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Influence of drying conditions on the moisture diffusion and fluidization quality during multi-stage fluidized bed drying of Bovine Intestine for pet food

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ABSTRACT

In order to establish the influence of the drying air characteristics on the drying performance and fluidization quality of Bovine Intestine for pet food, several drying tests have been carried out in a laboratory scale heat pump assisted fluid bed dryer. Bovine intestine samples were heat pump fluidized bed dried at atmospheric pressure and at temperatures below and above the materials freezing points, equipped with a continuous monitoring system. The investigation of the drying characteristics have been conducted in the temperature range -10~25°C and the airflow in the range 1.5~2.5 m/s. Some experiments were conducted as 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 temperature on the effective diffusivity, calculated with the method of slopes in terms of energy activation, and this was found to be sensitive to the temperature. The effective diffusion coefficient of moisture transfer was determined by the 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.

Bovine particles were characterized according to the Geldart classification and the minimum fluidization velocity was calculated using the Ergun Equation and generalized equation for all drying conditions at the beginning and end of the trials. Walli’s model was used to categorize stability of the fluidization at the beginning and end of the drying for each trial. The determined Walli’s values were positive at the beginning and end of all trials indicating stable fluidisation at the beginning and end for each drying condition.

Key words: intermittent drying, diffusion, fluidisation, bovine intestine, Ergun model
1. Introduction

Drying of foods is a major operation in the industry and consumes larger amounts of energy. Drying operation is used as a primary operation for preservation of food materials or as a secondary process in some manufacturing operations. This is a complex process involving mass and heat transfers 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 change their final texture and transport properties (Senadeera et al., 1998).

Fluidised bed drying has been recognized as a gentle, uniform drying process which lowers the residual moisture content with a high degree of efficiency (Li et al., 2013). In fluidized bed, conditions are favourable for rapid heat and mass transfer due to a thin boundary layer surrounding the food particles which are caused by very rapid mixing. This is a very convenient method for heat sensitive food materials as it prevents them from overheating (Fries et al., 2013).

Properly selected heat pump drying technology is an environmentally friendly type of technology. It is operated in a closed drying circuit so that there won’t be any gas or fines discharged into 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 dryer. Heat pump fluid bed drying offers better product quality, offsetting incremental increasing in drying costs with a high market value for the product (Alves-Filho and Strommen, 1996).

Bovine intestine is rich in lipids and minerals important in carnivorous diet. The content depends on the diet and age of the animal. 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 as well as fluidization quality.
Fluidization behaviour

The particle density, air density and size and shape of the material can be categorized according to the type of fluidization behavior by the use of the Geldart Classification (Geldart, 1973). Prediction of minimum fluidization is an important consideration when operating a fluidized bed, since the velocity of the fluidizing medium must always be maintained above this value during operation. At minimum fluidization velocity, drag force by upward moving gas is equivalent to the weight of the particles.

The Ergun equation (Ergun, 1952) is the widely accepted model used to determine minimum fluidization velocity of a fluid to fluidise any material (Kuni and levenspiel, 1969, Zenz and Harbor, 1971 and Michielis and Calvelo, 1994). The Ergun equation was used to calculate the minimum fluidization velocity of peas (Rios et. al, 1984), diced potato and potato strips (Vazquez and Calvelo, 1980; Vazquez and Calvelo, 1983).

\[
(1-\varepsilon_{mf})(\rho_p-\rho_f)g = 150 \frac{(1-\varepsilon_{mf})^2}{\varepsilon_{mf}^3} \frac{\mu u_{mf}^3}{(\phi d_p)^2} + 1.75 \frac{(1-\varepsilon_{mf}) \rho_f u_{mf}^2}{\varepsilon_{mf}^3} \phi d_p
\] (1)

