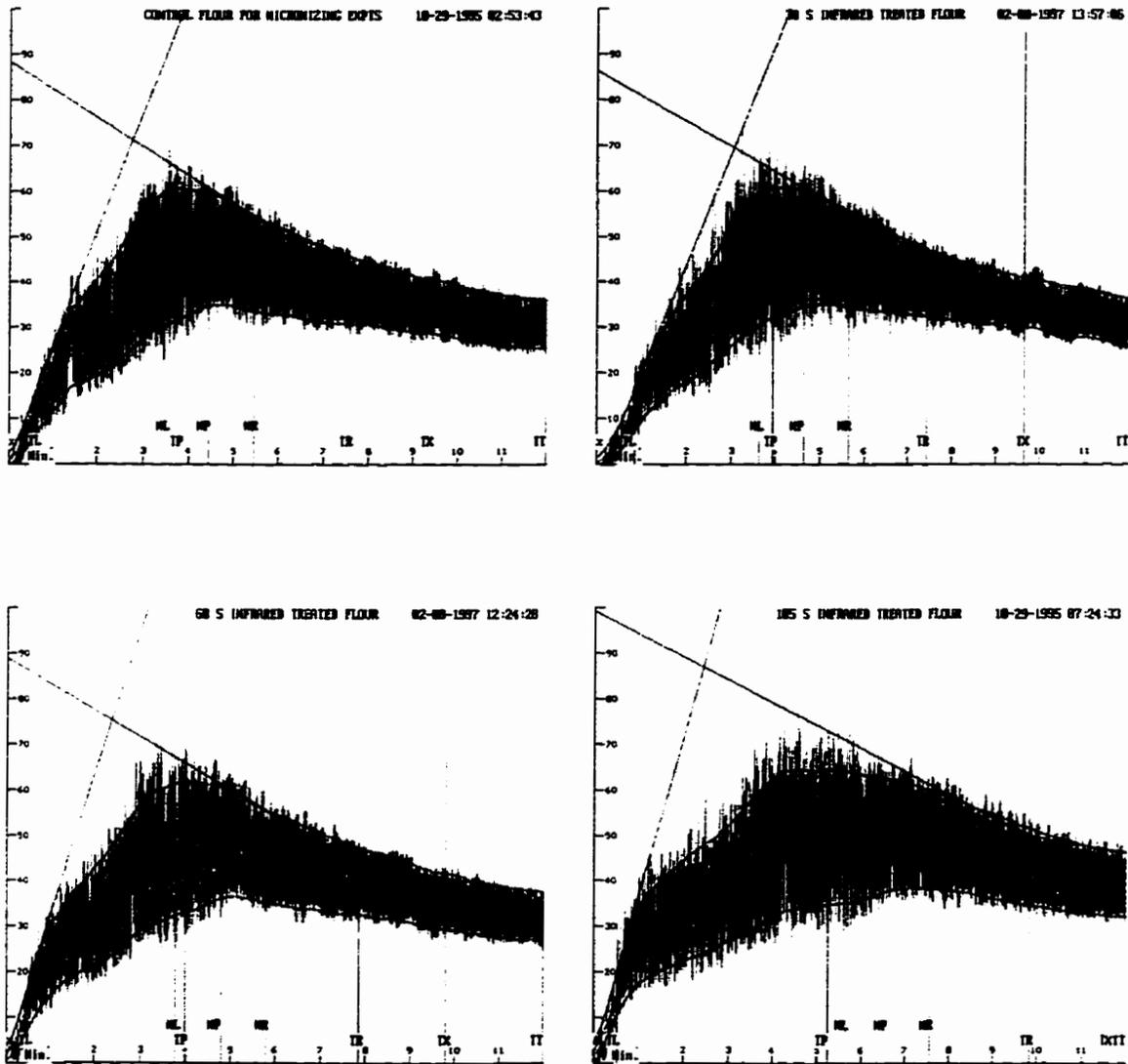


Fig. 4.7 Mixographs of CWRS flour. Each of the times in the envelope and mid line report is represented graphically as a vertical line which overlays the data. These lines are identified by two letter codes at their bases. The symbols used for the envelope: left of peak (TL), peak (TP), right of peak (TR), curve tail (TT), time (TX). Symbols used for the middle line: left of peak (ML), peak (MP), right of peak (MR), curve tail (TT), and time (TX).

Infrared exposure time decreased significantly the right of peak (ANOVA, $p \leq 0.0096$). All the exposure time means with the exception of 105 s were not significantly different from the control flour (DMRT, $p = 0.05$).

4.2.4 Falling Number

Falling Numbers for the control flour and the three infrared treatments are shown in Table 4.8. Infrared treatment did not have any effect on the α - amylase activity, even when the flour reached an average temperature of $78.9^\circ\text{C} \pm 1.5$.

