Dynamics of drying bentonite in superheated steam and air as a model food system

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Cenkowski, S., Bulley, N.R. and Fontaine, C.M. 1996. **Dynamics of drying bentonite in superheated steam and air as a model food system**. Can. Agric. Eng. 38:305-310. The objective of this research was to compare temperature patterns, drying rates, and diffusivities of bentonite as a food model with a high concentration of solids dried in hot air and superheated steam at 160°C. In our preliminary investigations on the drying of liquid food droplets in hot air and superheated steam, spherical samples of 13.5 mm in diameter were prepared from chemically stable bentonite paste. In superheated steam drying, bentonite samples reached the saturation temperature for steam (100°C) after the first minute of drying. During this period the samples gained approximately 0.1 kg/kg dry basis (db) of moisture, due to condensation of water on the surface of the sample. In air drying at 160°C, the temperature of a similar sized sample gradually increased to a wet bulb temperature of 80°C over a 10 min period. The drying rate in the superheated steam was higher by 8 to 10% than in the 160°C air in the initial stage of drying. However, this situation reversed when samples reached the falling rate-of-drying stage. For this period and below moisture content of 0.10 kg/kg db, the overall diffusion coefficient was 50 to 80% higher for samples dried in the 160°C air than in superheated steam of the same temperature.

L'objectif de cette recherche était de comparer le comportement des températures, les taux de séchage et les diffusivités de la bentonite utilisée pour simuler un aliment à haute teneur en solides qui est séché avec de l'air chaud et de la vapeur surchauffée à 160°C. Lors de nos travaux préliminaires sur le séchage de gouttelettes d'aliments liquides avec de l'air chaud et de la vapeur surchauffée, des échantillons sphériques de 13.5 mm de diamètre ont été préparés à partir d'une pâte de bentonite chimiquement stable. Pendant le séchage à la vapeur surchauffée, les sphères de bentonite ont atteint la température de saturation (100°C) après une minute. Durant cette période, le gain de poids des échantillons a été de 0.1 kg/kg base sèche, à cause de la condensation de l'eau à la surface des sphères. Lorsque le séchage se faisait à l'air à 160°C, la température d'un échantillon de même dimension augmentait graduellement jusqu'à une température humide de 80°C en 10 minutes. Lors de la première phase de séchage, le taux de séchage à la vapeur surchauffée a été de 8 à 10 % supérieur à celui du séchage à l'air. Cependant, la situation s'est inversée lorsque les échantillons ont atteint la phase où le taux de séchage décroît. Lors de cette période et pour des taux d'humidité inférieurs à 0.10 kg/kg base sèche, le coefficient de diffusion global des échantillons séchés à l'air à 160°C était de 50 à 80% supérieur à celui des échantillons séchés à la vapeur surchauffée à la même température.

INTRODUCTION

The potential of superheated vapour as a drying medium has been recognized by researchers and by the chemical industry (Wenzel and White 1951; Chu et al. 1953; Lane and Stern 1956; Trommelen and Crosby 1970; Faber et al. 1986; Zhang and Wang 1992). Drying solids by direct contact with superheated steam has been recommended and determined to be more efficient than hot air convective drying, providing that the dried solids are not temperature sensitive (Sheikholeslami and Watkinson 1992; Wenzel and White 1951).

Spray drying is a widely used dehydration technique for liquid products containing dissolved solids. Researchers have studied the evaporation from a single drop of liquid which was suspended in a controlled environment by measuring the change in weight of individual drops during drying (Charlesworth and Marshall 1960; Trommelen and Crosby 1970). To permit the weighing of a droplet evaporating in a flowing drying medium, deflection shields were used at the time a weight reading was taken. To avoid frequently interrupting the flow, several researchers measured the changes in weight over time of gelled spheres of skim milk of 10 mm in diameter, which were placed on a perforated tray in a drying chamber (Ferrari et al. 1989). The obtained data were used to determine the drying rates of single droplets. This fundamental information on the rate of water loss in individual drops during drying is essential to the design of modern spray drying units (Ondrey 1995).

Application of heat to food products usually induces chemical changes in the product. This complicates the mathematical analysis of the drying process. Bentonite pastes have been widely used as model food systems in the study of thermal processing (Tong and Lentz 1993). The pastes are homogenous, as well as thermally and chemically stable, making their use advantageous in thermal process investigations. This allows verification of the results of mathematical heat and mass transfer models of the drying process.