The values for minimum fluidization velocity obtained by the Ergun Equation are most reliable for spherical and relatively small particles. Most agro-food particulates, however comprise of various shapes and sizes, and consist of larger particles. For larger particles which comprise of various shapes and sizes, the minimum fluidization values obtained from Ergun equation not confirm to the experimental values (Mckay and Mclain, 1980; Mckay et. al., 1987). The Ergun equation has therefore, been generalized for its wider application for larger and irregular particles. For the case of larger particles at higher Reynolds numbers (Re >1000) fluidization behavior is mainly governed by the kinetic energy term in the Ergun Equation. Hence the Ergun equation can be simplified to (Kunii and Levenspiel, 1969) considering only kinetic energy term:

\[
u_{mf}^2 = \frac{\phi d_p^2 (\rho_p-\rho_f)}{1.75 \rho_f \varepsilon_{mf}^3} g
\] (2)

For a wide variety of systems it was found that the value $1/\phi \varepsilon_{mf}^3$ equals to 14 (Wen and Yu, 1966) and equation (2) can be modified predict $u_{mf}$ for larger particles when $Re > 1000$.

\[
u_{mf}^2 = \frac{d_p (\rho_s-\rho_f)}{24.5 \rho_f} g
\] (3)
where, $\rho_s$ – particle density (kg/m$^3$), $\rho_f$ – fluid density (kg/m$^3$), $u_{mf}$ – minimum fluidization velocity (m/s), $d_p$ – particle equivalent diameter (m), $Re$ – Reynolds number

The equation (3) is known as the generalised equation and is widely used in many calculations. Terminal velocity is another factor in fluidised bed drying. At terminal velocity the particles will transport from the drier in the incoming air stream. Terminal velocity is important in fluidised bed drying as operational velocity must always be kept between the minimum fluidisation velocity and terminal velocity (Mckay et al., 1992). Bovine intestines can be prepared for fluid bed drying in different size particles, in most cases they are resemble to either parallelepipeded or cubical shape. Depending on the size either Ergun equation or Generalised equation can be used to predict fluidization velocities. It is important to understand changes of fluidization behaviour, so that airflow during drying can be controlled to achieve an optimum fluidization conditions favourable for energy conservation.

Fluidization quality

Prediction of fluidization behaviour is needed for the best working conditions of a product in a fluidization system (Khoshtaghaza and Chayjan, 2007). The best condition for fluidization is at a velocity closer to minimum fluidization velocity where more energy savings could be observed. In any system finding of minimum fluidsation velocity is a necessity to optimize its operation. Also determination of fluidization quality is also necessary to carry out this operation smoothly. Wallis’s criteria is a good way of finding quality of fluidization when homogenous particles are concerned (Gibilaro, 2001) and used by some authors (Khoshtaghaza and Chayjan, 2007).

Wallis’s model (Equation 4) is used to determine the fluidization quality of any system by comparing the sign of the Walli’s factor ($V_e$) calculated by equation 4 suggested by Gibilaro (2001).

$$
\frac{1.79}{n} \left( \frac{gd_p}{u_t^2} \right)^{0.5} \left( \frac{\rho_p - \rho_f}{\rho_p} \right)^{0.5} \left( \frac{\epsilon_{st}^{1.5} \left( 1 - \epsilon_{st} \right)^{0.5}}{\left( 1 - \epsilon_{st} \right)^{0.5}} - 1 \right) = V_e
$$

(4)

Depending on the sign of the Walli’s factor $V_e$, fluidization quality is categorized as follows;

$V_e > 0$ stable fluidization (homogeneous)

$V_e = 0$ stability limit

$V_e < 0$ unstable fluidization (bubbling)

When determining the Walli’s factor, apart from the physical properties of the materials, terminal velocity of the material ($u_t$) and a coefficient named as Richard-Zaki coefficient (n) is needed to use in equation 4.

