Dehydration dynamics of potatoes in superheated steam and hot air

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Tang, Z. and Cenkowski, S. 2000. **Dehydration dynamics of potatoes in superheated steam and hot air**. Can. Agric. Eng. **42**:043-049. Superheated-steam at atmospheric pressure is an alternative drying medium for dehydrating materials insensitive to temperature equal to or above 100°C. This research compared the dehydration characteristics, temperature histories, drying rates, and overall moisture diffusivities of cylindrical potato samples exposed to superheated steam and hot air at 125, 145, and 165°C. A small amount of moisture (0.18 to 0.47 kg/kg db, dry basis) dependent on the steam temperature was gained from steam condensation on the sample surface during the warm-up period from the superheated-steam. The temperature of the drying medium had a greater effect on the drying rate, overall moisture diffusivity, and consequently dehydration time for the superheated-steam dehydration than for the hot-air dehydration. Increasing the temperature from 125 to 165°C decreased the dehydration time by 60 and 24% for the superheated-steam and hot-air dehydration, respectively. A constant-rate drying period was only observed with superheated steam at 125 and 145°C. There existed an inversion temperature point between 145 to 165°C for the first dehydration stage above 2.6 kg/kg db and between 125 and 145°C for the last dehydration stage below 2.6 kg/kg db.

La vapeur surchauffée à la pression atmosphérique est utilisée comme milieu de séchage alternatif pour déshydrater des matières insensibles à des températures égales ou supérieures à 100°C. Ces recherches comparèrent les caractéristiques de déshydratation, les variations de température, les taux de séchage et la diffusion globale de l'humidité d'échantillons cylindriques de pomme de terre exposés à de la vapeur surchauffée et à de l'air chaud à 125, 145, et 165°C. Lors du procédé à la vapeur surchauffée, et selon la température de la vapeur, un léger gain d'humidité (0.18 à 0.47 kg/kg bs, base sèche) se produisit à cause de la condensation de la vapeur à la surface de l'échantillon durant la période de réchauffement. La température du milieu de séchage eut un effet plus important sur le taux de séchage, la diffusion globale de l'humidité, et en conséquence sur le temps de déshydratation, dans le procédé de déshydratation à la vapeur surchauffée que dans le procédé à l'air chaud. Lorsque la température passa de 125 à 165°C, le temps de déshydratation diminua de 60 % pour la déshydratation à la vapeur surchauffée et de 24% pour le procédé à l'air chaud. Une période de séchage à taux constant fut observée avec la vapeur surchauffée à 125 et 145°C. Il y eut un point d'inversion de la température entre 145 et 165°C pour le premier stade de déshydratation au-dessus 2.6 kg/kg bs, et entre 125 et 145°C pour le dernier stade de déshydratation sous 2.6 kg/kg bs.

INTRODUCTION

Drying or dehydration is one of the most important operations in the food and chemical industries. Compared with hot-air drying, superheated-steam drying provides numerous advantages (Bond 1992; Dibella 1996; Erdesz and Kudra 1990; Jensen 1992; Lane and Stern 1956; Meunier and Munz 1986): (i) The circulation of superheated steam in a closed-loop drying system reduces the energy wastage that occurs with hot-air drying. Also, the heat energy in the exhaust steam resulting from the evaporation of moisture within the drying material can be recovered or used in other processes resulting in an energy saving. (ii) The high heat transfer coefficient of superheated-steam drying results in enhancing the drying rate under certain conditions, improving the production efficiency, and consequently reducing the equipment size and capital cost. (iii) No oxidation in superheated-steam drying, due to the oxygen-free environment, can improve product qualities and eliminate fire and explosion hazards. (iv) The environmental pollution caused by superheated-steam drying can be significantly reduced or eliminated. Only a small amount of vapour generated from the moist drying material is vented to the atmosphere from the closed-loop system. The exhaust vapour could be condensed and the dust present in the vapour be collected easily. (v) Some valuable volatile organic compounds generated from the drying material could be recovered and separated by a condenser.

