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Experimental study of drying kinetics of skim milk

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ABSTRACT

Drying kinetics of skim milk solution is investigated in this work. Dry oven method used to determine the characteristic drying curves. The experiments are carried out at two temperatures of 45°C and 60°C and three different initial solid contents. The obtained characteristic curves for drying rate are normalized, based on a simple mass transfer model in which the drying rate is considered as a first order reaction. These normalized curves are independent of temperature and initial concentration and coincide together. The obtained experimental data are applied to identify a simple mass transfer model parameter. Finally a relative humidity factor f, is obtained as a function of ϕ, characteristic moisture content. This model can be used in CFD modeling of spray dryers for simple and efficient calculations.

KEYWORDS

Drying kinetics;
Skim milk;
Characteristic moisture content.

INTRODUCTION

Dehydration operations are important steps in chemical and food processing industries. Regarding this fact, drying technologies along with better control and operational strategies have contributed to a better quality dried products. Spray drying is a well-known method for drying that nowadays covers large number of applications for products ranging from food to mineral ores and chemicals. It is the core component of a milk powder production plant. The moisture content of milk powder is one of the predominant factors for preserving the quality of the product[5]. There is a great need for drying models to describe the drying process which helps in its optimization and can be useful in effective design of dryers or improve existing drying systems[7]. A drying process can be described completely by using an appropriate drying model, which usually includes differential equations of heat and mass transfer in the interior of the product and at its inter-phase with the drying agent[9]. Having mixed a mass transfer model with the knowledge of the drying kinetics, the calculation might be simple and efficient. Drying kinetics of the products are the most important required data for design and simulation of air dryers[3]. Also these models can be used in CFD software to reduce calculations and achieve more realistic performance.

In fact characteristic drying curve which expresses the time history of temperature-moisture content could be used to propose a mass transfer model[6]. In the recent years, several investigations have been conducted on the drying kinetics of different food and chemical materials. There have been more than 200 drying kinetics models offered for various foods in the literature, which are formally characterized by two different physical and empirical approaches[7]. But the existing differences among the model formulations can be considerable. Chen & Lin[2] have studied air drying of milk droplet under constant and time-dependent conditions. An attempt has been made to examine two significant models in a more comprehensive manner. One model is the characteristic drying rate curve approach and the other (new) model is the reaction engineering approach. The model predictions are compared against a very wide range of experimental results including isothermal and time-varying temperature conditions. Both models predict and cover the experimental results reasonably well. Besides, the results indicated that the reaction engineering approach model is better than the others. The characteristic drying rate curve approach assumes beforehand the falling rate in all kinds of conditions for milk droplet drying, whereas the reaction engineering model simply reflects the experimental results closely. Zbicinski et al.[8] have developed a method for measuring drying kinetics of different products in a dispersed system. They used phase doppler anemometry (PDA) technique to determine initial spray atomization parameters, the structure of spray during drying, particle size distribution, velocity of the particles and mass concentration of the liquid phase, etc.

The main objective of this research is to formulate an accurate model for analyzing the simulated drying kinetics of skim milk samples based on a good fit on the corresponding moisture content. This kinetics model is to be used in CFD modeling of a spray dryer used for skim milk drying to reduce computational time and accurate calculations. For determination of drying kinetics, the dry oven method is much easier and its duration may vary considerably depending on the drying temperature. The range of the studied parameters was near to those used in industrial spray dryers.

THEORY

The drying kinetics is greatly affected by air temperatures, initial and instant moisture content and air humidity. A mass-transfer model can be introduced by using a characteristic drying curve. This approach assumes that there is a corresponding specific drying rate relative to the unhindered drying rate in the first drying period on each volume-averaged free moisture content that is independent of the external drying conditions[6].

