Influence of atmospheric sublimation and evaporation on the Heat pump fluid bed drying of Bovine Intestines

W. Senadeera\textsuperscript{1} O. Alves-Filho\textsuperscript{2} and T. Eikevik\textsuperscript{2}

\textsuperscript{1}School of Engineering Systems
Queensland University of Technology
4001, George Street, Brisbane, Australia

\textsuperscript{2}Department of Energy and Process Engineering
The Norwegian University of Science and Technology
7491, Trondheim, Norway

*Corresponding Author- Tel: +61-7-31386887, (E-mail: w3.senadeera@qut.edu.au)

Abstract

The experiments on atmospheric two stage fluidized bed drying of Bovine intestine with heat pump were carried out. The investigation covers innovative fluidized bed heat pump drying of Bovine Intestine. The two-stage drying consists of atmospheric moisture sublimation immediately followed by evaporation. Studies were done to establish the influence of the drying condition on the drying characteristics and product quality of Bovine Intestine and properties focusing on kinetics, diffusion and colour. The investigation of the drying characteristics has been conducted during moisture removal by evaporation and combined sublimation and evaporation. The effect of the drying temperature on the drying constants was determined by fitting the experimental data using regression analysis techniques. The investigation revealed that the drying kinetics is most significantly affected by temperature. Correlations expressing the drying constants and effective moisture diffusivity dependence on the drying conditions are reported.

Key words; intermittent drying, kinetics, drying curves, bovine intestine

1. Introduction

In preservation and energetic view points it is desirable to store food at ambient conditions. This can be achieved by drying operations, reducing moisture content and water activity to prevent spoilage under long term storage conditions at nearly ambient conditions. 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). New developments in heat pump technology offer alternatives to overcome draw backs in preservation and energy use.
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 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).

Fluidised bed drying has been recognized as a gentle uniform drying process down to low residual moisture content with a high degree of efficiency. In fluidized bed, conditions are favorable for rapid heat and mass transfer due to the thin boundary layer surrounding the food particles due as a result of 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).

Heat pump drying is finding increasing applications in food industry for drying of fruits, vegetables, fish and biological active products in many countries (Pal and Khan, 2008). The main advantages of using heat pump technology are an energy saving potential and the ability to control drying air temperature and humidity for wide range of drying conditions (Lee and Kim, 2009). Using a heat pump system in drying, both latent heat and sensible heat can be recovered from the exhaust air, thus improving overall thermal performance and providing effective control of air conditions at the inlet of the dryer. Heat pump system applications in drying give beneficial advantages. Through the evaporator, it recuperates sensible and latent heat from the dryer exhaust; hence energy is recovered. Condensation of moisture occurring at the evaporator reduces the humidity of the working air thus increasing the driving force for product drying (Phani et al., 2002).

Heat pump drying is a heat recovery process where the energy for boiling the refrigerant in the evaporator is supplied by the water-vapour condensing on the evaporator surface. After that the energy is transferred back to the drying air as refrigerant changes phase from vapor to liquid in the condenser. A larger fraction of energy recycled by the condenser is the latent heat water vapor condensing on the evaporator surface while a small fraction of energy corresponds to the work input for refrigerant compression that is rejected by the external condenser (Phoungchadang et al., 2009; Aware and Thorat, 2011).

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. The combination of heat pump and fluid bed dryer offers better product quality, offsetting incremental increasing in drying costs with a high market value of the products (Alves-Filho and Strommen, 1996).

A well designed heat pump efficiently supplies both heating and cooling which are required in a drying process. The heat pump evaporator can recover latent heat freely available in the water vapour coming out from the wet material and recycle through the condenser. It is possible to condensate and to recover valuable volatiles or to remove otherwise noxious condensable gases by controlling the surface temperature of the evaporator (Erbay and Filitz, 2009; Pal et al., 2008).

Hence, properly selected heat pump fluid bed technology is also environmentally friendly. Aside from complying with ozone depletion and global warming regulations it operates in a closed circuit and there is no gas, fumes or fines discharge to the atmosphere and can be treated as a Green drying technology.