Table 4.8 Falling Number and its standard deviation of CWRS flour exposed to different infrared radiation times (30, 60, and 105 s) when the lamp was operated at 120 V and placed 70 mm away from the sample

	Control	Infrared Treated		
		30 s	60	105 s
Falling Number	$538.0^A \pm 14.76$	$519.3^A \pm 8.18$	$517.7^A \pm 20.33$	$514^A \pm 5.72$

Means with the same letter are not significantly different (DMRT, $p = 0.05$), $n=3$

4.2.5 Viscoamylograph.

The Viscoamylograph results for control flour and the three infrared treated flours are shown in Table 4.9. Infrared heating up to 105 s did not have a significant effect on Amylograph viscosity.

Table 4.9 Amylograph peak and its standard deviation of CWRS flour exposed to different infrared radiation times (30, 60, and 105 s) when the lamp was operated at 120 V and placed 70 mm away from the flour.

	Control	Infrared Treated		
		30 s	60 s	105 s
Peak height (B.U.)	786.7 ^A ± 24.94	776.7 ^A ± 17.00	763.3 ^A ± 17.00	753.3 ^A ± 9.43

Means with the same letter are not significantly different (DMRT, $p = 0.05$), $n=3$

4.2.6 Wet gluten content

Wet gluten values for control flour and the three infrared treated flours are shown in Table 4.10. There was a significant effect from the infrared treatment on the flour gluten (ANOVA, $p \leq 0.005$). By comparing the treatment means using the Duncan Multiple Range Test (DMRT) it was observed that gluten in the control flour was significantly different from the gluten of the three infrared treated flours, although gluten contents of flour exposed for 30 and 60 s were not significantly different. Wet gluten percentage reduction due to infrared radiation was 5.3% in flours exposed for 30 and 60 s, and 11.5% in flours exposed for 105 s.

Table 4.10 Wet gluten content and its standard deviation of CWRS flour exposed to different infrared radiation times (30, 60, and 105 s) when the lamp was operated at 120 V and placed 70 mm away from the flour

	Control	Infrared Treated		
		30 s	60	105 s
Wet gluten content (%)	35.7 ^A ± 0.41	33.8 ^B ± 0.25	33.8 ^B ± 0.40	31.6 ^C ± 0.29

Means with the same letter are not significantly different (DMRT, $p = 0.05$), $n=3$

4.2.7 Starch damage

Starch damage values for control flour and the three infrared treated flour are shown in Table 4.11. This test gives an estimated proportion of total starch that is damaged (Farrand, 1964). Infrared radiation did not have a significant effect on the percentage of starch damage.

Table 4.11 Starch damage (%) and its standard deviation for CWRS flour exposed to infrared for 30, 60, and 105 s when the lamp was operated at 120 V and placed 70 mm away from the flour.

	Control	Infrared Treated		
		30 s	60 s	105 s
Starch damage (%)	26.0 ^A ± 0.00	25.5 ^A ± 0.70	26.0 ^A ± 0.00	26.5 ^A ± 2.12

Means with the same letter are not significantly different (DMRT, $p < 0.05$), $n=2$

4.2.8 Canadian short process method

Loaf volumes, bread appearance, crumb structure and colour scores for breads made with control flour and the three infrared treated flours are shown in Table 4.12. These values are one single reading. Infrared radiation did not decrease the loaf volume of breads made with flours that were exposed to infrared for 30, and 60 s, and slightly decreased loaf volume for the bread made with flour treated for 105 s which was reduced by almost 9%. Total score (crumb structure and colour) for bread made with flour treated with infrared for 30 s improved substantially (20%) compared to the control flour. Total score for bread made with

flour treated with infrared for 105 s decreased by 5%.

Table 4.12 Baking results for CWRS flour exposed to infrared for 30, 60, and 105 s when the lamp was rated at 120 V and placed at 70 mm away from the flour.

	Control	Infrared Treated		
		30 s	60 s	105 s
Volume (ml)	1050	1065	1040	960
Appearance	7.2	7.8	7.5	7.5
Crumb Structure	6.5	6.8	7.2	6.5
Crumb Colour	8.2	8.5	7.5	8.2
Total Score	74	89	78	71

4.2.9 Spectrophotometric method for measuring functional glutenin

Infrared radiation did not have a significant effect on the percentage of insoluble glutenin in propanol/DTT on the infrared treated flour.

Table 4.13 Percentage of insoluble glutenin for CWRS flour exposed to infrared for 30, 60, and 105 s when the lamp was rated at 120 V and placed 70 mm away from the flour.

	Control flour	Infrared Treated Flour		
		30 s	60 s	105 s
Insoluble glutenin (%)	21.62 [^]	21.65 [^]	21.40 [^]	23.30 [^]

Means with the same letter are not significantly different (DMRT, $p < 0.05$), $n=2$

4.3 Thermal Behaviour of Flour-Water Mixtures on the DSC

Flour water mixtures at 80% (w/w) moisture content made with control flours and three infrared treated flours exhibited one well defined gelatinization peak and three small peaks transitions when heated from 0 to 100 °C at a heating rate of 10 °C/min in the DSC. These peaks should mainly represent the thermal transitions of starch and gluten since they are flour main components (80% for starch and 9 to 18% for protein). Some lipids are also present in as small percentage but thermographs of separated wheat lipids do not give peaks (Elliason and Hegg 1980). Onset, peak and complete temperatures for the gelatinization peak and enthalpy differences of the control flour and the three infrared treated flours are shown in Table 4.14. Infrared treatment neither had a significant effect on gelatinization temperature nor on the enthalpy change.