In our preliminary investigations on the drying of liquid food droplets in hot air and superheated steam and reported here, samples were prepared from bentonite paste. Because of its chemical stability, high moisture bentonite paste was used to simulate the final stage of drying liquid food droplets. The objective of this research was to compare temperature patterns, drying rates, and diffusivities of bentonite as a food model with a high concentration of solids dried in hot air and superheated steam environment.

APPARATUS

The drying experiments were carried out in a drying chamber developed in the Department of Biosystems Engineering at the University of Manitoba. The apparatus consists of a steam generator, drying chamber, auxiliary equipment to control

and measure flow parameters of steam or hot air, and a data acquisition system. The drying chamber itself consists of an inner rectangular chamber and a surrounding air jacket. A simplified diagram of the drying chamber is shown in Fig. 1.
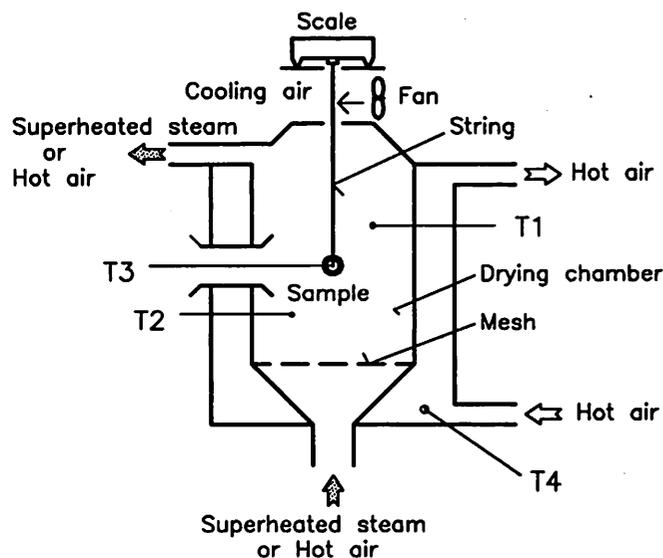

Fig.1. Drying chamber.

Hot air at a temperature of 160 ± 2°C (Fig. 1, T4) was forced through the air jacket during the entire experiment. This was to ensure adiabatic conditions for the inner chamber where the sample was placed. Two thermocouples placed on either side of the sample, above (T1) and below (T2), were used to monitor the temperature in the chamber. The average temperature of the two thermocouples was used to control the temperature in the inner (drying) chamber. An electronic balance connected to a computer allowed for continuous weighing of the sample. To avoid overheating of the balance, a cooling fan was installed between the chamber and the scale to prevent any rise in temperature due to hot air or superheated steam leaking from an opening in the inner chamber. The operating conditions in the drying chamber were controlled by a computer connected to a data acquisition system. A computer program handled the collection of all data and regulated the appropriate components to maintain the pre-determined conditions in the chamber, in response to feedback from sensors in the chamber.

MATERIAL

Sodium bentonite mined in Wyoming was obtained from Bentonite Corporation in Denver, CO. A mixture of bentonite and water was prepared by adding distilled water to pure bentonite and thoroughly mixing in a crucible. The resulting paste was then manually rolled by hand using a circular motion to produce spheres of approximately 12 to 14 mm in diameter. Since these samples were not perfectly spherical, three measurements of their diameter were taken and averaged. The average diameter of individual samples is indicated in the figures. The initial moisture content was measured for each sample using the oven drying method

based on the AACC (1995) procedure and ranged from 1.7 to 2.7 kg H_2O/kg dry basis (kg/kg db).

PROCEDURE

Moisture and temperature changes during the drying process were measured in two separate series of experiments. In one series of tests, the mass of the sample was recorded as it dried, and in the other series of tests the temperature at the centre of the sample was recorded during the course of drying. Both types of tests were performed in superheated steam and then in hot air at a temperature of 160 ± 2°C. This specific temperature was selected as it is a typical temperature range used in industrial spray drying of liquid egg. The samples were dried for 35 min in either superheated steam at 0.6 m/s or hot air at 1.0 m/s.