Simple models that can be used to design drying systems are desirable to provide an optimum solution to different aspects of drying operation, with minimum number of
parameters (Sirinivasakannnan, 2008). There are several simple models based on exponential behavior with time that are available and continually improved and used. These are the Newton model, Page model, Henderson and Pabis model, two term exponential model and approximate diffusion model. These models are used by several authors (Mujumdar and Passos, 2000 Doymaz, 2005 and Senadera et al., 2003) to describe drying kinetics.

Bovine intestine is rich in lipids and minerals important in Carnivores diet and used as a core ingredient in pet food manufacture. 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. Studies on the modeling of Bovine intestine drying are relatively scarce. No reports have reported the use of drying temperatures at below and above the material freezing point of Bovine Intestine for drying. This information is valuable to the pet food industry where bovine intestine is used as input material in the preparation of pet food.

The objective of this work on fluidized bed heat pump drying of bovine intestine is to quantify the drying kinetics to facilitate production of Pet food of bovine origin and relate these to their quality. The present study further attempts to verify the compatibility of experimental drying kinetics with various simple models reported in the literature, and with complex models such as Fick’s diffusion equation.

2. Materials and methods

2.1. Raw Materials

The bovine intestine was obtained from local market supplied by a Norwegian slaughter house in frozen blocks. Material were cut into 4 mm cubes and kept at -25º 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 Norwegian University of Science and Technology, Trondheim, Norway was used for the experimentation. The dryer has a drying air loop and heat pump refrigerant circuit. The drying loop has an air dehumidifier and heater and a blower. The batch of bovine intestine (thickness when loaded is about 10 mm) is loaded into the drying chamber, the blower is turned on and the air flows through the chamber. Bed thickness of, 10 mm ensure prevention of evaporation and condensation inside the bed. 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 air velocity was adjusted for proper fluidization and air supplied by a blower.

The conditioned air enters the chamber, contacts and fluidized the wet materials and removes moisture from the wet material and promotes drying. The removed moisture from the material flows through the filter and evaporator where it was cooled below its dew point which leads to condensation of water vapour on the surface of the evaporator and was drained out from the loop. The evaporator absorbs latent heat of condensation of moisture to boil the fluid inside the tubes. The compressor changes the nearly saturated vapour from evaporating
to condensing pressure and high temperature. The discharged fluid is now superheated gas and ready to enter the condensers. The dehumidified air flowed through the condenser and was heated and re-enter into 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.

![Schematic of the drying loop](image1.jpg)

**Fig. 1. Schematic of the drying loop**

![Experimental heat pump fluid bed dryer](image2.jpg)

**Fig. 2. Experimental heat pump fluid bed dryer**
2.3. Experimental procedure

The Bovine Intestine was frozen and stored at -25°C and prior to each drying run the material temperature was equilibrated to -10°C. There were two drying trials where the temperatures in the first and second stages of drying were set to -5°C and 25°C and -10°C and 25°C respectively to reproduce the conditions (temperature and residence time) used in commercial production of similar products. The first stage is the atmospheric freeze drying and second stage uses medium temperature drying. The gentle conditions taking place in the first stage results in preservation of quality and properties of the dried material. The temperature above freezing used in the second stage increases heat and mass transfer with consequent improvement on dryer capacity due to reduction in drying time. They were compared with two atmospheric freeze drying modes at -5°C and -10°C and three medium temperature modes at 5, 15 and 25°C. All experiments were done under stable fluidization condition and fluidization velocity was kept at 1.5~2.5 m/s.

Sampling and measurements were taken during each drying test to characterize quality and properties. Sampling and measurement were done during each drying test and three replications were used for each drying condition. Moisture content was determined by vacuum oven method. Total of twenty one experimental runs (7 x 3 replicates for each run) were conducted and residence time, drying conditions and final moisture content are shown in Table 1. The average initial moisture content of the sample was 54.5% (wb). For two stage drying initial drying at low temperature was run for 5 hrs and second stage high temperature was for 2 hrs. The experiments were conducted as a completely randomized single factor experiment. All the experimental treatments were conducted in three replicates.