The main limitations of superheated-steam drying (Erdesz and Kudra 1990; Kumar and Mujumdar 1990; Lane and Stern 1956; Meunier and Munz 1986; Shibata 1991) are that the high temperature of the product in superheated steam imposes problems for temperature-sensitive products, and that more complex drying systems are needed in comparison with hot-air drying (Woods et al. 1994; DiBella 1996).

Researchers have made considerable investigations on theoretical and experimental aspects of superheated-steam drying. In the constant-rate drying period there exists an inversion temperature, above which the drying rate is higher in superheated steam than in hot air, and below which the situation is reversed (Bond 1992; Faber et al. 1986; Hyodo and Yoshida 1976 Nomura and Hyodo 1985; Sheikholeslami and Watkinson 1992; Yoshida and Hyodo 1970).

Drying in the falling-rate period could be expected to be faster in superheated steam than in hot air under certain conditions. This was concluded by Hyodo and Yoshida (1976) with clay drying, by Chen et al. (1992) with silkworm cocoon drying, and by Shibata (1991) with drying sintered spheres of glass beads. In addition, the critical moisture content is lower in superheated-steam drying than in hot-air drying (Shibata 1991). Therefore, the total drying rate is expected to be higher in superheated steam than in hot-air drying.

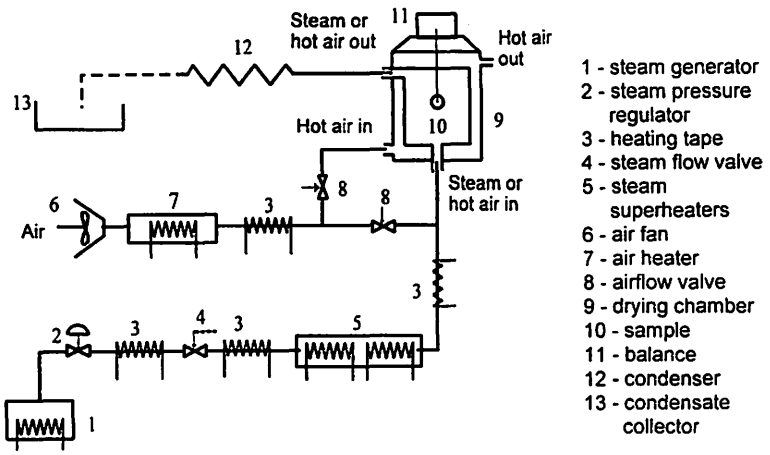

Fig. 1. Superheated steam dehydration system.

A study on drying vegetables and green teas (Akao 1983, cited by Shibata and Mujumdar 1994) showed that the quality of dried products, such as colour and scent, is excellent. Nomura and Hyodo (1985) stated that superheated-steam drying causes greater porosity in instant foods such as noodles than hot-air drying, and there is no case hardening on the surface of molasses dried in superheated-steam. Much research work on the effect of steam drying on paper strength and its optical properties has been done in Canada, primarily at McGill University (Poirier et al. 1994, 1995; Cui et al. 1986).

Up to now, a broad industrial acceptance of superheated-steam drying has not been reached due to the lack of suitable equipment. The application of this technique is mainly limited to only a few industrial drying fields, such as paper product drying, sugar beet pulp drying, and sludge drying (Svensson 1985; Jensen 1992). The first industrial-scale steam dryer used in South Africa could dry 200 kg/h (db) of activated carbon pellets from an initial moisture content of 50% down to 2% db (Faber et al. 1986). The first commercial steam dryer for drying paper pulp in Sweden was installed at Husum in 1979 (Svensson 1985). For drying sugar beet pulp, a full-scale steam dryer started operation in Sweden in 1983 (Svensson 1985), another one was installed at Stede Sugar factory in Denmark in 1985, and a pressurized-steam dryer (8 m diameter at the top, 2500 kPa steam pressure) was built in France in 1990 (Jensen 1992). A fluid-bed dryer for drying sludge with superheated steam was mounted at a landfill in Northern Germany in 1993, and 10 Niro-type steam dryers for different drying purposes had been installed or ordered in several countries in Europe by 1994 (Wimmerstedt and Hager 1996).