The Richard-Zaki coefficient ‘n’ is derived according to Equation 5, using Archimedes number which is derived from equation 6.
\[
\frac{4.8 - n}{n - 2.4} = 0.043 \text{Ar}^{0.57}
\]  \hspace{1cm} (5)

\[
\text{Ar} = \frac{g d^3 \rho_f (\rho_p - \rho_f)}{\mu_f^2}
\]  \hspace{1cm} (6)

Calculation of the terminal velocity \((u_t)\) of the particle is accomplished by relating the Reynolds number to the Archimedes number using equation 7 suggested by Dallavalle (1948) and then solving for terminal velocity by equation 8.

\[
\text{Re}_t = \left[-3.809 + \left(3.809^2 + 1.832 \text{Ar}^{0.5}\right)^{0.5}\right]^{b}
\]  \hspace{1cm} (7)

\[
\text{Re}_t = \frac{d_p u_t \rho_f}{\mu_f}
\]  \hspace{1cm} (8)

Drying behavior

Drying of food is relatively complex. It involves the application of heat to vaporize water and some means of removing water vapor after its separation from the food material. Hence it is a combined mass and heat transfer operation, which occurs simultaneously. Internal moisture transport during drying of food materials is important in industry, but the way it occurs is very complex and different transport mechanisms are involved. In drying literature several mechanisms of internal moisture transport have been proposed and transport mechanisms are explained in detail (Mitra et al., 2012). 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 9).

\[
\text{MR} = \exp(-kt)
\]  \hspace{1cm} (9)

Where \(\text{MR} = \) moisture ratio, \(k = \) drying constant and \(t = \) drying time.

The drying of food materials normally occurs in the 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 10).

\[
\frac{\hat{m}}{\hat{t}} = D_{\text{eff}} \nabla^2 m
\]  \hspace{1cm} (10)

Fick’s equation has simple analytical solutions based on several assumptions; unidimensional moisture transfer, uniform initial moisture content, constant effective diffusivity throughout the material, constant solid geometry and negligible external resistance to heat and mass transfer, so the surface of the solid is at equilibrium with the surrounding air and
constant drying conditions are maintained throughout the process. Also shrinkage is negligible or not taken into account. The internal movement is its main resistance and external resistance and internal heat transfer effects are negligible (Sablani et al., 2000), and it also neglects the initial thermal transient effect.

For long drying times \( \text{MR} < 0.6 \), when half slab length \( L \) of the samples are small and drying time \( t \) is large, limiting forms of the equation is obtained for the slab by considering only the first term in their series expansion (Brennan, 1994). Then Equation 10 can be written as Equation 11.

\[
\text{MR} = \frac{m - m_e}{m_o - m_e} = \frac{8}{\pi^2} \left[ -\frac{\pi^2 D_{\text{eff}}}{L^2} t \right] \tag{11}
\]

Where, \( D_{\text{eff}} \) = effective diffusion coefficient (m\(^2\)/s), \( t \) = time, \( L \) = slab half thickness (m), \( \text{MR} \) = dimensionless moisture ratio

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):

\[
\text{MR}_x \text{MR}_y \text{MR}_z = \frac{8}{\pi^2} \exp \left[ -\frac{\pi^2}{a^2} D_{\text{eff}} t \right] \frac{8}{\pi^2} \exp \left[ -\frac{\pi^2}{b^2} D_{\text{eff}} t \right] \frac{8}{\pi^2} \exp \left[ -\frac{\pi^2}{c^2} D_{\text{eff}} t \right] \tag{12}
\]

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

\[
\text{MR} = \frac{8^3}{\pi^6} \exp \left[ -\frac{3\pi^2}{L^2} D_{\text{eff}} t \right] \tag{13}
\]

To make physical sense, the factor \((8^3)/\pi^6\) of Equation 13 is not considered (Mulet et al., 1989), which yield:

\[
\text{MR} = \exp \left[ -\frac{3\pi^2}{L^2} D_{\text{eff}} t \right] \tag{14}
\]

A general form of Equation (14) can be written in logarithmic form (Equation 15)

\[
\ln \text{MR} = A - Bt \tag{15}
\]

where, constant B is \( 3\pi^2 D_{\text{eff}}/L^2 \) for this case and can be calculated from the slope B of the graph \( \ln \text{MR} \) vs time. The effective diffusivity and drying constant is derived from the slope.