Table 1 Experimental runs and drying conditions with 54.5% (wb) initial moisture

<table>
<thead>
<tr>
<th>Run</th>
<th>T (°C)</th>
<th>t (h)</th>
<th>m_f (%wb)</th>
<th>Sampling, min</th>
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<tbody>
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<td>-10</td>
<td>21.00</td>
<td>12.9</td>
<td>30</td>
</tr>
<tr>
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<td>5.00/2.00</td>
<td>11.6</td>
<td>30/10</td>
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<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>

2.4. Water activity

The water activity of dried samples was measured using an Aqualab water activity meter for all drying conditions. The equilibrium moisture content was calculated from GAB
Guggenheim-Anderson-De Boer) equation which is frequently used by several investigators (Myhara et al., 1998, Joshi and Thorat, 2008).

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

Where, \( C \), \( K \) and \( M_m \) 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 had similar trend in water activity and equilibrium moisture content.

2.5. Colour Measurement

Spectrophotometric methods are used to measure differences in colour during drying time. The colour was measured with an X-Rite 948 spectrocolorimeter. This device records and display the colour component mean values from four sets of consecutive measurements. The \( L \), \( a \), and \( b \) coordinates in CIELAB space were measured. The \( L \) component is associated with the sample’s brightness and it ranges from full black at 0 to full white at 100 units. The coordinate \( \text{‘a’} \) is associated with the red-green spectrum, coordinate \( \text{‘b’} \) with the yellow-blue spectrum and both ranges from -60 to +60 units. This quality parameter is selected as consumers prefer colour to choose the products.

2.6. Mathematical Modeling

The data were analysed by the analysis of variance (ANOVA) to evaluate differences and non-linear regression to obtain suitable models. Model parameters were estimated separately for all replicates. The significance differences were examined by comparing parameters in equations fitted to the different replications. The final model was constructed using least square mean parameter values.

Simplified drying models have been used to quantify drying kinetics of various agro food materials (Roberts et al., 2008, Babalis and Belessiotis, 2004 and Hii et al., 2009). Mathematical modeling was used to explain the drying behaviour of Bovine intestine. Mass transfer mechanisms considered are moisture diffusion in the solid phase towards its external surface, followed by vaporization and convective moisture transfer to the drying stream.

**Moisture ratio**

Average moisture content was expressed as a dimensionless parameter denoted by moisture ratio (MR) and used to model the drying curves with time (h). Initial moisture content was used as the critical moisture content due to the absence of a constant rate period. Equation 2 relates the sample moisture content in real time (\( m_t \)) to the initial moisture content (\( m_i \)) and equilibrium moisture content (\( m_e \)) (Law and Ong, 2009).

\[ \text{MR} = \frac{m_t - m_e}{m_i - m_e} \quad (2) \]

**Semi-Theoretical and empirical models**

Semi-theoretical and empirical models that are commonly applied for vegetable food materials were adopted from literature as shown in Table 2. The empirical constants for the drying models were determined experimentally from normalized drying curves at different
temperatures. Modeling was carried out using the least square method and the Microsoft Excel spreadsheet (Microsoft 2003) was used to perform this task using the SOLVER tool based on the Generalized Reduced gradient (GRG) method. The goodness of fit for each model was established using non-linear optimization method where the objective function is to minimize the sum of squares of residuals and thus perform least-square curve fitting. The goodness of fit for each model was evaluated based on statistical parameter coefficient of determination ($R^2$).