Mass change measurements

A spherical sample of bentonite was weighed and then placed in a holder of known mass made of tin wire (Fig. 2). It was then hung from a string attached to the scale in the drying chamber. The mass of the sample in the chamber was monitored continuously using a balance connected to a data acquisition system. The chamber temperatures (T1, T2 and T4, Fig. 1) were recorded every 5 s. After the drying was complete, the sample was oven dried to obtain the dry mass required for determination of the exact initial moisture of the sample and its moisture changes during the course of drying. Calculation of the initial moisture content of the sample based on its mass determined before the drying test usually led to erroneous results as the sample kept losing its moisture during handling for several seconds in the chamber which was preheated to 160°C.

Temperature measurements

A second sample was prepared from the same mixture as in the previous test. A thermocouple tip (T3, Fig. 1) was inserted at the centre of the spherical sample. The sample was dried in the chamber using the same conditions, however, the changes of mass were not recorded this time. Because of the light mass of the sample (1.2 to 1.8 g), the sample was suitably supported by the thermocouple. The sample was again dried in either superheated steam or hot air, and the temperature at its centre (T3), as well as the temperature in the chamber at T1 and T2 were recorded while the sample dried for 35 min.
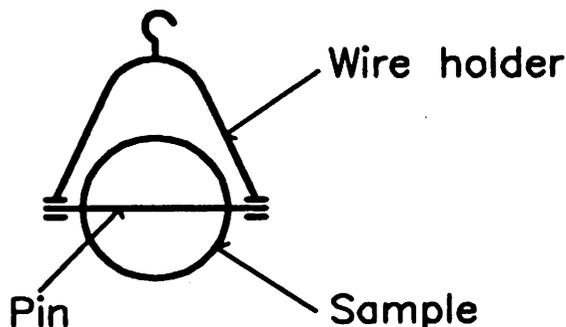

Fig. 2. A sample placed in the wire holder.

Data analysis

The flow of the drying medium moving upward past the sample creates a "lifting force". To compensate for this apparent loss in mass, a series of tests were performed on 10 to 15 mm wooden beads instead of the bentonite spheres. To prevent any changes in mass during testing, the wooden beads were oven dried prior to being tested in the chamber.

The mass of the wooden bead placed inside the chamber and exposed to superheated steam or hot air was compared with the actual mass of the bead for both superheated steam and hot air. The compensation factors were obtained using linear regression on the data from the beads. Linear regression was also used to establish that there was no significant difference, in terms of resistance to flow, between the wooden spheres and the bentonite spheres. It was also determined that spheres of different diameters behaved similarly in the chamber over the range of tested diameters.

Researchers generally agree that the velocity of the drying medium has no or little effect on drying rate for the falling rate-of-drying period (Jayas et al. 1991). Therefore, the calculation of the mass diffusion coefficient for samples dried with two different media was done for this period. The critical moisture for the falling rate-of-drying period was determined based on the experimental drying curves. An average moisture content of a sphere can be calculated from a series solution of a mass diffusion equation (Crank 1956):

$$\frac{\overline{M}(\theta) - M_e}{M_o - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n^2 \pi Fo_m\right) \quad (1)$$

where:

$\overline{M}(\theta)$ = average moisture content of a sphere at any time (kg/kg db),
θ = drying time (s),
M_o = initial moisture content (kg/kg db),
M_e = equilibrium moisture content (kg/kg db),
n = index of summation, and
Fo_m = Fourier number for mass transfer.

The Fourier number for mass transfer was defined as:

$$Fo_m = \frac{D_m \theta}{R^2} \quad (2)$$

where:

R = radius of a sphere (m), and
D_m = mass diffusion coefficient (m²/s).

Since the variables on the left hand side of Eq. 1 were determined experimentally, the mass diffusion coefficient was calculated after incorporating Eq. 2 into Eq. 1 and rearranging. To simplify the calculations, only the first series was used. Because of the high temperature of the drying media (160°C) the equilibrium moisture content of the bentonite samples was zero in our experiments. Thus, after rearrangement, Eq. 1 can be written in a symbolic form as:

$$D_m = \frac{R^2}{\theta} f^{-1}\left(\frac{\overline{M}(\theta)}{M_o}\right) \quad (3)$$

In the analysis of the data, the shrinkage of the spherical samples was neglected. Jaros et al. (1992) determined that the maximum error in calculation of the diffusion coefficient for wheat was up to ±3% when compared with the calculation at the constant radius of a kernel.

RESULTS AND DISCUSSION

Figures 3 and 4 show the drying characteristic, temperature changes, and drying rates of samples dried in the superheated steam and hot air, respectively. The numbers associated with each curve indicate the run number and the arrows attached to curves show the corresponding axis.

