INFLUENCE OF DRYING CONDITIONS ON THE MOISTURE DIFFUSION DURING SINGLE STAGE AND TWO STAGE FLUIDIZED BED DRYING OF BOVINE INTESTINE FOR PET FOOD

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ABSTRACT

Bovine intestine samples were heat pump fluidized bed dried at atmospheric pressure and at temperatures below and above the material freezing points equipped with a continuous monitoring system. The investigation of the drying characteristics has been conducted in the temperature range -10~25^{o}C and the airflow in the range 1.5~2.5 m/s. Some experiments were conducted as a single temperature drying experiments and others as two stage drying experiments employing two temperatures. An Arrhenius-type equation was used to interpret the influence of the drying air parameters on the effective diffusivity, calculated with the method of slopes in terms of energy activation, and this was found to be sensitivity of the temperature. The effective diffusion coefficient of moisture transfer was determined by Fickian method using uni-dimensional moisture movement in both moisture, removal by evaporation and combined sublimation and evaporation. Correlations expressing the effective moisture diffusivity and drying temperature are reported.

INTRODUCTION

Drying of foods is a major operation in the industry consuming larger amounts of energy. Drying operation is used as a primary operation for preservation of food materials or as secondary process in some manufacturing operations. This is a complex process involving mass and heat transfer accompanied by physical and structural changes (Senadeera, 2009). The quality of food materials that undergo drying depends on their initial quality and changes during drying. Shape and size changes occur influencing their physical properties which will change their final texture and transport properties (Senadeera et al., 1998).

Fluidised bed drying has been recognized as a gentle uniform drying process down to low residual moisture content with a high degree of efficiency (Borgotte and Simon, 1981). In fluidized bed, conditions are favourable for rapid heat and mass transfer due to thin boundary layer surrounding the food particles due to very rapid mixing. This is a very convenient method for heat sensitive food materials as it prevents them from over-heating (Giner and Calvelo, 1987).

Properly selected heat pump drying technology is an environmental friendly technology. It is operated in a closed drying circuit hence there won't be any gas or fines discharge to the atmosphere. The drawback of the heat pump technology is the low moisture removal rates for atmospheric pressure freeze drying with greater residence times for stationary beds. This problem can be overcome by agitation, fluidization and intermittent drying (Mujumdar and Alves-Filho, 2003). Any drier that uses convection as the primary mode of heat input can be fitted with a suitably designed heat pump such as fluid bed dryers. Heat pump fluid bed drying offers better product quality, offsetting incremental increasing in drying costs with a high market value of the product (Alves-Filho and Strommen, 1996).

Bovine intestine is rich in lipids and minerals important in Carnivores diet. The heat pump drying is a gentle process to remove moisture from the raw material and preserve the chemical constituents. The dried BI has a great potential for application in the pet food market.

In the present study, in an effort to fill the gap that exists in the literature regarding the drying of Bovine Intestine, several relevant studies were undertaken. In this way effective moisture diffusivity on drying conditions were determined. The objective of this work on fluidized bed heat pump drying of bovine intestine are, to study the effect of operating conditions on the moisture movement during drying and describe drying kinetics and drying rates.

Theoretical Considerations

Drying of food is relatively complex. Knowledge of drying kinetics is important in the design, simulation and optimization of the drying processes. Drying curves are usually modeled by defining the drying rates constants based on first order kinetics. The basic model of drying kinetics is known as the simple (exponential) model (Equation 1).

$$MR = \exp(-kt) \tag{1}$$

where MR = moisture ratio, k = drying constant and t = drying time.

The drying of food materials normally occurs in falling rate period. The moisture and/or vapour migration during this period is controlled by diffusion. The diffusion could include molecular diffusion, liquid diffusion through solid pores, vapour diffusion in air filled pores, Knudsen flow and all other factors which affect drying characteristics. Since it is difficult to separate individual mechanism, the rate of moisture movement is described by an effective diffusivity, a lumped value (Sablani et al., 2000). In most situations, Fick's second law of diffusion is used to describe a moisture diffusion process (Equation 2).

$$\frac{\partial m}{\partial t} = D_{eff} \nabla^2 m \tag{2}$$

Fick' equation has simple analytical solutions when shrinkage is negligible or not taken into account. The internal movement is its main resistance and negligible external resistance and internal heat transfer effects (Sablani et al., 2000), and it also neglects the initial thermal transient effect.

