Computational Fluid Dynamics Modelling of the Heat Pump Drying of Banana: Preliminary Studies

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Abstract - The distribution of local temperature, moisture and velocity gradients obtained in CFD calculations can be used to develop models for predicting the parameters in a drying process. This article reports a preliminary result on the efforts to characterize the performance of a heat pump dryer using Computational Fluid Dynamics (CFD). A three dimensional, pressure based, transient, laminar, incompressible model of heat pump drying of banana slices using Ansys 14.5 (15), a CFD package- FLUENT was investigated. Turbulent cases were also examined. The geometry was considered as elemental volume with symmetrical walls while the banana slices were designed as solids with pores containing a mixture of water and air. Parameters/variable/geometry investigated include velocity, moisture and temperature distribution of the air within the dryer and of the banana slices. The result of the numerical simulation was validated with experimental results from a heat pump dryer and there were agreements. The model is successful in predicting the temperature profile and mass fraction of moisture.

Keywords — Ansys, Banana, Computational Fluid Dynamics (CFD), Contour plots, Drying, Velocity and temperature distribution

1 INTRODUCTION

Drying is a complex process involving simultaneous transient heat and mass transfer, both inside and at the border of the food. Temperature and velocity of air in the dryer are very important determinants of the quality of dried products as well as the energy consumed. It is important to characterize the drying performance in dryers to be able to understand its operation and design process and can proffer necessary steps for its control/optimization/scale up.

Heat pump dryers have been found to possess several advantages over traditional oil-fired dryers or conventional gas-fired dryers for the drying of food products and agricultural materials (Fayose and Huan 2017). They are one of the most promising technologies for improving product quality and reducing energy consumption of drying, particularly for high value products like fruits and vegetables. Non-uniform drying is a usual limitation of many drying units. Therefore, it is very imperative to study the air flow patterns of air dryers. This becomes more difficult for large batch drying systems used especially for dehydration of agricultural products.

Computational fluid dynamics (CFD) has proven to be effective in the design of dryers: for improvement in the uniformity of the humidity of the dried product (Marqgaris and Ghiaus 2006), predicting the air flow and velocity during drying (Xia and Sun 2002) and simulating air movement during fruits drying (Mathioulakis et al. 1998). These result in optimum total drying time and maximum energy efficiency of the dryer (Jung et al 2008). Moreover, drying of fruits and vegetables involve coupled heat and mass transfer through a porous media. Many food stuffs have been successfully modelled as porous media (Wang and Sun 2004; Wang et al 2016).

In this study, the effect of some geometries of a heat pump dryer on the temperature distribution, velocity /air flow pattern as well as the air humidity were considered. This was done to be able characterize the performance of a heat pump dryer developed by the Energy and Industrial Power Group of TUT. It is expected that once one or more of parameters under study can be predicted correctly, other parameters which were not measured or measurable can be predicted right.

2 MATERIALS AND METHODS

2.1 DRYER SPECIFICATION AND OPERATING CONDITIONS

The system modelled was an experimental heat pump dryer (Figure 1). The size of the drying chamber is 700×410×355 mm (length×width×height). The airflow runs parallel in relation to the drying banana chips which were placed on a stainless-steel mesh. The drying chamber was connected to a condenser with a fan of 1480m³ maximum airflow rate. The fan had an outlet dimension of Ø35mm. Thermocouples, anemometers, pressure and humidity sensors were installed at strategic positions for data collection using a LabVIEW data acquisition system.

2.2 THEORETICAL ANALYSIS AND GOVERNING EQUATION

The governing equations for the solution of the problem are the mass, energy and momentum equation etc., having the following general form as in equation (1):

\[ \frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{V}) = -\text{div}(\rho \mathbf{v} \mathbf{V}) = S_g \]

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Where \( \rho \) is the density in kg/m³, \( \mathbf{V} \) is any conserved property, such as enthalpy, momentum per unit mass, turbulence energy etc., \( \mathbf{v} \) is the velocity vector in m/s, \( \Gamma \) is the exchange coefficient of the entity \( \mathbf{V} \), in appropriate units depending on the units of \( \mathbf{V} \); and \( S_g \) is the source rate of \( \mathbf{V} \), also in appropriate units depending on the units of \( \mathbf{V} \).

For flows through porous media, an extra source term is required to the standard fluid flow equation. Darcy in
Equation 2 introduced a one-dimensional empirical model for laminar flow through porous media.