In the first minute of drying in the superheated steam the samples gained approximately 0.1 kg/kg db of moisture (Fig. 3b, plots 1 to 4). This was due to condensation of water on the surface of the sample while it warmed up to the saturation point (100°C). The two selected plots of the temperature history (plot No. 5 and 6) at the centre of the bentonite sample drying in superheated steam confirm this. A very sharp rise in temperature is seen during the first minute followed by a period of fairly stable temperature beginning at 100°C (the saturation temperature of steam). In the first 18 min of drying, the temperature of a centre of the sample slowly increased from 100°C to approximately 110°C. This upward drift in sample's temperature was probably caused by the high velocity of the superheated steam. In case of drying in the conditions of the natural convection, temperature of a sample remains constant until the end of the constant-drying period (Pabis 1982). Also, our preliminary experiments conducted with single water drops dried in the same conditions showed that the possible heat conduction through a thermocouple could be excluded as the droplet temperature remained constant at the saturation point throughout the entire drying period.

The four drying curves obtained in the superheated steam environment have approximately the same slope. A graphical differentiation of these curves allowed for determination of drying rates. The results of the differentiation are shown in Fig. 3a. In the first several minutes of drying the drying rate was in the range between -0.11 to -0.13 min⁻¹ which corresponded to a moisture content range between 2.5 and 1.5 kg/kg db. When the moisture of a sample fell below approximately 1.5 kg/kg db, a constant decrease in the drying rate was observed, although (based on the temperature history of the sample) this was still the 1st drying period. It is difficult to determine precisely when the constant rate-of-drying period (1st drying period) ends and the falling rate-of-drying (2nd drying period) begins. However, taking under consideration the temperature history, shape of drying characteristics, and drying rate, it was concluded that the falling rate-of-drying period definitely began when the moisture content was approximately 0.4 to 0.5 kg/kg db. This moisture is also known as the critical moisture (m_c).

The drying characteristics of four samples dried in hot air (Fig 4b, plots 7 to 10) have more linear shapes than the drying characteristics measured in the superheated steam environment. Also, no initial gain in moisture was observed. Figure 4a shows the results of the graphical differentiation of the four drying curves (plots 7 to 10). The maximum drying rate was obtained within the first 4 min of drying and was in the range between -0.10 to -0.12 min⁻¹. In spite of the air having
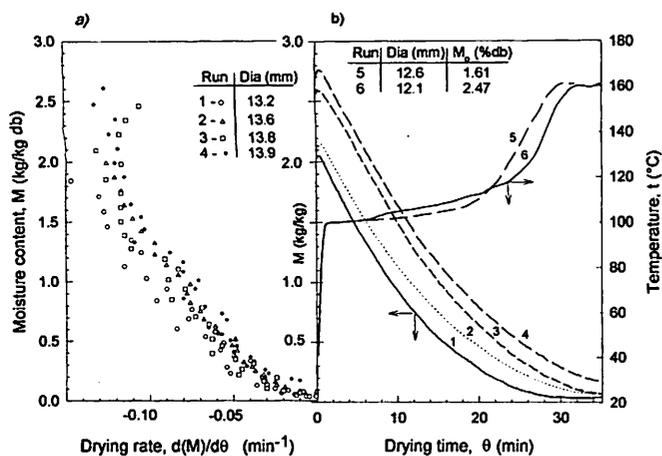
Fig. 3. Drying characteristics in the superheated steam environment of 160°C (plots 1 to 4), temperature patterns of the geometric centre of two samples (plots 5 and 6), and drying rates corresponding to runs 1 to 4. The average diameters of spherical samples (Dia) and corresponding initial moisture contents (M_o) are indicated in the graph.
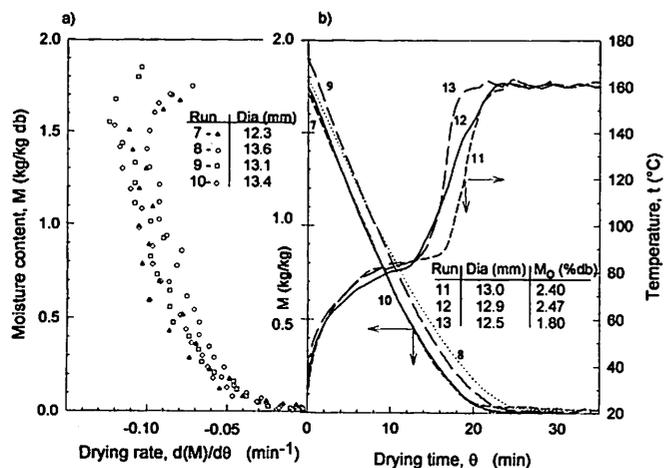