The high steam temperature exceeding the saturation temperature of steam could cause a problem for temperature-sensitive food materials which might undergo such processes as browning reaction, discolouration, starch gelatinization, enzyme destruction, and protein denaturation. However, in some cases, changes in textural properties due to dehydration in superheated steam could be beneficial. For example, baking potatoes involves simultaneous dehydration, and some instant foods also need to be dehydrated and baked at the same time. In addition, the lack of oxidative reaction during dehydration with superheated steam could improve the quality of some food products. Therefore, superheated steam can be applied to dehydrating selected food products.

The knowledge of the basic dynamics of food dehydration with superheated steam is needed to characterize the baking and dehydration process in mathematical relationships, which will lead to computer simulation, optimization, and development of suitable equipment. Therefore, the objective of this preliminary study was to compare the dehydration kinetics of potato samples in superheated steam and in hot air at different temperatures.

EQUIPMENT

The superheated-steam dehydration system developed in the Department of Biosystems Engineering at the University of Manitoba consists of a steam generator, steam conveying pipelines, a drying chamber, auxiliary heaters (superheaters and heating tapes), a hot-air supply system, and a data acquisition and control system (Fig. 1).

Saturated steam at 0.58 MPa and 158 °C is produced by the steam generator (1). When the steam passes through the steam pressure regulator (2), its pressure drops to 0.13 MPa, and superheated steam is generated. The pressure regulator ensures a steady flow of steam through the pipelines and the drying chamber (9). The flow rate is adjusted by the steam flow valve (4), which is actuated by a computer. After passing though the electrical superheaters (5), where its temperature is adjusted to the desired level, the steam goes through the drying chamber (9). Finally, the steam goes to the condenser (12) and is condensed. By measuring condensation rate and knowing the steam properties, the steam velocity in the chamber (9) was determined. The heating tapes (3) on the pipelines keep the pipes warm to avoid the heat losses and the possible steam condensation inside the pipes. Several thermocouples placed at different points on or in the pipes (not shown in Fig. 1) sense the temperatures of the pipes and the steam inside the pipes. In addition, hot air is used to insulate the drying chamber. Air is moved by the fan (6) and heated by the heater (7) and the heating tape (3) on the airflow line. The airflow rate is adjusted by changing the speed of the fan (6) with a variable auto-transformer. The temperature of the hot air is adjusted by a computer-controlled unit which turns the heater (7) and the heating tape (3) on the airflow line on or off.

The drying chamber itself consists of an inner rectangular cavity (i.e., the inner chamber) and a surrounding air jacket (Fig. 2). Hot air is forced through the air jacket during superheated-steam dehydration and can also be forced through the inner chamber for hot-air dehydration by repositioning the airflow valves (8) (Fig. 1). The air velocity was measured at the fan inlet (6) using an anemometer (Model HHF300A, OMEGA Engineering Inc., Stamford, CT)

The sample is hung in the chamber by a thin string attached to an electronic balance (Fig. 2). The balance connected to a computer allows for continuous weighing of the sample. To avoid overheating the balance, a cooling fan is installed between the chamber and the balance to prevent any rise in temperature due to superheated steam or hot air leaking from