The mass transfer between the gas and droplet could be calculated according to the following first order reaction kinetics:

$$\frac{\mathbf{am_p}}{\mathbf{dt}} = -\mathbf{fA_pK_g(Y'_e - Y')} \qquad (1)$$

where in eq. (1) A_p is the surface of mass transfer, Y'_e and Y' are the equilibrium moisture and air humidity respectively. Also K_g is the mass transfer coefficient that can be obtained from eq. (2) with suitable coefficient values for η, β, ξ and ξ and f is the relative drying rate and is defined as eq. (3).

$$\mathbf{sh} = \beta + \eta\,\mathbf{Re}^{\zeta}\,\mathbf{Sc}^{\xi} \qquad (2)$$

$$\mathbf{f} = \frac{\mathbf{DR}}{\dot{\mathbf{DR}}} \qquad (3)$$

where DR is the drying rate and defines in eq. (4), $\dot{DR}$ is the rate in the first drying period.

$$\mathbf{DR} = -\frac{\mathbf{x_2 - x_1}}{\mathbf{t_2 - t_1}} \qquad (4)$$

where x is the moisture content (kg_{H2O}/kg dry solid) and *t* is drying time between two successive steps. Parameter f takes on the values in Eq. (5)[4].

Unhindered moisture $\mathbf{f = 1; \phi \geq 1}$ (5)

Hindered moisture $\mathbf{0 < f < 1; 0 < \phi < 1 <}$

ϕ, so called characteristic moisture content, and defined in terms of critical moisture content[4].

$$\boldsymbol{\phi} = \frac{\mathbf{x - x_e}}{\mathbf{x_{cr} - x_e}} \qquad (6)$$

where, x_e is the equilibrium moisture content and x_{cr} is the critical moisture content. A unique relationship between f and ϕ can be found for any specific material.

The drying curve is normalized and at critical point, there is a transition in drying behavior. By definition of correction factor f, a simple lumped-parameter expression for the drying rate can be obtained.

MATERIALS AND METHODS

Skim milk solutions with three different initial solid contents of 0.05, 0.1 and 0.15 (w/w) were prepared by adding water to milk powder at 24°C for experiments. The concentrated milk samples then were poured into a glass plate with 6 cm diameter.

The experimental set-up was consisted of a drying oven (Fan Azma Gastar) with On/Off control and digi-