Fig. 4. Drying characteristics in the hot air environment of 160°C (plots 7 to 10), temperature patterns of the geometric centre of three spherical samples (plots 11 to 13), and drying rates corresponding to runs 7 to 10. The average diameter of the samples (Dia) and corresponding initial moisture contents (M_o) are indicated in the graph.

a higher velocity than the superheated steam, the drying rate in the air was lower by 8 to 10%. This was probably caused by a much slower build up in the temperature of the geometric point of a sample.

Also, Fig. 4b shows three plots of temperature changes (plots 11 to 13) of the geometric centre of the sample. The samples were initially at the 1.8 to 2.5 kg/kg db moisture content. The temperature of the geometric centre gradually increased to approximately 80°C over a 10 min period and then, due to high velocity of the drying air, slowly increased

by an additional 1 to 3°C in the next several minutes. Based on the temperature history, it was concluded that the falling rate-of-drying began at the point where the temperature after reaching the plateau (between 80 to 83°C), suddenly increased sharply. This point occurred between the 12th and 16th min of drying. This corresponds to the critical moisture content (m_c) of approximately 0.4 to 0.6 kg/kg db.

The drying rate (Fig. 4a) kept decreasing as the sample moisture decreased, however, this decrease was slower than that for the sample dried in the superheated steam. For example, at 0.4 kg/kg db moisture for drying in the superheated steam and hot air, the drying rates were in the range from -0.04 to -0.06 min^{-1} and from -0.06 to -0.08 min^{-1}, respectively. In summary, the drying rate in the superheated steam was higher than in air during the initial stages of drying, however, the situation was reversed in the final stage - in the falling rate-of-drying period. This could probably explain the disagreement with respect to the evaporation rates in these two different drying environments (Trommelen and Crosby 1970; Wenzel and White 1951). Trommelen and Crosby (1970) reported that evaporation of water from a droplet was found to take place more slowly in superheated steam than in air. However, they also indicated the need to take into account the characteristics of the material dried. This last statement supports the results obtained by Wenzel and White (1951) which indicated that higher drying rates and thermal efficiencies are possible when drying with superheated steam rather than air.

The falling rate-of-drying periods of samples dried in superheated steam and hot air were compared by analyzing the overall diffusion coefficients. Only the portions of the drying characteristics below the critical moisture point (m_c) were used in the calculations. The critical moisture range has been
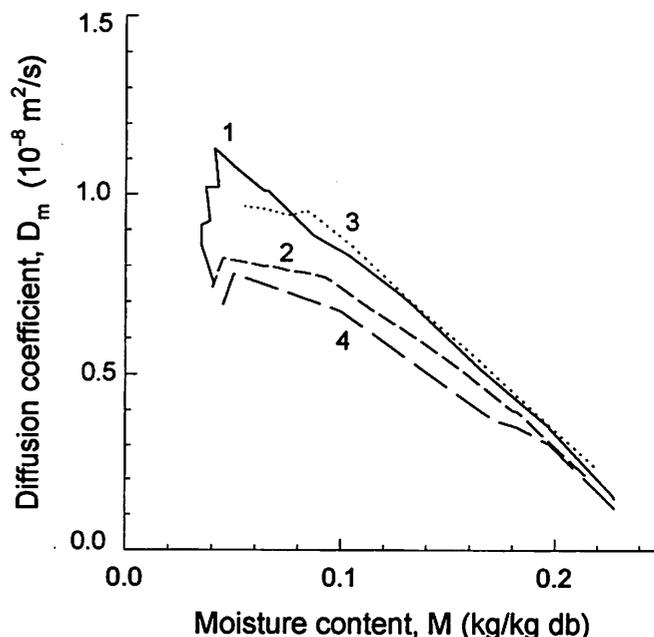