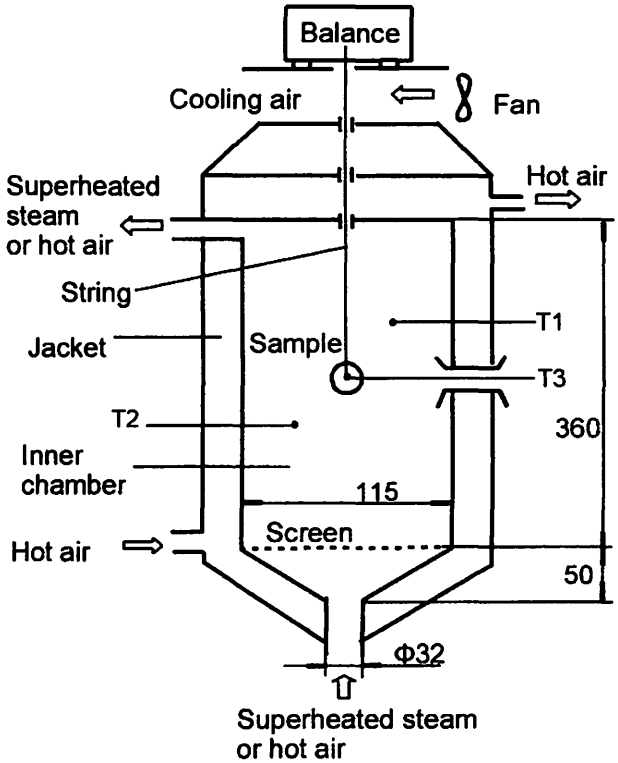

Fig. 2. Simplified diagram of the drying chamber. The dimensions are in mm.

the opening in the inner chamber. Thermocouples T1 and T2 sense the temperature inside the chamber. Thermocouple T3, inserted at the centre of the sample, monitors the sample temperature for the runs when mass changes are not monitored. The temperature inside the chamber can be controlled between 110 and 170°C for superheated-steam dehydration, and between 40 and 170°C for hot-air dehydration.

MATERIAL and PROCEDURE

Material

Cylindrical potato samples (5-mm diameter and 30-mm length) were prepared using a die. The initial moisture content of the potato samples was 4.17 kg/kg db, which was determined by following the AOAC (1984) oven drying method.

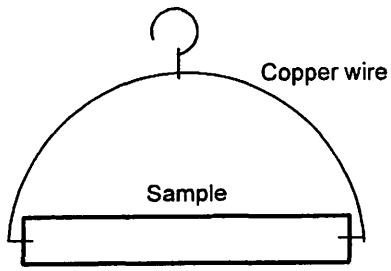

Fig. 3. A cylindrical sample attached to a sample holder made from a piece of copper wire. Sample: 5-mm diameter, 30-mm length; wire: 0.4-mm diameter.

Mass change and temperature measurements

During the experiments, the velocity of the drying medium in the drying chamber was set at 0.35 ± 0.01 m/s, and the temperatures of the drying medium inside the chamber were kept at three levels: 125 ± 3, 145 ± 3, and 165 ± 3°C. Under each set of dehydration conditions, mass and temperature changes of a sample were measured in two separate series of experiments. In one series of tests, the sample was placed in the chamber with a copper-wire sample holder (Fig. 3), and its mass was recorded every 3 s as it was dehydrated. In another series of tests, the sample was placed in the chamber with the thermocouple T3 (Fig. 2), the tip of which was inserted at the centre of the sample. The temperature at the centre of the sample was recorded every 3 s while the same conditions of the drying medium as in the previous experiments were maintained. Both types of tests were performed at least three times in superheated steam and in hot air under the same temperature and airflow conditions.

Compensation for the "lifting force"

The flow of the drying medium moving past the sample created a "lifting force" which affected the mass change readings. To compensate for this apparent loss in mass, a series of tests were conducted using a cylindrical metal bar which had the same dimensions as the wet potato sample. The bar was placed in the chamber and hung from the balance. The mass of the bar exposed to the drying medium at the same flow rate as in the dehydration test was recorded every 3 s for 1 min. The difference between the actual mass of the bar and the average reading over the 1-min interval was the "lifting force", which was incorporated into the calculations of the true mass losses of the potato samples. The change in the "lifting force" due to the shrinkage of the potato samples during dehydration was not considered in these experiments.