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton</td>
<td>$MR = \exp (-kt)$</td>
</tr>
<tr>
<td>Page</td>
<td>$MR = \exp (-kt^n)$</td>
</tr>
<tr>
<td>Henderson and Pabis</td>
<td>$MR = a \exp (-kt)$</td>
</tr>
<tr>
<td>Two term</td>
<td>$MR = a \exp(-k_1 t) + b \exp (-k_2 t)$</td>
</tr>
</tbody>
</table>

**Modified quasi-stationary mode**

The modified quasi-stationary model (MQSM) has been used to describe the drying kinetics of particulate materials that dry mostly in the falling rate period, and was applied by Kudra and Efremov (2003) to describe the drying of particles in fluidized bed dryers. The model is based on mass conduction of solid materials in bulk, given in terms of effective moisture diffusivity resulting in the following semi-theoretical equation for drying kinetics

$$MR = \frac{1}{1 + \left(\frac{t}{\sigma}\right)^p}$$

(3)

Where, $p =$ hydrodynamic intensity of the bed, $\sigma =$ characteristic drying time (h), and $t =$ drying time

**Theoretical model**

Drying of most food materials occurs in the falling rate period (Wang and Brennan, 1992) and moisture transfer during drying is controlled by internal diffusion. Fick’s second law of diffusion, as shown in equation 3, has been widely used to describe the drying process during the falling rate period for most biological materials (Sablani et al., 2000).

$$\frac{\partial m}{\partial t} = \nabla[D_{\text{eff}} (\nabla m)]$$

(4)

$D_{\text{eff}}$ is the moisture diffusivity representing the conductive term of all moisture transfer mechanisms. Based on assumptions of uniform initial moisture distribution, negligible external resistance, negligible temperature gradients, and negligible shrinkage during drying and constant diffusion coefficient, the analytical solution of the diffusion equation for infinite slab is given as the following equation (Crank, 1975):
Where L is the sample thickness

Effective diffusivity and Activation energy

Effective diffusivity constant (Deff) can be determined from the linearized first term of the Fick’s infinite equation as shown in Equation 5, by assuming that constant diffusivity applied to the internal moisture movement during the first falling rate period suggested by several researchers (Madamba et al., 1996; Sawhney et al., 1999 and kaya et. al., 2007).

\[
\ln \text{MR} = \ln \left( \frac{8}{\pi^2} \right) - D_{\text{eff}} f \left( \frac{\pi}{2L} \right)^2 t
\] (6)

From the graph of ln MR vs t, \(D_{\text{eff}}\) can be found by its slope.

The relation between effective diffusivity \(D_{\text{eff}}\) and drying temperature (T) can be evaluated with Arrhenius type equation (Equation 6).

\[
D_{\text{eff}} = D_o \exp \left( \frac{-E_a}{R \left( T + 273.15 \right)} \right)
\] (7)

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

Experimental Uncertainty

Errors and uncertainties in the experiments are performed using an uncertainty analysis by the method described by Holman (2001).

\[
w_F = \left[ \left( \frac{\partial F}{\partial x_1} \right)^2 w_1 + \left( \frac{\partial F}{\partial x_2} \right)^2 + \cdots + \left( \frac{\partial F}{\partial x_n} \right)^2 \right]^{0.5}
\] (8)

3. Results and Discussion

Equilibrium moisture content

The equilibrium moisture content was calculated from GAB (Guggenheim-Anderson-De Boer) equation which is frequently used by several investigators (Keey, 1992) and shown in Table 3.

Where, C, K and \(M_{m1}\) 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 had similar trend in water activity and equilibrium moisture content
### Table 3 GAB parameters

<table>
<thead>
<tr>
<th>Temperature</th>
<th>C</th>
<th>K</th>
<th>$M_m$ (kg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>0.7156</td>
<td>1.8585</td>
<td>0.0235</td>
</tr>
<tr>
<td>-5</td>
<td>0.7501</td>
<td>0.9739</td>
<td>0.0376</td>
</tr>
<tr>
<td>5</td>
<td>0.4023</td>
<td>1.6089</td>
<td>0.0212</td>
</tr>
<tr>
<td>15</td>
<td>0.0889</td>
<td>0.9257</td>
<td>0.0596</td>
</tr>
<tr>
<td>25</td>
<td>0.2096</td>
<td>1.2906</td>
<td>0.0054</td>
</tr>
</tbody>
</table>

### 3.1. Drying kinetics

Fig 3 shows moisture ratio versus time at -10°C for single stage drying of Bovine samples. This graph shows an exponential trend for the drying curves and samples reached equilibrium moisture content in a shorter time at higher temperatures reported by many researchers (Doymaz, 2005, Hatamipour and Mowl, 2003). Also Fig 4 shows moisture ratio vs time graph for two stages drying at -5/25°C.