When the product is assumed as one-dimensional and to have uniform initial moisture content, the solution of Fickian equation for infinite slab is described by Equation 3 (Senadeera et al., 2003).

$$MR = \frac{m - m_e}{m_o - m_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left[-(2n-1)^2 \frac{\pi^2 D_{eff} t}{L^2} \right] \tag{3}$$

where D_{eff} = effective diffusion coefficient (m^2/s), t = time, L = slab half thickness (m), MR = dimensionless moisture ratio, n = positive integer.
For long drying times (MR <0,6), when L are small and t is large, limiting forms of equation is obtained for the slab by considering only the first term in their series expansion (Brennan, 1994). Then Equation (3) can be written as Equation 4.

$$MR = \frac{m - m_e}{m_o - m_e} = \frac{8}{\pi^2} \left[- \frac{\pi^2 D_{eff} t}{L^2} \right] \tag{4}$$

For a finite slab, the geometry corresponds to the intersection of three infinite slabs, with lengths of a, b and c, which yields the following expression (Crank, 1975):

$$MR_x MR_y MR_z = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2}{a^2} D_{eff} t \right] \frac{8}{\pi^2} \exp\left[-\frac{\pi^2}{b^2} D_{eff} t \right] \frac{8}{\pi^2} \exp\left[-\frac{\pi^2}{c^2} D_{eff} t \right] \tag{5}$$

For a finite slab with a=L, b=L and c=L, this expression is reduced to:

$$MR = \frac{8^3}{\pi^6} \exp\left[-\frac{3\pi^2}{L^2} D_{eff} t \right] \tag{6}$$

To make physical sense, the factor $(8^3)/\pi^6$ of Equation 6 is not considered (Mulet et al., 1989), which yield:

$$MR = \exp\left[-\frac{3\pi^2}{L^2} D_{eff} t \right] \tag{7}$$

A general form of Equation (1) and (4) can be written in logarithmic form (Equation 8)

$$\ln MR = A - Bt \tag{8}$$

where, constant B is $\pi^2 D_{eff}/L^2$ for this case and can be calculated from the slope B of the graph ln MR vs time. The effective diffusivity and drying constant is derived from the slope.

MATERIALS AND METHODS

Raw Materials

Bovine intestine was used as the material for testing. Material were cut into 4 mm cubes and kept at -25^o C before drying to maintain original characteristics and heated close to melting point prior to drying. The bovine intestine is composed of a large fraction of white tissue and a smaller portion of dark tissues.

Drying

The heat pump dehumidifier system in the Department of Energy and Process Engineering at Norwegian University of Science and Technology, Trondheim, Norway was used for the experimentation. The dryer has a drying loop and heat pump circuit. The drying loop has an air dehumidifier and heater and a blower. The conditioned air enters the chamber, contacts and fluidized the wet materials. The removed water from the material was condensed on the surface of the evaporator and was drained out from the loop. The dehumidified air flowed through the condenser and was heated and re-enter the drying chamber at the desired drying temperature. In this way the latent heat of removed water is used to boil the fluid inside the evaporator. The energy recovered is transferred to the air flow as the fluid liquefies inside the condenser. The external parts of the drying loop and heat pump circuit are thermally insulated to minimize energy losses to the surroundings (Alves-Filho et al., 2002). Schematic of the drying loop and experimental set up is shown in Figure 1 and Figure 2 respectively.

The drying chamber is cylindrical with a diameter of 0.25 m, and particle bed height was kept at constant for all trials by using a bed volume of $2x13^{-3}$ m^3 of material. The drying temperatures were -10, -5, 5, 15, 25^{o}C and combinations of -10/25^{o}C and -5/25^{o}C. All experiments were done under stable fluidization condition and fluidization velocity was kept at 1.5~2.5 m/s.