Diffusion analysis

During the falling-rate drying period, the internal resistance of moisture transfer is the limiting factor which governs the dehydration process, and the moisture transfer phenomenon occurring within the sample may be characterized in terms of overall moisture diffusivity (McMinn and Magee 1997). The diffusion equation for an infinite cylinder is given as (Pabis et al. 1998):

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

$$B_n = \frac{4}{\mu_n^2} \tag{2}$$

$$Fo_m = \frac{D_m \theta}{R^2} \tag{3}$$

where:

$\overline{M}(\theta)$ = average moisture content of an infinite cylinder at any time (kg/kg db),

θ = drying time (s),

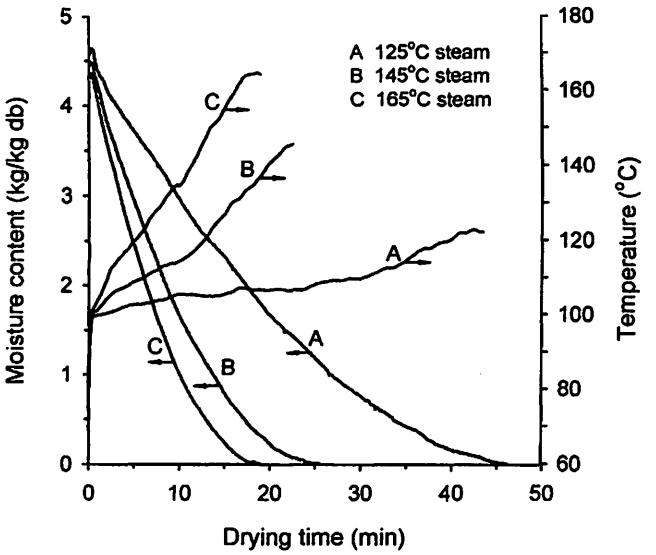

Fig. 4. Dehydration curves and temperature histories of cylindrical potato samples dehydrated in superheated steam at 15, 145, and 165°C.

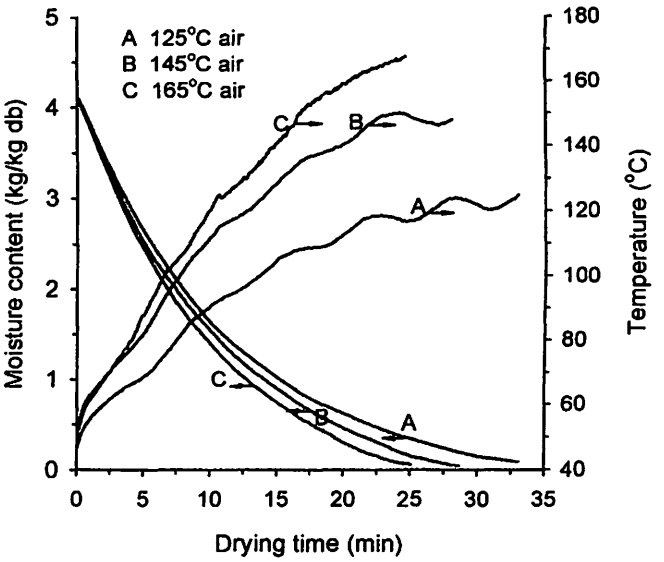

Fig. 5. Dehydration curves and temperature histories of cylindrical potato samples dehydrated in hot air at 125, 145, and 165°C.

M_0 = initial moisture content (kg/kg db),
M_e = equilibrium moisture content (kg/kg db),
n = index of summation,
μ_n = root of the Bessel equation of the first kind of zero order ($J_0(\mu_n) = 0$, $\mu_1 = 2.4048$, $\mu_2 = 5.5201$, $\mu_3 = 8.6537$, ...),
D_m = overall moisture diffusion coefficient (m^2/s),
R = radius of the cylinder (m), and
Fo_m= Fourier number for mass transfer.

In Eq. 1, the exponential function $\exp(-\mu_n^2 Fo_m)$ strongly attenuates with increasing n. For small values of Fo_m, the first term of the series in Eq. 1 is sufficient for approximate calculations. Therefore, to simplify the calculations, only the first term of the series was used for analysing the moisture diffusivities of the potato samples in the experiments. Zero was taken for M_e during calculations because the high temperature (125, 145, and 165°C) caused the equilibrium moisture of the samples to reach zero. Thus, rearranging Eq. 1, 2, and 3 gives:

$$D_m = -\frac{R^2}{\theta\mu_1^2}\ln\left(\frac{\mu_1^2\overline{M}(\theta)}{4M_o}\right) \quad (4)$$

The moisture diffusion coefficients were calculated by Eq. 4 with the experimental data without considering the shrinkage of the samples.