Fig. 5. The overall diffusion coefficient of spherical samples of bentonite dried in 160°C superheated steam. The numbers associated with each curve correspond to runs 1 to 4 in Fig. 3b.
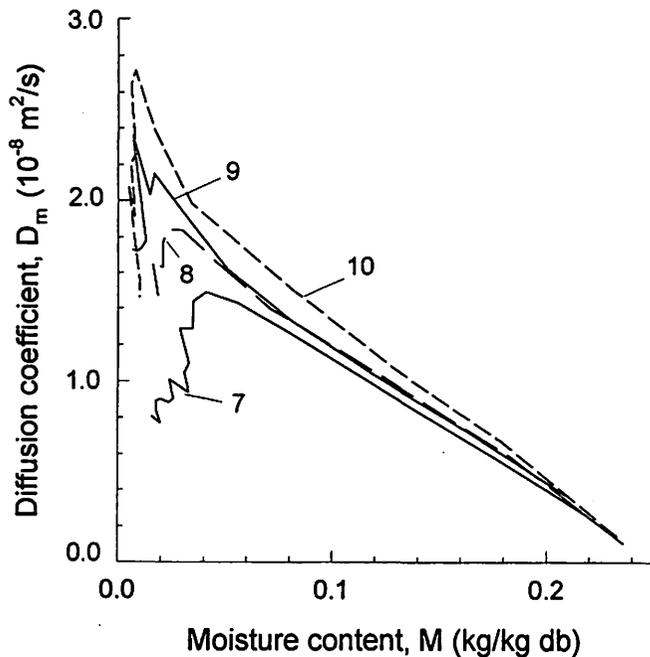
Fig. 6. The overall diffusion coefficient of spherical samples of bentonite dried in 160°C hot air.
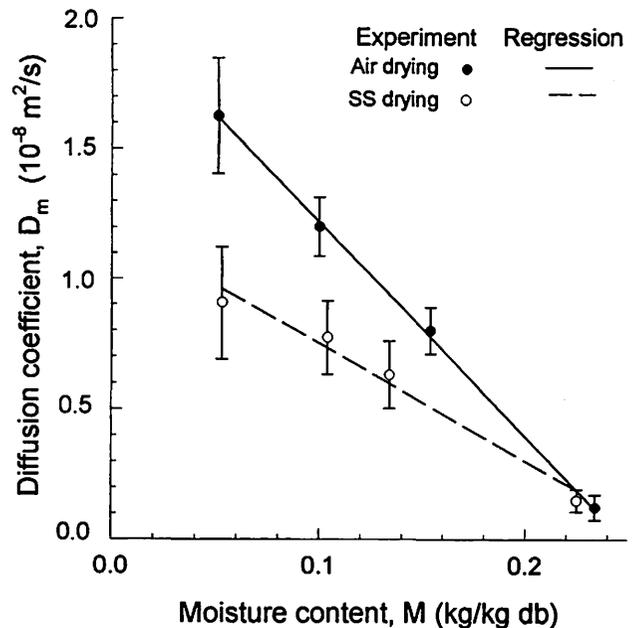The numbers associated with each curve correspond to runs 7 to 10 in Fig. 4b.

Fig. 7. The comparison of overall diffusion coefficients for spherical samples of bentonite dried at 160°C in the superheated steam and hot air environment.
The symbols are the averages of the experimental data and the lines are the best fit lines to the experimental data.

already discussed, and the m_c of 0.4 kg/kg db was used in our calculations. Figures 5 and 6 show the overall diffusion coefficient as a function of moisture content as calculated for samples dried in the superheated steam and hot air environments, respectively. The numbers associated with each curve correspond to drying characteristics in Figs. 3b and 4b. The characteristics follow a trend reported in the literature (Jaros et al. 1991; Fortes et al. 1981; Keey 1972). The overall diffusivity increased with a decrease in moisture up to approximately 0.02 or 0.04 kg/kg db for the samples dried in the hot air or superheated steam, respectively, and then dropped sharply. Fortes et al. (1981) analyzed liquid diffusivity in wheat kernels and concluded that the vapour-phase diffusivity falls with increasing moisture in wheat in the range between 0.05 to 0.25 kg/kg db. This explanation follows the trend observed in our experiments, however, no attempt was made to separate the liquid from vapour diffusion.