Atmospheric freeze drying combined with medium temperature drying involves removal of moisture from the solid 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). An important aspect is that as drying progresses the drying curve moves asymptotically to equilibrium and the drying rate drops quickly to 0. Therefore, it is relevant to study the behaviour of the graphs for the kinetics and drying rates and to select the most feasible way to remove the residual moisture.

The average moisture content was expressed as non-dimensional moisture ratio ‘MR’ (Equation 2) and used to plot the drying curves with time (h). Drying kinetics of other drying conditions follow the similar pattern and not shown.

![Fig.3. Single stage drying kinetics at -10°C](image-url)
It was observed that most moisture removal happening during first 2 hours of drying. This indicates it is more feasible, practical and economical to remove the remainder of the moisture by simply keeping the product or use of an intermittent drying process.

Again combined temperature drying process removed the moisture preserving quality at the first stage and second stage increased heat and mass transfer. 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°C and -5/25°C) moisture removal depends on the point at which the change of drying temperature occurs (Fig. 4).

The first stage which is atmospheric freeze drying and second stage uses medium temperature for drying. The gentle conditions prevail in the first stage (-5°C and -10°C) results in preservation of quality of the Bovine Intestines. The temperature above freezing point used in second stage of drying increases heat and mass transfer. Correct scheduling of the times is necessary to obtain less energy intensive operation while keeping the product quality at higher values.

In the first stages of drying, drying occurs as the frozen core gradually shrinks. Heat is transported from the surface of the product and used for sublimation of nearby ice. The resulting water vapour is transported from the surface to the surrounding air. Heat and mass transfer between the product surface and the atmosphere is assumed purely convective. Also during the first stage of drying, it showed a linear behaviour indicating almost all moisture is removed in this stage. After a threshold time at sublimation process the process can be shift to evaporation by increasing the air temperature possible in the heat pump system. This increases noticeably drying rate and enhances the dryer throughput with consequent reduction in the production cost.

**Semi-empirical and theoretical models**

To date there is very little literature reports on the drying kinetics of Bovine Intestine. Four commonly used mathematical models were taken to identify the most suitable model to describe the drying behaviour. Mathematical modeling of the drying curves under different temperature conditions was conducted by using non-linear regression analysis coupled with generalized reduced gradient algorithm. All the model constants were calculated based on the iterative method and estimated parameters are given in table 3.
Table 4. Estimated parameters of the drying models

<table>
<thead>
<tr>
<th></th>
<th>-10°C</th>
<th>-5°C</th>
<th>5°C</th>
<th>15°C</th>
<th>25°C</th>
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<td><strong>Newton</strong></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>K</td>
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<td>(0.0750)</td>
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<td>0.0056</td>
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<td>0.0897</td>
<td>0.0878</td>
<td>0.0579</td>
<td>0.0717</td>
</tr>
<tr>
<td><strong>Henderson and Pabis</strong></td>
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<tr>
<td>a</td>
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<tr>
<td>k</td>
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<td>K₁</td>
<td>0.1226</td>
<td>0.1168</td>
<td>0.3984</td>
<td>0.2902</td>
<td>0.3801</td>
</tr>
<tr>
<td>(0.0025)</td>
<td>(0.0011)</td>
<td>(0.0054)</td>
<td>(0.0037)</td>
<td>(0.0027)</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>-3.5448</td>
<td>-0.4807</td>
<td>0.8125</td>
<td>0.3937</td>
<td>0.6064</td>
</tr>
<tr>
<td>(0.1159)</td>
<td>(0.2314)</td>
<td>(0.0989)</td>
<td>(0.0186)</td>
<td>(0.0285)</td>
<td></td>
</tr>
<tr>
<td>K₂</td>
<td>0.1482</td>
<td>0.5622</td>
<td>0.3983</td>
<td>1.6061</td>
<td>0.3801</td>
</tr>
<tr>
<td>(0.0016)</td>
<td>(0.0037)</td>
<td>(0.0021)</td>
<td>(0.0118)</td>
<td>(0.0054)</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.9393</td>
<td>0.9435</td>
<td>0.9493</td>
<td>0.9825</td>
<td>0.9501</td>
</tr>
<tr>
<td>χ²</td>
<td>0.0045</td>
<td>0.0046</td>
<td>0.0048</td>
<td>0.0036</td>
<td>0.0043</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.0626</td>
<td>0.0619</td>
<td>0.0577</td>
<td>0.0449</td>
<td>0.0538</td>
</tr>
</tbody>
</table>