Table 4.15 shows temperature for the second, third and fourth peaks. Infrared heat did not affect significantly temperatures for the second and fourth peak transitions. The third transition temperatures were significantly affected by infrared radiation (ANOVA, $p \leq 0.028$). However, only exposure time of 60 s or longer was significantly different from the control flour. (DMRT, $p = 0.05$). Fig. 4.8 shows a thermogram.

Table 4.14 Temperatures, °C, for Onset (To), Peak (Tp), and Completion (Tc), and enthalpy change (ΔH) and their standard deviation for flour-water mixtures at 80% (w/w) made with control flour and flour exposed to infrared radiation for three different times (30, 60, and 105 s).

Flour	Temperature			Enthalpy change(J/g)
	To	Tp	Tc	
Control	49.0 ^A ± 0.82	59.0 ^A ± 0.57	68.7 ^A ± 1.25	9.0 ^A ± 2.15
30 s	49.3 ^A ± 0.47	58.3 ^A ± 0.83	68.7 ^A ± 1.26	9.2 ^A ± 1.34
60 s	50.7 ^A ± 1.70	59.0 ^A ± 1.76	69.3 ^A ± 4.03	9.7 ^A ± 2.11
105 s	50.0 ^A ± 0.82	57.8 ^A ± 0.59	68.0 ^A ± 0.82	8.7 ^A ± 0.76

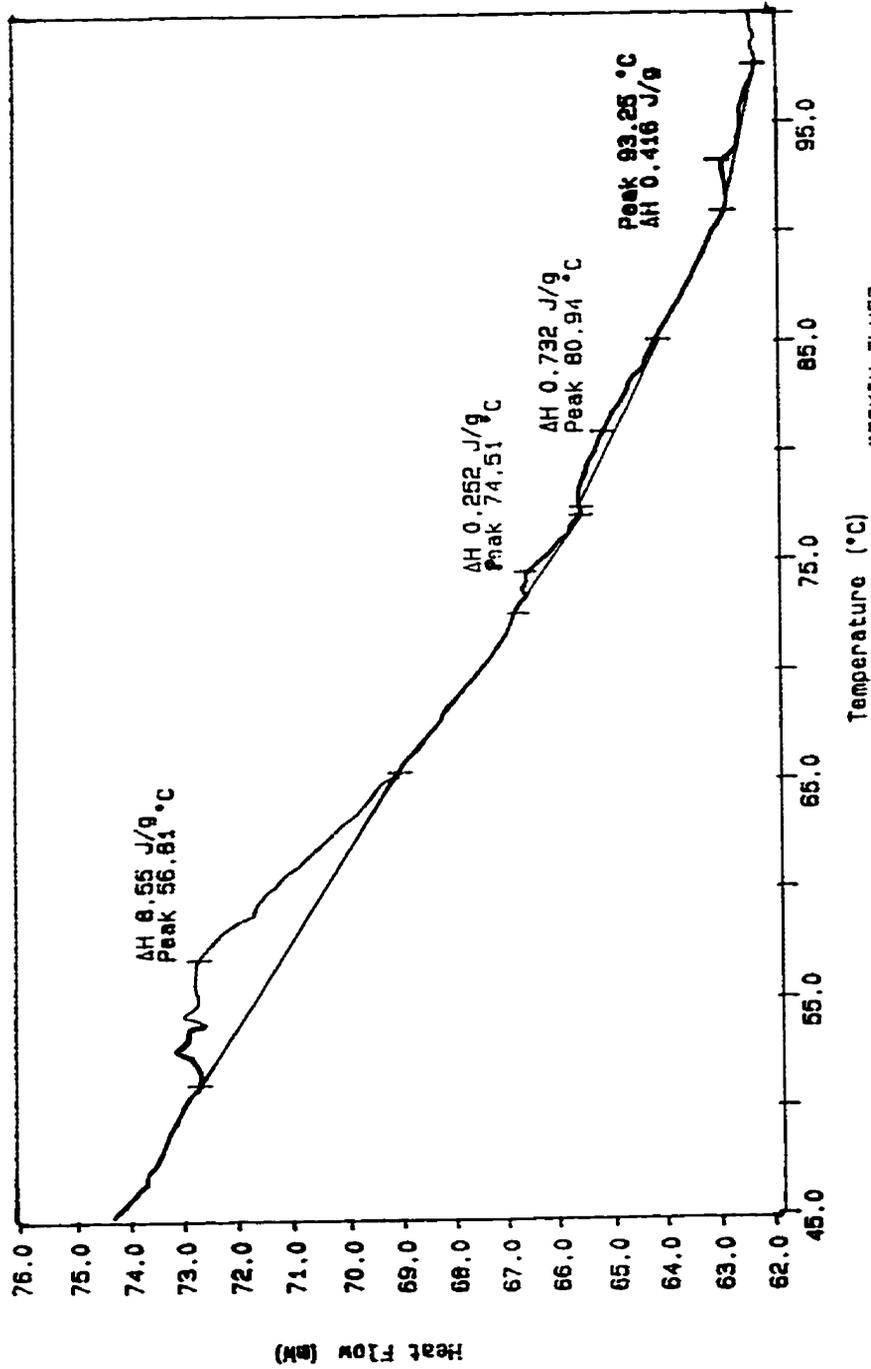
Means with the same letter for a column are not significantly different (DMRT, p=0.05), n = 3

Table 4.15 Temperature and standard deviation for the second, third, and fourth transitions of flour-water mixes at 80% (w/w) made with control flour and the three infrared treated flours (30, 60, and 105 s).