Fluidised bed heat pump drying of bovine intestine samples were done in atmospheric pressure at below and above the material freezing temperature. Sampling and measurements were taken during each drying test to characterize quality and properties. Sampling and measurement were done during each drying test and seven experimental runs and their drying conditions are shown in Table 1.

Table 1. Experimental runs and drying conditions with 54.5% (wb) for all runs

Run	T (^{o}C)	T (h)	m_f (%wb)	Sampling, min
1	-10	21.00	12.9	30
2	-10/25	5.00/2.00	11.6	30/10
3	-5	20.00	9.0	30
4	-5/25	5.00/2.00	9.6	30/10
5	5	5.30	13.4	15
6	15	7.45	6.8	15
7	25	2.20	9.2	10

Experimental design

The experiments were conducted as a completely randomized single factor experiment. All the experimental treatments were conducted in three replicates. The data were analysed for the analysis of variance (ANOVA) to evaluate differences and non-linear regression to obtain suitable models. The curve which best fitted the data was taken as the model. Model validity was tested using statistical parameters such as correlation coefficient R^2.

The significance differences between the samples were examined by comparing parameters in equations fitted to the different replications. Only situations where differences were not significant have been reported.

The moisture equilibrium equation

The equilibrium moisture content was calculated from GAB (Guggenheim-Anderson-De Boer) equation which is frequently used by several investigators (Keey, 1992).

$$m = \frac{M_m\, C\, K\, a_w}{[1 - K\, a_w][1 + [C-1]\, K\, a_w]} \tag{9}$$

Where, C, K and M_m, are the GAB equation parameters which determined from experimental data for all drying runs. The relationship between equilibrium moisture content versus water activity is obtained by GAB equation with parameters. Results indicated that the Bovine intestine have similar trend in water activity and equilibrium moisture content.

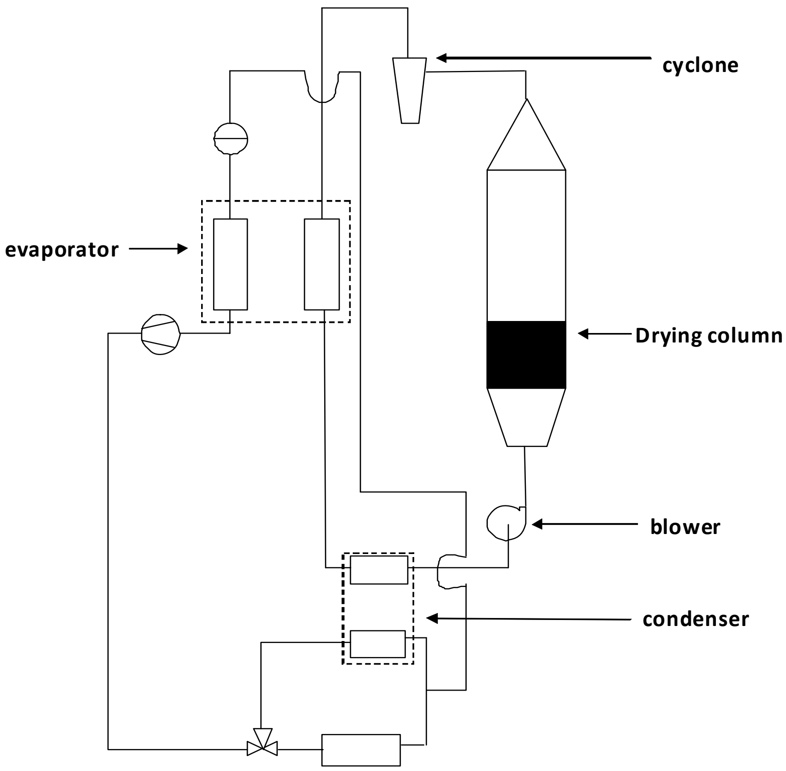

Figure 1. Schematic of the drying loop.