There was not much literature was available at the time of investigation concerning the systematic experimental investigation of fluidization behavior of bovine intestine particles. This is an experimental investigation to assist understanding, design and development of fluidisation processes for drying of food material such as Bovine Intestine particles. Bovine intestine is rich in lipids and minerals important in carnivorous diet used in pet food. 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. The procedures developed can be used as the basis for general predictive correlations to study the behavior of food material concerned.

The objective of this work on fluidized bed heat pump drying of bovine intestine is to study the effect of operating conditions on the fluidization characteristics and its effect on the drying kinetics. Also to compare the minimum fluidization velocity with the generalized model and Ergun model and confirm stability of the fluidization during experiments.

2. Materials and methods

2.1. Raw Materials

Bovine intestine was used as the material for testing. Material were cut into 4 mm cubes and kept at -25°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.

2.2. Drying

The heat pump dehumidifier system in the Department of Energy and Process Engineering at the 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 2x13³ m³ of material. The drying temperatures were -10, -5, 5, 15, 25°C and combinations of -10/25°C and -5/25°C. All experiments were done under stable fluidization condition and fluidization velocity was kept at 1.5~2.5 m/s. These low temperatures only permitted evaporation of moisture.

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 (colour) 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

<table>
<thead>
<tr>
<th>Run</th>
<th>T (°C)</th>
<th>t (h)</th>
<th>mᵣ (%wb)</th>
<th>Sampling, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10</td>
<td>21.00</td>
<td>12.9</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>-10/25</td>
<td>5.00/2.00</td>
<td>11.6</td>
<td>30/10</td>
</tr>
<tr>
<td>3</td>
<td>-5</td>
<td>20.00</td>
<td>9.0</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>-5/25</td>
<td>5.00/2.00</td>
<td>9.6</td>
<td>30/10</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>5.30</td>
<td>13.4</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>7.45</td>
<td>6.8</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>2.20</td>
<td>9.2</td>
<td>10</td>
</tr>
</tbody>
</table>

2.3. 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 R².

The significant 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.

2.4. 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). This model was selected as this is suitable for many food applications and provides a good description of almost every food products with water activity less than 0.9.

\[
m = \frac{M_m C K a_w}{[1 - K a_w][1 + (C - 1) K a_w]} \quad (16)
\]

Where, C, K and Mₘ are the GAB equation parameters which were 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.
2.5. Material Characterization
Some important average particle characteristics of the bovine intestine are described below. The equivalent diameter given here is the diameter of a sphere having the same volume as the particle (Table 2).

Table 2 Bovine Material Characterization

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Fresh Bovine</th>
<th>Dried Bovine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent diameter</td>
<td>0.004962 m</td>
<td>0.00485 m</td>
</tr>
<tr>
<td>Particle density</td>
<td>990 kg/m³</td>
<td>1100 kg/m³</td>
</tr>
<tr>
<td>Bulk density</td>
<td>200 kg/m³</td>
<td>500 kg/m³</td>
</tr>
<tr>
<td>Bed porosity</td>
<td>0.49</td>
<td>0.81</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.81</td>
<td>0.90</td>
</tr>
</tbody>
</table>

2.6. Physical property measurement

To determine particle density, a known number of particles were weighed and their volume was determined through volume displacement method using paraffin. Care is taken to avoid bubble formation and absorption paraffin during measurements. For bulk density, a measuring cylinder was used. Particles were weighed and their volume was determined by filling the cylinder. Particle diameter and sphericity was calculated from initial dimensions of the product. Particle density and bulk density was used to calculate bed porosity at both initial and final conditions for all drying conditions.

2.7. Analysis of experimental data and modeling

Particle characteristics were used to calculate minimum fluidization velocity at the beginning and end of the experiments. In these calculations volume shrinkage was not considered and assumed the particle shape remains the same throughout the entire drying period. Both Ergun values and generalized values were calculated using equations 1 and 3 respectively.

The drying data, when plotted in ln \( (D_{\text{eff}}) \) versus \( 1/T_{\text{abs}} \) diagram, resulted in a straight line similar to equation 15. 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 9, the data was plotted in a ln(MR) versus drying time \( (t) \) diagram. The slope of the straight line found by applying linear regression resulted in drying parameter \( k \). 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.