(Standard errors of the parameters are given inside the brackets)
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. Drying rates increased as the temperature increases during drying.

**Modified quasi stationary model**

The parameters for the modified quasi stationary model, is shown in Table 4. The value $p$ (Index of hydrodynamic intensity), which is a representation of hydrodynamic condition of the bed during drying experimentation at different drying conditions. It was observed that hydrodynamic intensity ($p$) increased from -5°C to 5°C and again reduced to a lower value and started increasing again. This may be attributed to interlocking of the particles within the bed and also depend on the changes of aerodynamics characteristics of the bed. Characteristic drying time decreased with increased temperature conditions up to 15°C. But at 25°C it showed an increased value may be due to case hardening effect of the material which increased resistance to moisture transfer.

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$\sigma$</th>
<th>$p$</th>
<th>$R^2$</th>
<th>$\chi^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>9.2782</td>
<td>1.1386</td>
<td>0.8857</td>
<td>0.0079</td>
<td>0.0860</td>
</tr>
<tr>
<td>-5</td>
<td>9.1906</td>
<td>2.2140</td>
<td>0.9426</td>
<td>0.0042</td>
<td>0.0623</td>
</tr>
<tr>
<td>5</td>
<td>2.4067</td>
<td>2.2479</td>
<td>0.9526</td>
<td>0.0036</td>
<td>0.0558</td>
</tr>
<tr>
<td>15</td>
<td>1.7630</td>
<td>1.4094</td>
<td>0.9775</td>
<td>0.0029</td>
<td>0.0509</td>
</tr>
<tr>
<td>25</td>
<td>2.1174</td>
<td>1.8647</td>
<td>0.9537</td>
<td>0.0032</td>
<td>0.0518</td>
</tr>
</tbody>
</table>

As expected, the drying temperature had a significant effect on the drying kinetics of the samples. The moisture content decreased continuously with time and an increase in temperature resulted in reduced drying time.

The best model describing drying characteristic was chosen as the one with the highest $R^2$ values. Two term model was proposed to describe the drying behavior of bovine Intestine.

**3.2. Effective diffusion coefficient ($D_{eff}$)**

The effective diffusivity was calculated using equations (6) described in the materials and methods. One dimensional mass transfer was used to calculate effective diffusion coefficient. This approximate solution is the most widely investigated theoretical model and used by several authors to calculate effective diffusion coefficient (Babalios and Belessiotis, 2004; Reyes et al., 2002). The effective diffusivity coefficient changes from $9.34 \times 10^{-8}$ m$^2$/h to $6.4 \times 10^{-7}$ m$^2$/h from -5°C to 25°C drying temperatures (Fig 5). For the combined drying operations it exhibit two values for moisture removal. At below freezing temperatures and above freezing temperatures moisture transfer is assumed to be controlled by internal resistances and described by a diffusion coefficient. For the case of drying at -10°C/25°C it changes from $0.86 \times 10^{-7}$ h to $2.06 \times 10^{-7}$ m$^2$/h during operation and for the case of -5°C/25°C changes from $1.13 \times 10^{-7}$ h to $2.64 \times 10^{-7}$ m$^2$/h (As combined drying involve two temperature
values hence not shown in Figure 5). The moisture removal rate and effective diffusivity doubled by shifting from single stage to two stages.

\[ D_{\text{eff}} \times 10^8 \text{ (m}^2\text{/h)} \]

![Graph](image)

**Fig. 5. Effective diffusivity as affected by drying air temperatures**

- single stage  
- two stage (-10°C/25°C)  
- two stage (-5°C/25°C)

It is clear from Figure 5 that the diffusivity is strongly influenced by the temperature. Calculated \( D_{\text{eff}} \) values were fitted to the Arrhenius-type of Equation (Equation 7). The less value of diffusivity observed at 25°C may be attributed to case hardening at higher temperatures.