Analysis of the drying data

The drying data, when plotted in ln (D_{eff}) versus $1/T_{abs}$ diagram, resulted in a straight line similar to equation 8. The slope of the curve, found by application of linear regression, which gives coefficient E_a/R and intercept ln (D_o). Applying drying kinetics equation, in the form similar to Equation 8, the data was plotted in a ln(MR) versus drying time diagram. The slope of the straight line found by applying linear regression resulted in drying parameter k, while the intercept is equal to ln A.

The correlation coefficient R^2 was the primary criterion to select the best equation to account for the variation in the drying data experimentally obtained.

Figure 2. Experimental heat pump fluid bed dryer.

RESULTS AND DISCUSSION

Drying kinetics

Figure 3 shows drying kinetics at -10 ^{o}C. Drying occurred only in the falling rate period for all experiment trials. The average moisture content was expressed as non-dimensional moisture ratio 'MR' (Equation 1) and used to plot the drying curves with time (h) for different air drying temperatures and value of velocity of air was kept constant. Drying kinetics of other drying conditions follow the similar pattern of kinetics and not shown.

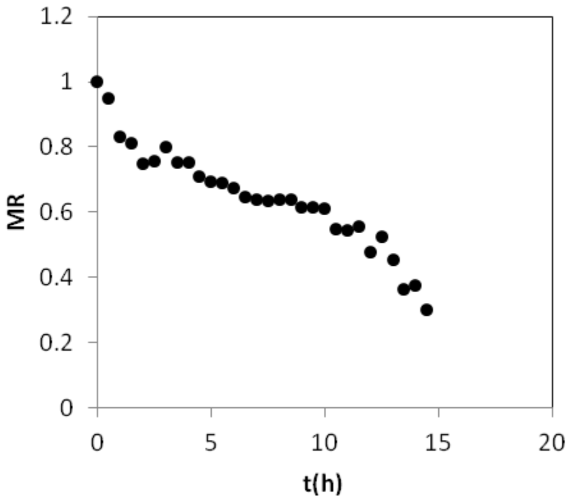

Figure 3. Drying kinetics at -10^{o}C.

The initial moisture content was used as the critical moisture content due to absence of constant period of drying. Final moisture content after the drying was used as equilibrium moisture content for all drying experiments. The estimated parameters for the drying kinetics are shown in Table 2. Drying rates increased as the temperature increases during drying.

In the drying curves the effect of increasing air temperature is evident and increased with temperature. The value of moisture ratio decreases rapidly, with consequent increase of the drying rate, when air temperature increased. The experimental results are agreed with the values reported in the literature for other food materials in which major factor affecting drying rate is the temperature.

Atmospheric freeze drying combined with medium temperature drying involve removal of moisture from solids both by sublimation and evaporation. In such combined process the moisture is removed sequentially by ice sublimation and liquid evaporation by avoiding structural collapse (Alves-Filho and Roos, 2006). In those two cases (-10/25 and -5/25^{o}C) diffusion coefficient depends on the point at which the change of drying temperature occurs.

Table 2. Drying constant at various drying conditions

T (^{o}C)	**K**	**D_{eff} (m^2/h)**
-10	0.0575	9.34x10^{-8}
-10/25	0.7653~1.2726	1.36~2.06x10^{-7}
-5	0.1129	1.83x10^{-7}
-5/25	0.1542~1.6291	1.13~2.64x10^{-7}
5	0.5145	4.34x10^{-7}
15	0.3943	6.39x10^{-7}
25	0.3951	6.40x10^{-7}

Effective diffusion coefficient (D_{eff})

The effective diffusivity was calculated using equations (7 and 8) described in the introduction section. One dimensional mass transfer was used to calculate effective diffusion coefficient. The calculated values of effective diffusion coefficients are shown in Figure 4. It was considered and evidenced that drying was occurred in falling rate period only. This means liquid diffusion is the driving force controlling the drying process and curves are straight lines. The effective diffusivity was calculated with the method of slopes as previously described and the calculated values are reported above in Table 2. For two stage drying diffusion coefficient for each stage is also given.