3. Results and Discussion

3.1. Fluidisation Characteristics
Figure 3 shows initial and final particle classification in the Geldart chart. Particles lies in the Geldart D category showing characteristics similar to grains which can be fluidized in shallow beds or in spouted beds. When drying proceeds its position moved from right to left in the chart showing its fluidizability increase for all the drying conditions considered. This may be attributed to changing of particle size from cubical shape to spherical shape increasing their sphericity. Fig 3 only two points are visible but actually initial and final characteristic points are very close to each other and appeared as the one point in the chart.

The calculated minimum fluidization value varies between 1.35 to 2.33 m/s for the Ergun Model and between 1.21 to 1.35 m/s for the Generalized Model. It was observed that minimum fluidization velocity (taken as the instant the bed starts to expand) occurred between 1.41 m/s and 2.32 m/s. Experimental values changed between 1.5-2.5 m/s for the fluidization.

There was an increase in minimum fluidisation velocity at very low moisture values. This can probably be attributed to an increase in the particle density due to shrinkage and interlocking of particles in the fluid bed. The change in minimum fluidization velocity may not only be due to the reduction in moisture content, other physical changes (such as geometrical shape and dimensions) could also have contributed to this effect.

Low value of bulk density (200 kg/m$^3$) at the end of drying compared to initial bulk density of 500 kg/m$^3$ and higher particle density at the end of drying (from 900kg/m$^3$ initially and 1100 kg/m$^3$ finally) is attributed to the difference in shrinkage producing a very porous product.

![Fig. 3. Particle Classification according to Geldart chart](image)

3.2. Quality of fluidization

Stability criterion value of Walli’ model $V_e$ varies between 0.5641~0.6488 at initial and final stages of all drying conditions. The calculated values are shown in table 3. Those are positive
values and according to Walli’s criterion material shows stable fluidization. The visual observation during experimentation also confirmed good fluidization.

Table 3 Walli’s factor for fresh and dried bovines at different drying conditions

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Fresh bovine</th>
<th>Dried bovine</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>0.648872</td>
<td>0.564155</td>
</tr>
<tr>
<td>-5</td>
<td>0.648871</td>
<td>0.564156</td>
</tr>
<tr>
<td>5</td>
<td>0.648869</td>
<td>0.564158</td>
</tr>
<tr>
<td>15</td>
<td>0.648867</td>
<td>0.564159</td>
</tr>
<tr>
<td>25</td>
<td>0.648865</td>
<td>0.564160</td>
</tr>
</tbody>
</table>

3.3. Modelling of minimum fluidization velocity

To characterize the behaviour of minimum fluidization velocity Ergun equation and Generalized equation were used for different drying conditions (temperatures). The parameters required for Ergun Equation and Generalized Equation were either measured or calculated from physical properties of Bovine or drying air. In Ergun equation bed voidage at minimum fluidization ($\varepsilon_{mf}$) was estimated form particle density and bulk density at minimum fluidization. Pressure drop vs velocity of incoming air graphs were constructed to find the instance at which the minimum fluidization occurred. Other physical properties, such as sphericity and particle diameter obtained from physical dimensions of the Bovine particles at the start and finishing of the drying. Figure 4 shows variation of Initial fluidization velocity variation with the temperature for both Ergun and Generalised values. Also calculated values are given in Table 4. When using the Ergun model a sphericity values were calculated based on measured dimensions of the Bovine intestine particles during drying and comparing it with equivalent diameter given by the volume of the particle. Fluidization behavior of the particles changed progressively with temperature of drying as the drying proceeds. Experimental values were kept at 1.5~2.5 m/s and calculated Ergun values changed from 1.35 to 2.33 m/s. The generalized model predicted velocities underestimate minimum fluidization velocity at higher drying temperatures.
### Table 4 Minimum fluidization velocity (m/s)