Flour	Temperature Transitions (peak temperatures)		
	2nd	3rd	4th
Control	72.6 ^A ± 1.18	80.0 ^B ± 0.85	89.5 ^A ± 3.44
30 s	70.5 ^A ± 1.80	77.6 ^C ± 0.83	90.1 ^A ± 1.08
60 s	73.9 ^A ± 4.71	85.1 ^A ± 3.01	94.3 ^A ± 0.73
105 s	72.9 ^A ± 0.86	82.5 ^{AB} ± 2.33	91.1 ^A ± 3.70

Means with the same letter for a column are not significantly different (DMRT, p = 0.05), n=3.

Curve 1: DSC
 File Info: 60j27807 Sat Jul 27 23: 05: 22 1996
 Sample Weight: 8.220 mg
 60j27808



TEMP: 18.8 8 TIMES: 0.0 MIN RATE: 10.0 C/MIN
 PERKIN-ELMER
 7 Series Thermal Analysis System
 Thu Jun 5 19: 15: 20 1997

Fig. 4.8 Thermogram of CWRS flour

5 DISCUSSION

5.1 Effect of infrared treatment on starch

Infrared radiation did not have a significant effect on the susceptibility of starch to hydrolysis by the α -amylase action as the Falling Number, the Viscoamylograph peak, and the amount of damaged starch were not significantly affected by the infrared treatment, nor were the DSC peaks associated with starch affected by infrared treatment.

The Falling Number measures the α - amylase activity which depends on the amount of enzyme present and on the susceptibility of starch to hydrolysis (Shuey 1975). The amount of enzyme present in the CWRS flour was quite low from the beginning as shown by the high Falling Numbers obtained (between 538 and 514). These values are even higher than the acceptable range of 200-300 for wheat used in the production of leavened bread (Mailhot and Patton 1988). The susceptibility of starch to hydrolysis by α - amylase was not affected by infrared radiation (Table 4.9 and 4.11).

In a similar manner, infrared treatment did not significantly affect the rate at which starch gelatinizes nor the rate at which the α -amylase liquefies starch as the maximum viscosity of the flour paste (Amylograph peak) was not affected. The percentage of damage starch exhibited by the flour fall into the range of a North American bread flour (15 to 30 %) (Farrand 1964) and was not further increased by the infrared treatment. Similar results were obtained by Ghaly et al. (1973) who measured the effect of heat induced damage in wheat as a consequence of sprouted bed drying. They found that heat treatment did not have any effect on the α -amylase activity and on the susceptibility of starch to hydrolysis.

Further support for the Viscoamylogrph result is provided by the DSC results (Table

4.14 and 4.15). Starch gelatinization properties seems not to be significantly affected by infrared radiation. This is concluded from the characteristics of the first transition peak shown in the thermogram of the flour water mix (Fig. 4.8).

Gelatinization characteristics were obtained from the onset, peak and completion temperature and process enthalpy. The gelatinization peak temperature, obtained around 57.8 to 59 °C, was not significantly affected by infrared radiation. Similar results were obtained by Jovanovich et al. (1992) and Ghiasi et al. (1983) who reported gelatinization peaks at 62 and 61°C in flour-water mixtures at 60% and 66 % respectively. Although the flour-water mixtures used in this experiment were at 80%, the comparison between samples is valid since the temperature of the first transition does not vary significantly with water (Eliasson 1980, Wootton and Bamunuarachchi 1979). The onset, and completion temperature as well as the process enthalpy were also not significantly affected by infrared radiation. Therefore, it can be concluded that infrared radiation did not significantly affect the amylose-amylopectin arrangement, and the molecular and physical structure in starch as gelatinization characteristics which result from the amylose-amylopectin arrangement (Medcalf 1969) were not significantly affected by infrared rays.

The second and fourth peak transitions observed in the thermogram showed that the fusion of more stable starch crystals (Jovanovich et al. 1992) and the dissociation of the amylose lipid complex (Kugimiya et al. 1980) were not significantly affected by infrared radiation. The third peak obtained in the thermogram corresponds to protein denaturation. The second peak occurred between 70.5 and 72.9 °C and corresponds to the fusion of more stable starch crystals. Jovanovich et al. (1992) reported this transition at 80 °C in flour-water

mixtures at 60%. The discrepancies in temperature are due to the differences in water content in the samples. The higher the moisture content the lower the temperature of the peak transition (Eliasson 1980, Wootton and Bamunuarachchi 1979).