RESULTS and DISCUSSION

Moisture and temperature changes

In the first half a minute of superheated-steam dehydration, the samples gained a small amount of moisture due to steam condensation on the surface of the samples while they were warming up to the steam saturation point (100°C) (Fig. 4). The samples gained more moisture in low-temperature steam than in high-temperature steam. The initial gains of moisture on the samples in the superheated steam at 125, 145, and 165°C were 0.47, 0.31, and 0.18 kg/kg db, respectively. The dehydration times for reaching equilibrium were 45, 25, and 18 min for the steam at 125, 145, and 165°C, respectively. Thus, increasing the temperature of steam from 125 to 165°C decreased the dehydration time by 60%. The temperature histories measured at the centre of the samples in superheated steam showed a sharp rise in samples' temperature (to 100°C) during the warm-up period, and then the temperature increased gradually from 100°C to the steam temperature during the dehydration process (Fig. 4).

For the dehydration with hot air, moisture changes over time followed an exponential function (Fig. 5), typical for the drying of agricultural products in hot air. The dehydration times for reaching the equilibrium were 33, 28, and 25 min for the dehydration in the hot air of 125, 145, and 165°C, respectively. The dehydration time decreased by 24% when the steam temperature increased from 125 to 165°C. The temperature at the centre of the samples kept increasing gradually from about 50°C to the temperature of the hot air passing through the drying chamber (Fig. 5). Some white powdery matter was observed on the surface of the samples dehydrated in hot air probably because of the oxidative reactions (Jensen 1992). However, this was not noticed on the samples dehydrated in superheated steam.

Drying rates

Graphical differentiation of the dehydration curves shown in Fig. 4 and 5 allowed for the determination of drying rates (Pabis et al. 1998). During the initial period of superheated-steam dehydration, the drying rate increased rapidly due to the warm-up (Fig. 6). In the dehydration with the steam of 125 and 145°C, there existed a constant-rate drying period, which ended at the moisture content of about 2.2 kg/kg db. However, there was no obvious constant-rate drying period observed in the dehydration with the 165°C superheated steam. This was

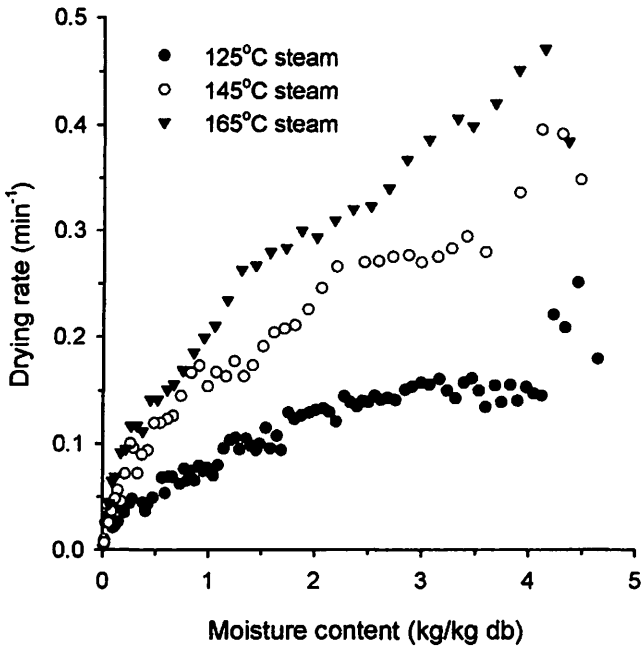

Fig. 6. Drying rates for cylindrical potato samples dehydrated in superheated steam at 125, 145, and 165°C.