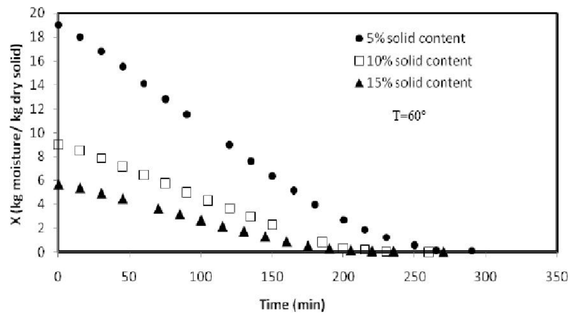

Figure 1 : Drying curves of skim milk solutions

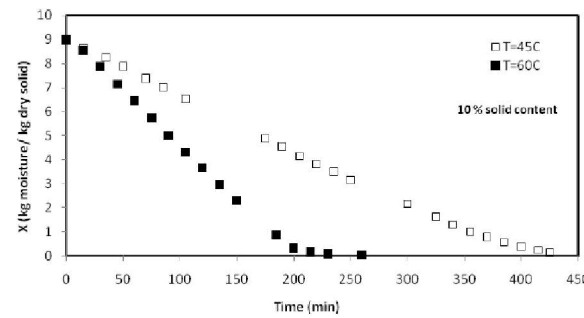

Figure 2 : Effect of drying temperature on drying time

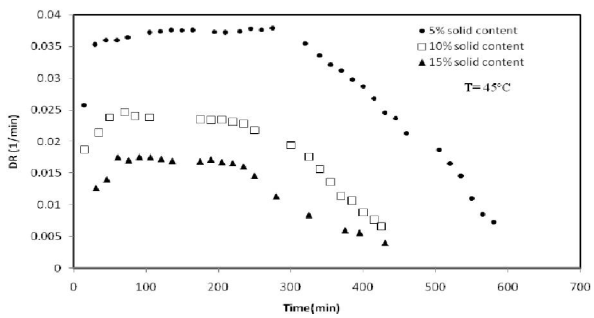

Figure 3 : Drying rate curve at different initial solid content

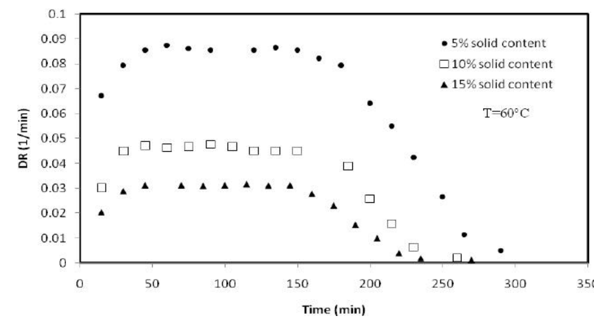

Figure 4 : Drying rate curve at different initial solid content

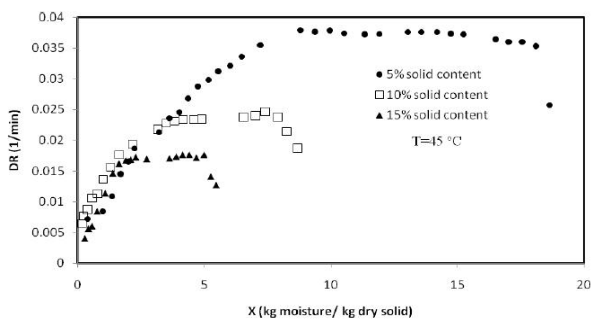

Figure 5 : Drying rate curve vs. x for different of initial solid content

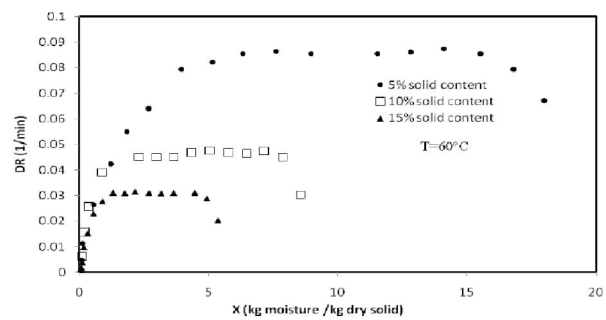

Figure 6 : Drying rate curve vs. x for different of initial solid content

tal indicator. For each experiment, changes in weight of sample were measured continuously using a digital balance (Sartorius BP 310s model) with an accuracy of ±0.001 gr. The balance was kept outside the oven and the sample was placed on a special sample holder which was hung from the balance. The drying oven was calibrated for temperature using a calibrated thermometer. In order to obtain an accurate and uniform temperature inside the oven, intensive air ventilation was used. All the required data were recorded every 15 min. To determine the equilibrium weight at a specified temperature, the samples were kept in the oven until the difference between two successive mass measurements became less than 0.02 g.

Before putting any sample into the oven the drying air temperature was fixed. It was assumed that the thickness of the milk solution sample is quite thin, so that the conditions of the drying air (temperature and humidity) were kept constant throughout the drying process, while the relative humidity in the room condition was 16%.

To consider the effect of temperature on the rate of drying the experiments were carried out at similar conditions and different temperatures including 45ºC and 60ºC.