In laminar flows through porous media, the pressure drop is typically proportional to velocity and the constant $C_1$ can be zero. Ignoring convective acceleration and diffusion, the porous media model then reduces to Darcy’s Law:

$$ \nabla p = \frac{\alpha}{\mu} u $$

(2)

Where $u$ is the flux per unit area of porous medium, $\alpha$ is the permeability of the porous medium, $\mu$ is the dynamic viscosity of the fluid and $\nabla p$ is the pressure gradient in the flow direction. Forchheimer added a term (Equation 3) to Darcy’s law to take account of non-linearity for high flow rates.

$$ \nabla p = \frac{\alpha}{\mu} u + \beta_0 u^2 $$

(3)

Where $\beta$ is the non-Darcy coefficient or the inertial resistance coefficient and $1/\alpha$ is the viscous resistance coefficient (Ansys Inc., 2009).

To calculate the flow and pressure drop through porous media numerically, the inertial resistance coefficient, and the viscous resistance coefficient have to be obtained. Correlations therefore must be found linking porous media properties, such as porosity and pore size, to these coefficients. Ergun’s equation (Equation 4) describes the pressure drop for flows going through packed beds of cylinders and others.

$$ \nabla p = \frac{150(1-\varepsilon)^2}{dp2/3} u + \frac{1.75(1-\varepsilon)}{\varepsilon^3} $$

(4)

Where $\delta$ is the average diameter of the spherical particles in the porous medium.

Banana has a pore diameter of 20 ×10−6μm and a cylindrical geometry ([Léonard et al 2008; Rodriguez-Ramirez et al, 2012; Ansys Inc. 2009]. It is considered of varying diameter embedded in the solid matrix (Kahveci and Cihan, 2007; Datta 2007). From Carman Cozen principle (in Fluid Mechanics Tutorials), the porous layer is modelled as many small capillary tubes of diameter $D$ making up of a layer of cross section A. The diameter, $D$ of the cylindrical tubes which is the pore diameter can be determined using equation 5 according to Fluid mechanics Tutorials.

$$ \text{Pore Diameter } D = \frac{4Q_0}{3(1-\varepsilon)} $$

(5)

Where $Q_0$ is Volume of the solid, $\varepsilon$ - porosity, $S$ - Surface area of tubes and also the surface area of the solid, $S = ndD^2$, $l^1$ is the mean length of tubes which is the thickness of the layer and $n$ is the number of tubes or pores.

In the present study, taking a microscopic view of banana as a porous media with a pore diameter of 20 μm (Léonard et al, 2008), $\varepsilon = 0.08$ (Yan et al, 2008), a diameter of 30mm (Karim and Hawlader, 2005) and thickness of banana slices = 2mm, $n=1.5 \times 10^7$: $s = 31.42 \text{mm}$, $n$ for the banana = 150.

From Carman Kozenzy equation,

$$ \text{Permeability, } K = \frac{\alpha \varepsilon^3}{180(1-\varepsilon)^2} $$

= 18050000. Also, from equation 4 above, the viscous resistance was calculated to be 3.846 x 10^7.

2.3 Determination of the Type of Flow in Dryer

The type of flow through the banana was estimated by Reynolds number (Re) according to Rhodes (1989) to be 2.686, hence the flow thru the banana is laminar. However, for estimation of flow through the dryer space, the Re according to Sun et al (2002) was determined to be 38625 in which case the flow is turbulent. Therefore, in this study, the result of CFD modelling for turbulent and laminar flow situations will be considered. For the laminar flow, an airflow velocity of 0.5 m/s will be used while 1.5m/s was considered for the turbulent flow.

2.4 Considerations for the Numerical Modelling

An elemental volume of the system was considered, therefore there are two symmetrical planes to reduce the memory space and time required for the analysis. Figure 2 show the three dimensional/physical representation of the dryer with the sample of banana slices, Figure 3 shows the Y-X Cross section of the banana slice as represented in the computational domain as well as the elemental volume of the banana slice inside the dryer which was used as the computational domain in this study. The banana was also modelled.
This study first assumes that the flow within the banana slice is lamina and transient and then parallel and turbulent air flow within the dryer. Also, the flow is uniformly distributed to all. Ambient temperature and relative humidity were assumed to be 18±0.3 and 26±0.2% respectively. The results of the parameters for the different situations were compared. The computational domain was meshed using the automatic method comprising hexagonal/wedge, tetrahedron and pyramid elements. The mesh model was generated using tetrahedral volume meshing elements with details as shown in Table 1.

Table 1. Details of Mesh

| Mesh metrics          | No of elements | No of nodes |
|-----------------------|----------------|-------------|
| Orthogonal quality    | 0.20           | 478079      |
| Skewness (max)        | 0.89           | 94235       |

The minimum orthogonal quality obtained was > 0.1 while the maximum skewness < 0.95. This metrics falls within acceptable spectrum of mesh quality (Ansys 2012). The boundary conditions considered are 37.6°C and 0.18 and 1 bar for temperature, air humidity and outlet pressure respectively the initial mass fraction of water was set as 0.75. For the turbulent models, the specification method was set to intensity and hydraulic diameter. The temperature and air flow distribution within the geometry used in this study was determined by solving the conservation of mass, momentum and energy equations numerically.