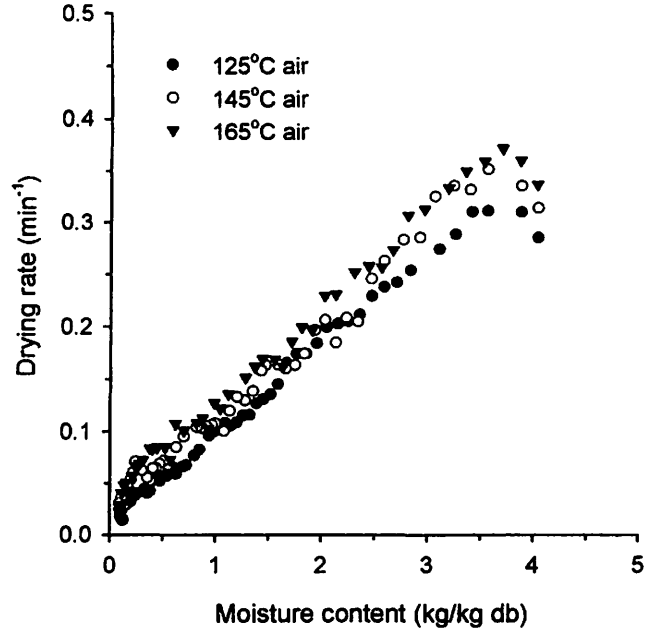

Fig. 7. Drying rates for cylindrical potato samples dehydrated in hot air at 125, 145, and 165°C.

probably caused by immediate surface hardening, which could increase the resistance to moisture migration, at the high temperature (Elson and Treagus 1984). Another reason might be that the high temperature increased the thermal driving force in the boundary layer and made the internal moisture transfer potential be the controlling factor during the whole dehydration process (Chen et al. 1992; Shibata and Mujumdar 1994).

The temperature change of superheated steam in the range from 125 to 165°C had a substantial impact on the drying rate due to the differences between the degrees of superheat, which was determined by the difference between the temperature of superheated steam and the vaporization temperature (100°C). For example, at the same moisture content 3 kg/kg db, increasing the steam temperature from 125 to 165°C increased the drying rate by 140% (Fig. 6).

The drying rates of the potato samples dehydrated in the hot air of the three temperatures are shown in Fig. 7. The drying rate also increased during the short initial warm-up period. Like the drying of most agricultural products with hot air, there was no constant-rate drying period observed during the dehydration, as discussed by Bimbenet et al. (1985) and Ferrao et al. (1998). The drying rates kept decreasing almost linearly except for the short initial period. Because of the small difference between the drying forces coming from the wet-bulb depression, which was the difference between the temperature of hot air and the wet-bulb temperature, the three drying rate curves were close to each other.

For dehydration in 125°C drying media, the drying rate of the potato sample in superheated steam was lower than that in hot air, but the situation became reversed for dehydration in 165°C drying media (Figs. 6 and 7). For dehydration in 145°C drying media, the drying rate of the potato sample in superheated steam was lower in the first stage, which was above 2.6 kg/kg db, but higher in the last stage, which was below 2.6 kg/kg db, than that in hot air. Extending the concept of inversion temperature to the whole dehydration process, we conclude that there exists an inversion temperature point between 145 and 165°C for the first stage and between 125 and 145°C for the last stage of dehydration.

Overall moisture diffusivities

A constant-rate drying period was noticeable only in the dehydration of potato samples exposed to the superheated steam of 125 and145°C, and the critical moisture content at the end of the constant-rate drying period was about 2.2 kg/kg db and it was quite visible when drying at 145°C (Fig. 6). Therefore, the overall diffusivity was determined for the samples when their moisture dropped below the critical moisture content. The overall diffusivity includes the diffusion of water inside the solid in the form of liquid and vapour or vapour only (Pabis et al. 1998).