Equation 7 can be literalized by applying natural log at both sides and a plot of ln \( D_{\text{eff}} \) vs 1/T will produce a smooth line. The proposed relationship shows good agreement between the effective diffusivities and temperature (\( R^2 = 0.99 \)). The activation energy and the Arrhenius constant can be determined from the slope and the y-intercept, respectively. The Arrhenius constant is a diffusivity constant equivalent to the diffusivity at infinitely high temperature. The activation energy is the energy barrier that must be overcome in order to activate moisture diffusion. By increasing the temperature and hence the drying rate this energy barrier can be overcome easily but there should be a compromise between high temperature and acceptable product quality.

The values of \( D_o \) and \( E_a \) were estimated as 0.00134 m\(^2\)/h and 2.33 KJ/mol, respectively. These values are within the range as reported in literature (Z0gzas et al., 1994).

**Effect of drying temperature on product quality**

Figure 6 shows changes in colour component for -10°C and 15°C drying conditions. It is shown from the graph samples dried above 0°C had brighter colours than lower temperatures. The colour components for 25°C drying condition were continuously measured during drying and the results are plotted (not shown). It is observed that the L and b values fluctuate only in the intermediate position of the drying range while the initial and final colour remains unchanged. The a, b and L values of 0, 18 and 75 suggested that the sample is pale-yellow and
bright, which is the preferred colour by the end users. Therefore, the temperature 25°C maintained the colours keeping the original colour constituents.

![Graph showingColour L variation with time](image)

**Figure 6.** The colour component L variation with time

○ -10 °C • 15 °C

Uncertainty analysis of experimental measurements

The detailed uncertainty analysis was performed for experiments. Results of uncertainty analysis of experimental measurements are given in Table 6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>g</td>
<td>± 0.0052</td>
</tr>
<tr>
<td>Moisture content</td>
<td>g</td>
<td>± 0.0018</td>
</tr>
<tr>
<td>Moisture ratio</td>
<td></td>
<td>± 0.12%</td>
</tr>
</tbody>
</table>

4. 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 scheduled residence times for two stage drying lead to optimum drying rates, and improved dryer capability. This work provides the basis for selection of the operating conditions to dry bovine intestine.

This study showed that the drying of Bovine intestine can be predicted using thin layer drying models of either Newton, Henderson and Pabis, Lewis and two term models. The
moisture transfer can be described by diffusion. The effective diffusivity coefficient changes from $9.34 \times 10^{-8}$ m$^2$/h to $6.4 \times 10^{-7}$ m$^2$/h from -5°C to 25°C drying temperatures. The drying kinetics showed some variation with temperature, this may be attributed to the fluidsation quality of the bed and needs further investigation.

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, A, B, N constant

C centigrade

$D_{\text{eff}}$ effective diffusion coefficient m$^2$/h

$D_0$ Arrhenius factor m$^2$/h

$E_a$ Activation energy KJ/mole

F Function

$k, k_1, k_2$ drying constant h$^{-1}$

$k, M_m$ parameter

$L$ sample thickness m

$m$ moisture content kg/kg

$M_R$ moisture ratio/dimensionless moisture ratio

$n$ constant

$p$ hydrodynamic intensity

$R$ ideal gas constant KJ/kmol K

$\text{RMSE}$ root mean square error

$t$ time h

$T$ temperature °C

$\text{wb}$ wet basis

$x$ independent variable

$\nabla$ operator

$\Sigma$ summation

$\partial$ partial differential coefficient

$\chi^2$ chi-square

$\sigma$ characteristic drying time h

Subscripts

e equilibrium

f final

i initial

t at time ‘t’

References