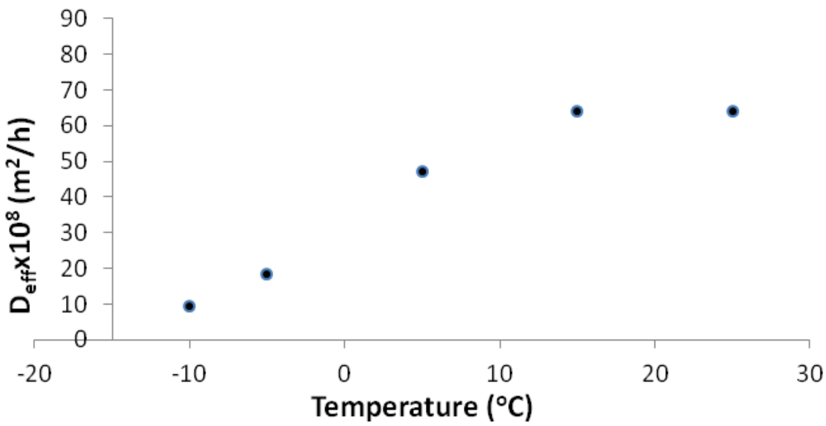

Figure 4. Effective diffusivity as affected by drying air temperatures.

The effective diffusivity coefficient changes from $9.34\text{x}10^{-8}$ m^2/h to $6.4\text{x}10^{-7}$ m^2/h from -5^{o}C to 25^{o}C drying temperatures. For the combined drying operations it exhibit two values for below freezing temperatures and above freezing temperatures. For the case of drying at -10^{o}C/25^{o}C it changes from $1.36\text{x}10^{-6}$ to $2.06\text{x}10^{-6}$ m^2/h during operation and for the case of -5^{o}C/25^{o}C changes from $1.13\text{x}10^{-7}$ to $2.64\text{x}10^{-7}$ m^2/h (not shown in Figure 4).

Effect of temperature on D_{eff}

It is clear from Figure 4 that the diffusivity is strongly influenced by the temperature. Calculated D_{eff} values were fitted to the Arrhenius-type of Equation (Equation 10).

$$D_{eff} = D_o \exp\left(\frac{-E_a}{R\left(T+273.15\right)}\right) \tag{10}$$

where, Do = reference diffusion coefficient at infinitely high temperature
This results in D_o as 0.00134 m^2/h and E_a as 2.33 KJ/mol.

CONCLUSIONS

Experiments on drying of Bovine Intestine particles were carried out in a laboratory-scale fluidized heat pump dryer. By shifting single stage to two stage drying effective diffusivities and moisture removal rates increased. Properly schedules residence times for two stage drying leads to optimum drying rates, improved dryer capacity.
Higher diffusivity values were obtained considering materials with infinite surface. Effective diffusivity increased with the increased in temperature of drying. Most of the drying takes place in the falling rate period for all temperatures and temperature combinations are concerned. The closer values for effective diffusivity at 15^{o}C and 25^{o}C may be attributed to development of case

hardening at higher temperatures and shrinkage effects.The calculated values of effective diffusivity lie within the general range typical to drying of food materials, as reported in the literature.
This investigation suggests that two-stage fluid bed heat pump drying of Bovine Intestine is an efficient and environmentally friendly technology that has the potential to improve moisture removal keeping improved product quality at reduced costs.

NOTATION

A,B	constant	
C	centigrade	
D_{eff}	effective diffusion coefficient	m^2/h
Do	Arrhenius factor	m^2/h
Ea	Activation energy	KJ/mole
k	drying constant	h^{-1}
L	sample thickness	m
m	moisture content	kg/kg
MR	moisture ratio/dimesionless moisture ratio	
n	constant	
R	ideal gas constant	KJ/kmol K
t	time	h
T	temperature	^oC

Greek Symbols

∇	operator
Σ	summation
∂	partial differential coefficient

Subscripts

e	equilibrium
f	final
i	integer
o	initial

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