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Ergun Model (calculated)</th>
<th>Generalised Model (calculated)</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Final</td>
<td>Initial</td>
</tr>
<tr>
<td>-10</td>
<td>1.35</td>
<td>2.2</td>
<td>1.21</td>
</tr>
<tr>
<td>-5</td>
<td>1.36</td>
<td>2.22</td>
<td>1.22</td>
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<tr>
<td>5</td>
<td>1.38</td>
<td>2.26</td>
<td>1.24</td>
</tr>
<tr>
<td>15</td>
<td>1.4</td>
<td>2.29</td>
<td>1.26</td>
</tr>
<tr>
<td>25</td>
<td>1.42</td>
<td>2.33</td>
<td>1.28</td>
</tr>
</tbody>
</table>

**Fig.4.** Initial Fluidisation behavior (calculated)

It was found that the difference in initial fluidisation velocity and final fluidsation velocity calculated using Ergun Equation showed a linear trend with the drying temperature. The behavior of difference in initial fluidization velocity values \( \Delta u_{mf} = u_{mf} \) (initial) – \( u_{mf} \) (final) with temperature of drying is shown in Figure 5.
The relation between difference in initial and final fluidization velocity is linearly correlated to the following equation.

$$\Delta u_{mf} = 0.8683 + 0.0016T$$  \hspace{1cm} (17)

Where, \(U_{mf}\) is the minimum fluidization velocity and \(T\) is the drying temperature.

The difference in minimum fluidization velocity helps to estimate the velocity of air needed for the complete operation of drying. It also provides the range of the fan velocity needed for a complete drying process from fresh to dried bovine at different temperatures. These will help in selecting a fan for the operation at factory level.

### 3.4. Drying kinetics (k) and effective diffusion coefficient (\(D_{eff}\))

Drying occurred only in the falling rate period for all experiment trials. The average moisture content was expressed as non-dimensional moisture ratio ‘MR’ and used to plot the drying curves with time (h) for different air drying temperatures keeping air velocity constant. Drying kinetics of all drying conditions followed similar pattern but not shown. Drying constant ‘k’ and effective diffusion coefficient were calculated from the construction of graphs \(\ln MR\) vs time using Equation 15. A typical plot for \(\ln mR\) vs time is shown in Figure 6.

The initial moisture content was used as the critical moisture content due to the absence of constant period of drying. Final equilibrium moisture content was calculated from the GAB equation (Equation 16) for all drying experiments. Three dimensional mass transfers was considered and effective diffusivity was calculated with the method of slopes as previously described and the calculated values are reported above in Table 5 together with drying constants. This means liquid diffusion is the driving force controlling the drying process and curves are straight lines. As temperature increased the value of moisture ratio decreases rapidly, with consequent increase in the drying rate. The experimental results agreed with the values reported in the literature for other food materials in which the 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 a 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°C) the diffusion coefficient depends on the point at which the change of drying temperature occurs. For two stage drying diffusion coefficient for each stage is also given in table 5.

Table 5 Drying constant and effective diffusion coefficient at various drying conditions

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>k</th>
<th>$D_{\text{eff}}$ (m$^2$/h)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>0.0742</td>
<td>3.11x10$^{-8}$</td>
<td>0.92</td>
</tr>
<tr>
<td>-10/25</td>
<td>0.7653~1.2726</td>
<td>0.45~0.67x10$^{-7}$</td>
<td>0.90</td>
</tr>
<tr>
<td>-5</td>
<td>0.0789</td>
<td>0.61x10$^{-7}$</td>
<td>0.88</td>
</tr>
<tr>
<td>-5/25</td>
<td>0.1542~1.6291</td>
<td>0.37~0.88x10$^{-7}$</td>
<td>0.91</td>
</tr>
<tr>
<td>5</td>
<td>0.3098</td>
<td>1.44x10$^{-7}$</td>
<td>0.88</td>
</tr>
<tr>
<td>15</td>
<td>0.3700</td>
<td>2.13x10$^{-7}$</td>
<td>0.97</td>
</tr>
<tr>
<td>25</td>
<td>0.3951</td>
<td>2.15x10$^{-7}$</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Note: Drying constant k significantly different (p<0.05) with the temperature

The effective diffusivity coefficient changes from 3.11x10$^{-8}$ m$^2$/h to 3.1x10$^{-7}$ m$^2$/h for -5°C to 25°C drying temperatures and shown in figure 7 and values are given in Table 5. For the combined drying operations it exhibit two values for below freezing temperatures and above
freezing temperatures. For the case of drying at -10°C/25°C it changes from 0.45x10^{-6} to 0.67x10^{-6} m²/h during operation and for the case of -5°C/25°C it changes from 0.37x10^{-7} to 0.88x10^{-7} m²/h (not shown in Figure 7).