The fourth peak, occurring around 89.5 to 94.3 °C, corresponds to the dissociation of the amylose lipid complex (Kugimiya et al. 1980). Similar results were reported by Jovanovich et al. (1992) and Ghiasi et al. (1983) who found the amylose-lipid peak near 118 °C and at 100 °C in flour-water mixtures at 60 and 66% respectively. The differences in temperatures between Jovanovich et al. (1992) and Ghiasi et al. (1983) experiments and the results reported in this experiments are due to the fact that this peak transition depends on the water content. The higher the water content, the lower the temperature transition (Eliasson 1980, Wootton and Bamunuarachchi 1979).

5.2 Effect of infrared treatment on gluten

Infrared radiation had a significant effect on gluten as dough mixing characteristics and Farinograph water absorption were significantly affected in the infrared treated flour. Physical properties of dough, measured in the Farinograph and Mixograph, are in large extent attributable to its gluten (Doguchi and Hlynka 1967). The effect of infrared heat on gluten could be also observed by the decrease in wet gluten content and the increase in insoluble glutenin in propanol/DTT as infrared exposure time increased.

The flour water absorption decreased as infrared exposure time increased. However, the water absorption for the 30 and 60 s infrared treated flour still fall into the optimum range (60-64%) given by the bread industry. The reduction in flour water absorption is most

likely due to the effect of infrared heat on gluten water imbibing capacity. Absorption levels of flour are influenced by protein content, as the most important factor, starch condition, the presence of minor constituents such as dextrans, pentosans and cellulose. The water soluble proteins have no water imbibing properties (Hlynka 1964) whereas gluten has a relatively constant water-imbibing capacity (about 2.8 times to dry gluten content). Gluten present in the infrared treated flour for 60, and 105 s was affected as these flours reached temperatures of $64.2^{\circ}\text{C} \pm 1.8$ and $78.9^{\circ}\text{C} \pm 1.8$, respectively. At these temperatures gluten is affected (Schofield et al.1983). Starch was not significantly affected by infrared radiation as shown by starch damage test and the DSC results. Other flour compounds such as cellulose and dextrin may have been affected by infrared heat but their influence is minor because of the small amount present in flour (Hlynka 1964).

Control flour-dough and dough made with the infrared treated flours exhibited non-Newtonian behaviour in the shear rate range of 7.8 to 782.5 s^{-1} . Those results are in agreement with Bhattacharya and Hanna (1986) who stated that food dough are non-Newtonian in nature. Dough flow curves were shaped concave downward on the shear stress-rate axis. This shape denotes pseudoplastic behaviour in which dough appears to become less viscous as the shear rate increases. Similar results were obtained by Sharma et al. (1993) who found that wheat flour dough had a pseudoplastic behaviour at shear rate range of 9 to 5000 s^{-1} .

The effect of infrared radiation in the flour absorption capacity may be mainly responsible for the increase in the consistency coefficient or apparent viscosity (Mohsenin 1984). The water content of the doughs made with the infrared treated flour for 30, 60, and

105 s was 46.9, 46.4 and 45.3%, respectively. The dough water content decreased as infrared exposure time increased because infrared radiation decreased the flour water absorption and the amount of water added to the dough was determined by the flour water absorption. Dough consistency coefficient increases dramatically with decrease in the amount of the water in the dough (Sharma and Hanna 1992). For instance, a 10 % decrease in water content caused an increase of 95% in the consistency coefficient, and a 5 % water decrease produced a 74 % increases in this coefficient. The results obtained for the dough made with flour exposed to infrared for 30, 60, and 105 s showed that these treatments caused a decrease in dough water content of 0.3, 0.8 and 1.9% and an increase in the consistency coefficient of 9.6, 17 and 36.6% (Table 4.4) respectively. Denatured gluten may have also contributed to the increase in the consistency coefficient as seen in the dough made with the infrared treated flours. Denaturation of protein increases the viscosity of solutions (Neurath et al. 1944, Bhattacharya and Hanna 1986). Infrared treated flour reached temperatures at which gluten denaturation occurs (between 50 and 65 °C) (Alsberg and Griffing 1927). The CWRS flour reached temperatures of $50^{\circ}\text{C} \pm 1.8$, $64.2^{\circ}\text{C} \pm 1.8$ and $78.9^{\circ}\text{C} \pm 1.8$ when exposed to infrared radiation for 30, 60 and 105 s respectively. Consistency coefficient, which increased as infrared exposure time increased, reflects the viscosity of a fluid and can be used to assess the dough handling properties (Sharma and Hanna 1992). Therefore, bakeries have to take this into consideration when designing the pumping system. However, the consistency coefficient obtained for the infrared treated flour might not apply completely as bakeries use a yeast dough containing other ingredients besides water which affect the consistency coefficient as this depends on dough composition (Sharma and Hanna 1992).

Flour water absorption and loaf volumes were positively related. The 30 and 60 s infrared treated flours which had high water absorption values gave high loaf volume. Flour treated with infrared for 105 s had the lowest water absorption and the lowest loaf volume.