Based on the characteristics shown in Figs. 5 and 6, the average overall diffusivities were calculated for the samples dried in the two environments. The calculations were conducted for the 0.05 to 0.025 kg/kg db moisture range. The results are shown in Fig. 7. The symbols are the average overall diffusivities and the vertical bars indicate the 95% confidence intervals. The solid line and the dashed line are the best fit lines describing the overall diffusion coefficient as a function of moisture content:

Air drying:　$D_m = -8.21 \times 10^{-8} \, M + 2.04 \times 10^{-8}; \, m^2/s$

Superheated steam drying:
$$D_m = -4.50 \times 10^{-8} \, M + 1.20 \times 10^{-8}; \, m^2/s$$
$$\text{(4)}$$

The relationships in Eq. 4 were obtained for $M \in (0.050,$

0.225 kg/kg db) and the drying media temperature of 160°C.

Based on Fig. 7, it was concluded that, in the final stage of drying for samples dried in the hot air, the overall diffusion coefficient increased more rapidly with moisture decrease than in the superheated steam and was 50 to 80% higher for samples being at moisture content below 0.10 kg/kg db.

CONCLUSIONS

For superheated steam drying, the temperature in the centre of approximately 13.5 mm diameter bentonite samples reached the saturation point for steam (100°C) after the first minute of drying and then slowly increased by 10°C during the first rate-of-drying period. For air drying at 160°C, the temperature in the centre of a similar sized sample gradually increased to 80°C over a 10 min period and then, due to high air velocity, slowly increased, reaching 81 to 83°C at the end of the 1st period of drying.

In the first minute of drying in superheated steam the samples gained approximately 0.1 kg/kg db of moisture. This was due to condensation of water on the surface of the sample while it warmed up to the saturation point (100°C).

The beginning of the falling rate-of-drying stage, during drying in both media, was marked by a sharp increase in the temperature of the geometric centre of a sample. This corresponded to a critical moisture content ranging between 0.4 and 0.6 kg/kg db.

The drying rate in the superheated steam was higher by 8 to 10% than in the 160°C air in the initial stage of drying. However, the situation was reversed when samples reached the falling rate-of-drying. For this period the overall diffusion coefficient increased more rapidly with moisture

decrease for samples dried in the 160°C air than in superheated steam at the same temperature and was 50 to 80% higher for moisture contents below 0.10 kg/kg db.

REFERENCES

AACC. 1995. Method: 44-15A. Moisture - air-oven method. In *Approved Methods of the American Association of Cereal Chemists*. St. Paul, MN: American Association of Cereal Chemists.

Charlesworth, D.H. and W.R. Marshall, Jr. 1960. Evaporation from drops containing dissolved solids. *AIChE Journal* 6:9-23.

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

Crank, J. 1956. *The Mathematics of Diffusion*. London, England: Oxford University Press Amen House.

Faber. E.F. , M.D. Heydenrych, R.U.I. Seppa and R.E. Hicks. 1986. A techno-economic comparison of air and steam drying. In *Drying'86*, ed. A.S. Mujumdar, Vol.2:588-594. New York, NY: Hemisphere Publishing Corporation.

Ferrari, G., G. Meerdink and P. Walstra. 1989. Drying kinetics for a single droplet of skim-milk. *Journal of Food Engineering* 10:215-230.

Fortes, M., M.R. Okos and J.R. Barret, Jr. 1981. Heat and mass transfer analysis of intra-kernel wheat drying and rewetting. *Journal of Agricultural Engineering Research* 26:109-125.

Jaros M, S. Cenkowski, D.S. Jayas and S. Pabis. 1992. A method of determination of the diffusion coefficient based on kernel moisture content and its temperature. *Drying Technology* 10:213-221.

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

Keey, R.B. 1972. *Drying: Principles and Practice*. Toronto, ON: Pergamon Press.

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

Ondrey, G. 1995. Models demistify spray drying. *Chemical Engineering* 102:30-31.

Pabis, S. 1982. *Theory of the Convective Drying of Agricultural Products*. Warsaw, Poland: PWRiL.

Sheikholeslami, R. and A.P. Watkinson. 1992. Convective drying of wood-waste in air and superheated steam. *The Canadian Journal of Chemical Engineering* 70:470-482.

Tong, C.H. and R.R. Lentz. 1993. Dielectric properties of bentonite pastes as a function of temperature. *Journal of Food Processing and Preservation* 17:139-145.

Trommelen, A.M. and E.J. Crosby. 1970. Evaporation and drying of drops in superheated vapours. *AIChE Journal* 16:857-867.

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

Zhang, G.S. and H.T. Wang. 1992. Energy analysis of super-heated steam Yankee dryer. In *Drying'92*, ed. A.S. Mujumdar, 1108-1114. New York, NY: Elsevier Science Publishers B.V.