![Figure 7 Effective diffusion coefficient vs temperature of drying](image)

3.5. Effect of temperature on \( D_{\text{eff}} \)

It is clear from Figure 7 that the diffusivity is strongly influenced by the temperature. Calculated \( D_{\text{eff}} \) values were fitted to the Arrhenius-type of Equation (Equation 18).

\[
D_{\text{eff}} = D_o \exp \left( \frac{-E_a}{R(T+273.15)} \right) \tag{18}
\]

where, \( D_o \) = reference diffusion coefficient at infinitely high temperature

This results in \( D_o \) as 0.00134 m²/h and \( E_a \) as 2.33 KJ/mol.

4. Conclusions

This work showed modeling of minimum fluidization velocity of small Bovine Intestine particles in fluid bed dryer at different drying conditions. Fluidization behavior of the Bovine intestine particulates change progressively as the drying proceeded. The calculated minimum fluidization with both Ergun Equation and Generalised equation based on physical changes gave values confirming with the experimental values used. Both methods can be applied to predict minimum fluidization velocity with a reasonable accuracy. It is important to understand the changes, so that airflow during drying can be controlled to achieve an optimum fluidization. Further experiments are necessary to investigate the relation between bed heights and minimum fluidization velocity of Bovine Intestines.

Experiments on drying of Bovine Intestine particles were carried out in a laboratory-scale fluidized heat pump dryer. By shifting single stage to two stages, drying effective
diffusivities and moisture removal rates increased. Properly scheduled residence times for two stage drying leads optimum drying rates and improved dryer capacity.

Higher diffusivity values were obtained considering materials with infinite surface. Effective diffusivity increased with the increase 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°C and 25°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.

NOMENCLATURE

a, b, c finite slab half thickness
A, B constant
Ar Archimedes number
$a_w$ water activity
C GAB parameter
°C centigrade
$D_{eff}$ effective diffusion coefficient $m^2/h$
d diameter m
$D_0$ Arrhenius factor $m^2/h$
Ea Activation energy KJ/mol
g gravitational constant $m/s^2$
k drying constant $h^{-1}$
K GAB parameter
L slab half thickness m
m moisture content kg/kg
MR moisture ratio
Mm GAB parameter
n Richard-Zaki coefficient
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tr>
<td>R</td>
<td>ideal gas constant</td>
<td>KJ/kmol K</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>drying time</td>
<td>h</td>
</tr>
<tr>
<td>u</td>
<td>velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Ve</td>
<td>Wall’s factor</td>
<td></td>
</tr>
<tr>
<td>x, y, z</td>
<td>co-ordinates</td>
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</table>

Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<td>ε</td>
<td>voidage</td>
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</tr>
<tr>
<td>φ</td>
<td>sphericity</td>
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</tr>
<tr>
<td>μ</td>
<td>viscosity</td>
<td>Ns/m²</td>
</tr>
<tr>
<td>σ</td>
<td>density</td>
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<tr>
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<td>operator</td>
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<tr>
<td>Σ</td>
<td>summation</td>
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</tr>
<tr>
<td>∂</td>
<td>Partial differential coefficient</td>
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</tr>
</tbody>
</table>

Subscripts

| Symbol | Definition            | |
|--------|-----------------------||
| e      | equilibrium          | |
| eff    | effective            | |
| f      | fluid                | |
| i      | integer              | |
| mf     | minimum fluidization | |
| o      | initial              | |
| p      | particle             | |
| st     | static               | |
| t      | terminal             | |

References