Figure 8 shows the changes in the overall moisture diffusion coefficients with respect to moisture content for the potato samples dehydrated in superheated steam and hot air of different temperatures in the falling-rate drying period. The overall diffusivity increased with a decrease in moisture content, which followed the trend reported in the literature (Bouraoui et al. 1994; Jaros et al. 1992) except there was no sharp decrease at the short final dehydration stage. Increasing the temperature of the drying medium caused increase in the diffusion coefficient, and the effect of temperature on the diffusivity was greater in superheated-steam dehydration than in hot-air dehydration. For example, at the moisture content of 0.80 kg/kg db, increasing temperature from 125 to 165°C increased the overall diffusion coefficient by 165% in superheated-steam dehydration, but only 20% in hot-air dehydration. In addition, the overall diffusion coefficients were

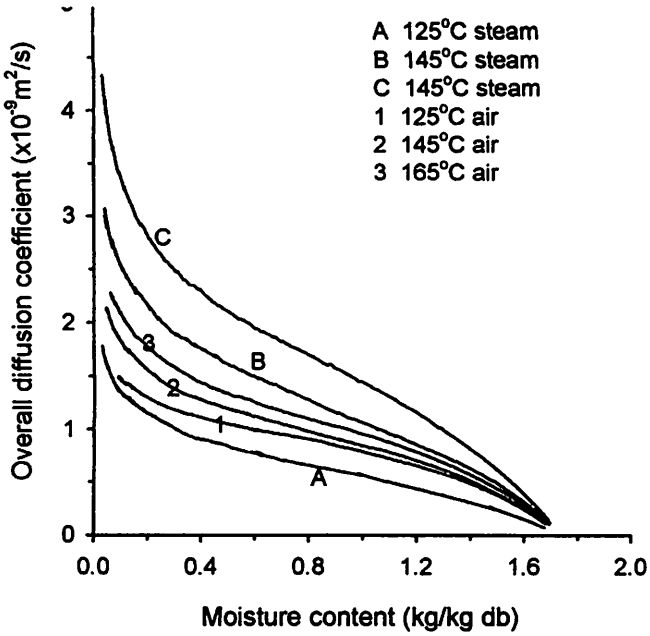

Fig. 8. Comparison of overall diffusion coefficients for cylindrical potato samples dehydrated in superheated steam and hot air at 125, 145, and 165°C in the falling-rate drying period.

higher in the dehydration with the superheated steam of 145 and 165°C than in the dehydration with the hot air of the same temperatures, but the situation reversed for the drying-medium temperature of 125°C. For example, at the moisture content of 0.80 kg/kg db, the overall diffusion coefficients were 1.3×10^{-9} and 1.0×10^{-9} m^2/s for the samples dehydrated in the superheated steam of 145°C and in the hot air of the same temperature, respectively; but 7×10^{-10} and 9×10^{-10} m^2/s for the samples exposed to the 125°C superheated steam and the 125°C hot air, respectively.

The research conducted by Cenkowski et al. (1996) on drying spherical bentonite samples as a food model showed that, for the falling-rate drying period, the overall moisture diffusion coefficient is 50 to 80% higher for samples dried at 160°C hot air than in the superheated steam of the same temperature. In our experiments with potato samples, this trend was followed only by the samples dehydrated in 125°C drying media, and the reverse was found for the samples exposed to the drying media at 145 and 165°C.

CONCLUSIONS

In the first half minute of dehydration of potato samples with superheated steam, a small amount of moisture (0.18 to 0.47 kg/kg db), depending on the steam temperature, was gained from the steam condensation on the sample surface.

For superheated-steam dehydration, the temperature at the centre of the potato samples rapidly rose to about 100°C during the initial warm-up period and then slowly increased to the temperature of superheated steam. For hot-air dehydration, the temperature increased gradually from about 50°C to the hot air temperature over the whole dehydration process.

In the range of 125 to 165°C used in the experiments, the effect of temperature on the drying rate, on the overall moisture diffusivity, and consequently on the dehydration time was greater for the superheated-steam dehydration than for the hot-air dehydration. Increasing the temperature of the drying medium from 125 to 165°C decreased the dehydration time by 60 and 24% for the dehydration with superheated steam and hot air, respectively.

A constant-rate drying period was noticeable only in the dehydration with the superheated steam of 125 and 145°C, and was not present in the dehydration with the superheated steam of 165°C and with the hot air of 125 to 165°C.

An inversion temperature point, if the concept of it could be extended to the whole dehydration process, existed between 145 to 165°C for the first dehydration stage above 2.6 kg/kg db, and between 125 to 145°C for the last dehydration stage below 2.6 kg/kg db.

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