They are two aspects relating to mixing characteristics. Firstly, those Mixograph and Farinograph indices that relate to dough development during mixing (arrival time and development time for the Farinograph and mixing time to peak development (MDT), work input to work (WIP) and peak height for the Mixograph). Secondly, those indices relating to stability, to breakdown of the dough upon continued mixing (stability and M.T.I. of the Farinograph and dough weakening angle of the Mixograph). Both of these aspects are affected by infrared treatment in ways that are dependent on changes in gluten functionality.

Dough made with infrared treated flour required longer mixing time to develop to an optimum, can be mixed for longer time before it starts to breakdown (dough development time and mixing time to peak development), became more resistance to mixing, over mixing, mechanical abuse and would hold longer fermentation (Mixing tolerance index, dough weakening angle, and stability). Arrival time was not significantly modified by infrared heat (Table 4.6). It is important to point out that doughs had different water content since the flour water absorption was reduced by infrared heat. The control flour had the highest absorption value (63.1%) and flour treated with infrared for 105 s had the lowest value (57.1%). Mixing time to peak development, which increased as infrared exposure time increased, is similar to the dough development and the longer the peak time, the more the dough requires to develop to an optimum consistency (Shuey 1975, Johnson et al. 1943). Similar results were reported by Neufeld and Walker (1990) who measured the mixing

characteristics of gluten samples heated at 110 °C for various time (2.5 to 10 hr) and found that the mixing time increased as the heating time increased.

No chemical analyses were conducted to determine the effect of infrared on gluten structure. However, it is suspected that the increase in the dough development time is mainly caused by the decrease in the degree of interactions between glutenin and gliadin due to glutenin denaturation by heat. During mixing, glutenin desegregates, depolymerizes and reaggregates with gliadin forming a viscous-elastic gluten (Mecham 1980, Belitz et al. 1986). The time required for this disaggregation and reaggregation depends on the degree of interaction between glutenin and gliadin (Dupuis et al. 1996). Cultivars that have more aggregated gliadin-glutenin in the flour could require less mixing for optimum development and vice versa. Sapirstein and Fu (1996) stated that gliadin-glutenin interactions in strong wheats would be lower than in weak wheats. It is suspected that glutenin properties were altered in the flour exposed to infrared radiation, since its properties start being affected by heat at 55 °C (Schofield et al. 1983), and the infrared treated flour for 60 and 105 s reached higher temperatures ($64.2\text{ °C} \pm 1.8$ and $78.9\text{ °C} \pm 1.8$ respectively). The effect of infrared radiation on glutenin could be also observed from the changes in the mixing characteristics of the infrared treated flours (Bietz and Huebner 1980). Glutenin contained in the infrared treated flours would not interact with gliadin as much as the glutenin in the control flour would do. Gliadin acts as a plasticizer by weakening the mutual interaction between the gluten aggregates (Fu 1996).

It is also suspected that the increase in glutenin size due to aggregation with itself might contribute to explain the increase in mixing time observed in the infrared treated flours.

Wheat flour proteins have a strong tendency to aggregate (Fu, 1996) and this susceptibility to aggregation is enhanced by heat (Neurath et al. 1944). Schofield et al. (1983) stated that heat induced changes in glutenin appears to involve disulfide and sulphhydryl interchange reactions and the effect of these reactions is to increase the molecular size of the glutenin aggregates. Gliadins do not appear to be affected by heat at the lower temperatures but at temperatures greater than 70 °C also undergo chemical changes, again involving SH group reactions. Jeanjean et al. (1980) also studied the changes that occur in gluten when heated at 100 °C and they suggested similarly that protein aggregation occurs through disulfide formation. Weegels et al. (1994b) found a high degree of aggregation of glutenin after heating. Time to peak development depends largely on the size, structure and concentration of glutenin polymers and ratio of gliadin to glutenin (MacRitchie 1992). Gupta et al. (1993) speculated that the average molecular size of gluten in strong gluten is larger than in weak gluten. Strong wheats generally have a longer mixing time than weaker ones (Pylar 1982).

The most noticeable effect of infrared treatment on the mixing characteristics of flour was the increase in stability of the dough, which increased 100 % on the flour exposed to infrared for 105 s. The resistance to mixing and mechanical abuse and fermentation time is directly related to stability (Pylar 1982, Shuey 1975). It is important to point out that the control flour had a high stability (14 minutes). Similar results were obtained by Kent-Jones and Amos (1967) who found that the addition of 0.7 % of highly overheated flour (heated at 82 °C for 10 hours) to ordinary flour increased the stability of the dough rendering it more elastic and less inclined to flow. As the infrared exposure time increased the mixing tolerance index decreased, and the dough weakening angle became larger (Table 4.7). Flour with low

MTI have a good tolerance to mixing while dough with high MTI's are sensitive to mixing and especially to over mixing (Shuey 1975). The greater the dough weakening angle is, the more rapid breakdown occurs (Pylar 1982). Stronger flours have a smaller dough weakening angle.