RESULTS AND DISCUSSION

Characteristic drying curve

The drying behavior of skim milk solution as a func-

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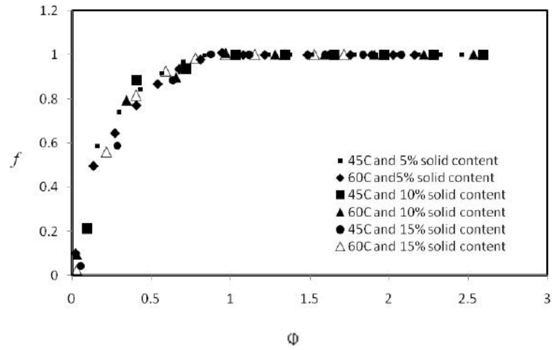

Figure 7 : The relative drying rate vs. ϕ

tion of time is shown in figure 1. It could be seen that the drying curve is almost a straight line with a continuous decrease of mass by the passage of time for all concentrations due to the fact of constant drying rate period. At final times, a deviation from the straight line can be observed which may be explained as the falling drying rate period. It also becomes obvious that skim milk solutions with lower initial concentrations have drying rate curves with higher intercepts.

Variations of the moisture content with the drying time at different air temperatures and initial concentrations are plotted also in figure 2. As a result, an increase in the temperature of the drying air decreases the total drying time as a result of increasing the rate of heat transfer. Besides, when the temperature increases from 45°C to 60°C, the total drying time decreases to about 40% of that for the solution with drying temperature of 45°C.

Drying rate curve as a function of time

The drying rate (DR) of the solutions during the drying process could be obtained by using eq. (4). Figure 3 and 4 show the variation of DR, with time for two different operating temperatures. As a result of the moisture transfer, the drying rate decreases, with elapse of time. Approximately entire drying process took place in the constant rate period. These figures illustrate that for a higher air temperature, the drying rate will be increased and drying will take placed at lower times.

Drying rate curve as a function of X

The drying rate curve for skim milk can be obtained also by plotting drying rate vs. moisture content (x). Figure 5 and 6 illustrate drying rate curve vs. x for two temperature of 45°C and 65°C and initial solid contents of 0.05, 0.1, 0.015 (w/w). These figures show drying rate curves of the samples at the selected temperatures, where about 83-87% of water content was evaporated at the end of constant rate period of drying, a linear falling rate can be observed at the end of process which is due to very low thickness of sample layers. It may indicate that the resistance to moisture transport is related to the thickness of solution.

Nomenclature

A	particle surface area (m^2)
DR	drying rate (s^{-1})
f	relative drying rate (¯)
K	mass transfer coefficient ($kg\ s^{-1}$)
Sh	Sherwood number (¯)
t	time (s)
T	temperature (°C)
X	moisture content (kg moisture kg^{-1}dry solid)
Y'	gas humidity ($kg\ kg^{-1}$)
ϕ	characteristic moisture content (¯)
B, η, ζ, ξ	constant in eq. (3) (¯)
	Subscripts
cr	Critical
e	Equilibrium
G	dry bulb, bulk gas

Prediction of f

Figure 5 and 6 represent drying rate as a function of X, according to eq. (1). When the characteristic drying curve became normalized, these curves are independent from the temperature and initial solid content. Figure 7 shows the relative drying rate as a function of ϕ. In this figure f is only a function of ϕ. These six curves at temperature 45°C and 60°C and initial solid content of 0.05, 0.1 and 0.15 (w/w) approximately coincide together.

It is possible to find a relation between relative drying rate f vs characteristic moisture content (ϕ). According to the best fitting of six data series of figure 5 and 6, eq. (7) can be obtained with R^2 in the range of (99-94%).

$$f = -0.325\phi^4 + 1.83\phi^3 - 3.752\phi^2 + 3.27\phi - 0.031 \quad (7)$$

CONCLUSION

Dry oven method applied for determination of characteristic drying curve of skim milk solution. Drying curves have in general two stages after an initial warm-up: constant drying and falling rate periods. Drying models for constant and falling rate period of skim milk solution based on the concept of characteristic drying rate are proposed, and found a unique relationship between relative drying rate f and characteristic moisture content for specific material. This model can be used in CFD software for simple and efficient calculations. In particular, the concept of a characteristic drying curve states that the shape of the drying-rate curve for a given material is unique and independent of gas temperature, humidity and velocity.

Convective drying of skim milk solutions was dependent on temperature, and the drying curve showed a constant rate period; only a short falling rate period was observed at the end of process.

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