It seems to be that infrared heat gave to the CWRS flour some characteristics of strong flour. Infrared heat increased development time and stability, and decreased mixing tolerance index of the dough. The first two indices are positively related and the last one is negatively related to dough strength (Pylar 1982). Strong flours are the preferred raw material for the production of bread. A flour might be too strong for bread making, such a flour can be used in blends to improve weaker flours (Bloksma and Bushuk 1988). It seems to be that infrared radiation has a similar effect as adding GLU-R fractions to flour and replacing gliadin by a HMW fraction (glutenin). Fu (1996) found that these fractions increased the DDT and WIP of the doughs at equivalent levels of protein enrichment. Preston et al. (1975) stated that replacing gliadin by a HMW fraction (glutenin) improved the strength of mixing curves for synthetic dough consisting of gliadin, glutenin and starch.

The effect of infrared radiation on gluten functionality could be also observed from the decreased in wet gluten content in the flour exposed to infrared rays for 60 and 105 s. These results are expected since gluten is affected by heat at temperatures above 55° C (Cook 1931, and Schofield et al. 1983) and the infrared treated flours reached temperatures of $64.2^{\circ}\text{C} \pm 1.8$ and $78.9^{\circ}\text{C} \pm 1.8$. Similar results were obtained by Swanson (1939) who found that heating wheat at 70 and 100° C decreased the amount of gluten. It is suspected that the decrease in wet gluten content is mainly due to the reduction of the gluten water-

imbibing capacity caused by denaturation as mentioned early. Gluten imbibes water that makes up for 2/3 of the wet gluten mass (Knight 1965) and its properties are affected by heat at 55 °C.

Visco-elastic properties of gluten obtained from flour treated with infrared for 105 s were altered by infrared heat. Gluten obtained from flour exposed to infrared for 105 s was less elastic than the control flour and it did not extend as much as the control flour gluten did. This was observed from stretching the gluten. No tests were performed to measure elastic properties of gluten. Gliadin and glutenin are responsible for the visco-elastic properties of gluten. Hydrated glutenin is more elastic than gliadin, and hydrated gliadin is more extensive than glutenin (Inglett 1974). The temperature reached by the flour after 105 s of infrared heat was $78.9\text{ }^{\circ}\text{C} \pm 1.5$. At this temperature not only glutenin but gliadin is affected by heat (Cook 1931, Schofield et al. 1983). Gluten might be denaturalized by this stage.

The results obtained in the DSC on protein denaturation are not very conclusive. The thermograph showed a peak (3rd peak) around 77.6 and 85.1°C that is most likely due to denaturation of protein. The ANOVA analysis showed that temperature was significantly affected by infrared radiation. However, the standard deviation was very high (2.3 and 3.1 for the 60 and 105 s treated flour respectively). Results obtained on gluten denaturation by other researchers are also not very conclusive. Some authors like Arntfield and Murray (1981), Schofield et al. (1983), and Hoseney et al. (1986) found that wheat gluten gives only extremely small or no denaturation peak when heated from 30 to 130 ° C in a DSC. Whereas, Eliasson and Hegg (1980) found that isolated wheat protein gave two peaks (88.4 and 101 °C) at 63% moisture content.

The amount of functional glutenin, determined by the amount of insoluble glutenin increased as the infrared exposure time increased (Table 4.14). This is consistent with the work of Sapirstein and Johnson (1996) who found a high degree of correlation between the amount of insoluble glutenin and Mixograph development time, and work input to peak. However, the increase in insoluble glutenin in the infrared treated flours was not significantly different from the control flour. It is important to consider that the experiments were done only in duplicated.

Infrared treated flour exhibited Farinograms corresponding to strong flours. Flours that show curves corresponding to strong flours usually give high loaf volumes (Pomeranz 1988). However, this was not always the case with infrared treated flour. The 30 and 60 s infrared treated flour exhibited Farinograph curves that correspond to strong flours and gave loaf volumes similar to that of the control flour. However, flour treated with infrared for 105 s showed a Farinograph curve for a strong flour but gave the lowest loaf volume. This behavior might be explained by the different role play by gliadin and glutenin on dough and on the bread baking characteristics, and by the difference in sensitivity to heat shown by those proteins. Water soluble proteins do not appear to play an important role in bread making (Inglett 1974). Glutenin is responsible for the mixing requirements of dough which are described by the Farinograph and gliadin controls the loaf volume potential (Bietz and Huebner 1980). Infrared exposure of up to 60 s seems to affect glutenin since the mixing characteristics of the dough were changed, and it might have not affected gliadin since maximum average temperature reached by the sample was $64.2^{\circ}\text{C} \pm 1.8$, and the loaf volume was not affected. However, when infrared treatment lasts up to 105 s, the flour reached

78.9 °C ± 1.5, temperature at which gliadin is affected by heat and glutenin may be locked into a denaturalized stage on cooling due to sulphhydryl/disulfide interchange between exposed group (Schofield et al. 1983). This is demonstrated by the decrease in loaf volume (Table 4.12). Glutenin is the first protein to be affected by heat (Cook 1931) whereas gliadin is unaltered by heat up to 75 °C (Schofield et al. 1983). Similar results were obtained by Ghaly et al. (1973) who found that severely heated samples gave typical strong flours and a poor loaf volume (42% of the control value). This might be also explained by the fact that there is a low correlation between the principal Farinograph characteristics and loaf volume (Geddes et al. 1940, and Johnson et al. 1943).

The decreased in volume seen in the 105 s infrared treated flour (Table 4.12) may indicate a deterioration of the gluten quality since alteration of the properties of heated gluten can be measured by the decrease in loaf volume of dough (Pence et al.1958 and Ghaly et al. 1973). Similar results were obtained by Schofield et al. 1983 who found a decrease in loaf volume of approximately 44% in wet gluten samples heated in a water bath at 75°C. The baking test used by the authors was a long fermentation procedure.

Crumb characteristics (colour and structure) and bread appearance were scored higher in the infrared treated flours for 30 and 60 s than the control flour (Table 4.12). Infrared treatment less than 105 s seem to make the cell walls in the bread thinner as the value for crumb structure relates to the thickness of the cell walls, the thinner the cell wall the higher the score (Kilborn and Tipples 1981). Those characteristics were slightly decreased on bread made with flour treated with infrared for 105 s. Information on the type of crumb expected could be derived from the peak height of the Viscoamylograph (Pylar 1982). Flour with a

high viscosity peak will give a “dry crumb” where as a low viscosity peak causes a moist, soggy crumb. Viscosity peaks obtained for the control and infrared treated flours fell into the intermediate level (between 753 and 786 B.U.).

6 CONCLUSIONS

The temperature distribution of a deep CWRS flour layer exposed to infrared radiation and the effect of three infrared treatments on the consistency coefficient, flow behaviour index, dough mixing characteristics, Viscoamylograph peak, Falling Number, wet gluten content, starch damage, flour baking performance, insoluble glutenin in propanol/Dithiothreitol, and flour thermal transitions were studied and the following conclusions were derived:

Reducing the distance between the lamp and flour from 100 mm to 70 mm increased the rate of temperature change at different depths, in particular, the dynamics of the surface temperature changes were greatly affected. Decreasing the lamp rated voltage from 120 V to 60 V caused a reduction on the severity of the treatment of the surface and a decrease in the rate change at different depth.

Starch was not affected by the infrared treatment as shown by the results obtained in the Viscoamylograph, Falling Number and starch damage tests and the peak transitions observed in the DSC.

Gluten was the main flour compound affected by infrared radiation as the dough mixing characteristics, the flour water absorption, wet gluten content and the bread baking characteristics were altered by this treatment.

Infrared radiation seems to have a strengthening effect on the CWRS flour as dough development time, stability, mixing time to peak development, and work input to peak increased, and mixing tolerance index decreased as infrared exposure increased.

The most noticeable effect of infrared on the mixing characteristics of the dough was

the increase in stability. It was increased by more than 50% for the dough made with the 30 and 60 s infrared treated flour and by 100 % in the dough made with flour exposed to infrared rays for 105 s. This means that infrared treated flour would have more resistance to mixing and mechanical abuse, and would allow longer fermentation.

The flour water absorption capacity was significantly reduced by infrared radiation. The flour exposed to infrared rays for 105 s ended having a flour water absorption capacity of 57 %. This is a detrimental effect from the baker's point of view.

The dough consistency coefficient increased as infrared exposure increased. However, doughs were prepared at different water content and consistency coefficient is very sensitive to differences in the amount of water in the dough. The doughs made with the control and the infrared treated flour behaved as a non-Newtonian fluid with a pseudo plastic behaviour in the shear rate range of 7.8 to 782.5 s⁻¹. This behaviour was not significantly affected by infrared radiation.

Functional glutenin expressed as the amount of insoluble glutenin in propanol/Dithiothreitol was not significantly affected by the infrared treatment.

Loaf volumes seem not to be significantly affected in the flour exposed to infrared radiation for 30 and 60 s. However, loaf volume for the flour treated with infrared for 105 s decreased. The appearance, crumb structure and colour and total score were noticeably improved in the infrared treated flour for 30 and 60 s , and slightly increased for the 105 s.

The DSC thermograms showed that gelatinization peak, as well as the other two peaks (fusion of more stable starch crystals and the dissociation of the amylose lipid complex) were not significantly affected by infrared radiation. These peaks occurred between 57.8 and

59 °C, 70.5 and 72.9 °C, 89.5 and 94.3 °C, respectively.

The following recommendations are suggested for future research:

Mild and medium infrared treatment (30 and 60 s) in which the flour reaches average temperature of $64.2\text{ }^{\circ}\text{C} \pm 1.8$ and $78.9\text{ }^{\circ}\text{C} \pm 1.5$ seems to increase the overall strength of the flour and improve bread baking characteristics such as appearance, crumb structure and colour. Therefore, further studies should be conducted on the effect of infrared radiation on flour of lower grade and the flour should not reached an average temperature higher than $78.9\text{ }^{\circ}\text{C}$ because at this temperature gluten properties are negatively affected.

Tests performed on gluten showed that its properties were affected by infrared radiation. However, the mechanism of this effect was not investigated in this research. Therefore, chemical analysis should be conducted to determine the effect of infrared on gluten structure. The effect of infrared radiation on gluten properties should also be examined more closely. Tests such as alveograph and extensiograph should be conducted.

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