2.4 THE NUMERICAL SIMULATION

These equations were solved numerically using a three-dimensional commercial CFD package, Ansys 14.5 (15), which employed a finite volume method A three dimensional, pressure based, transient, laminar/turbulent, incompressible model was employed. The species model was used to account for the dry air and moisture within the dryer. The pressure-based solver employs an algorithm which belongs to a general class of methods called the projection method (Fluent, 2006). In the projection method, the constraint of mass conservation (continuity) of the velocity field is achieved by solving a pressure (or pressure correction) equation.

The pressure equation is derived from the continuity and the momentum equations in such a way that the velocity field, corrected by the pressure, satisfies the continuity.

Since the governing equations are nonlinear and coupled to one another, the solution process involves iterations wherein the entire set of governing equations is solved repeatedly until the solution converges. A second order upwind scheme was used to discretise the combined convection and diffusion terms in the momentum equation while the coupled pressure-velocity fields in the equations were solved using the PISO algorithm. The Transient Formulation was set to Bounded Second Order Implicit. The solution is assumed to have converged when the normalised residuals of the continuity and momentum equation is less than 10-5 and that of energy equation less than 10-7. By this time the scaled residuals curve is now straight in accordance to fluent requirement.

The validation of the CFD code used was done by comparing the numerical results obtained with the experimental investigation of the heat pump dryer developed by the Energy and Industrial Power Group of TUT to investigate the drying application on banana. The average temperature reading $A_0$, $A_3$ and $A_1$, $A_4$ of two types of Temperature Sensors (V-T-H Multi-Channel Anemometer and Temperature Sensor 4 – 20 mA) from inlet and outlet points within the dryer in Figure 1 are presented in Table 2. The result of the tests conducted on the HPD is shown in Figure 6. The temperature in this numerical simulation followed the same decreasing trend (30.1-29.4). This gives us the confidence in the adopted numerical code.

Table 2. Average temperature readings from points within the dryer

| Inlet Temperature $A_0$ | Inlet Temperature $A_3$ | Outer Temperature $A_1$ | Outer Temperature $A_4$ |
|-------------------------|------------------------|-------------------------|------------------------|
| 34.95                   | 34.01                  | 33.24                   | 33.02                  |

3 RESULTS AND DISCUSSION

The results of the simulation studies are presented in Figures 4 - 9 and Table 3 and 4. The temperature fields of the banana/banana-pores were predicted as shown in Figure 4. From the contour legend, the temperature within the banana slices falls within the range of the blue/light green colours i.e. (28.8-30.8°C). This value falls within the range of temperature expected of products undergoing drying according to Traub (2002). This is an advantage over experimental set up because the temperature of the bananas could not be measured during drying.
Figure 4: Contour plots of turbulent flow

Figure 5 shows the distribution of temperature in the dryer. The temperature in this numerical simulation followed the same decreasing trend that was obtained from the experimental investigation. The simulated results for the laminar and turbulent models are presented in Table 3 and 4. The values were obtained from results menu in Fluent. From Table 3 the updraft airflow gives a better result in accordance with the principles of convection and buoyancy effect on heated air for the laminar flow. This is because by natural convention, movement of heated air upwards is better enhanced, thereby hasting the drying of products. However, for turbulent flows (Table 4) there was a deviation. It was evidenced that the increased air flow in the turbulent model resulted in a small range of temperature when compared with that of laminar model (Figures 6 and 7).

Table 3. The Simulated Results for laminar flow

|                | Mass flow rate, kg/s | Heat transfer rate (W) | Velocity (m/s) | Mass fraction of Water | Temp (°C)  |
|----------------|----------------------|------------------------|----------------|------------------------|------------|
| Parallel airflow | 0.00731              | 458.64                 | 0.15           | 0.179 - 0.18           | 39.87 - 40 |
| Downward draft  | 0.00126 (0.0032)     | 31.06 (202.367)        | 0.61           | 0.179 - 0.18           | 39.83 - 40 |
| Upward draft    | -0.0023              | 29.70                  | 0 - 0.38       | 0.179 - 0.195          | 39.66 - 40.03 |

Table 4: The Simulated Results for turbulent flow

|                | Mass flow rate, kg/s | Heat transfer rate (W) | Velocity (m/s) | Temp (°C) | Mass fraction of Water |
|----------------|----------------------|------------------------|----------------|-----------|------------------------|
| Parallel airflow | -0.081              | 201.83                 | 0.816          | 39.98 - 40| 0.179 - 18             |
| Downward draft  | -0.014               | 70.99                  | 3.32           | 39.93 - 40| 0.179 - 0.18            |
| Upward draft    | -0.0048              | 70.77                  | 0.49           | 39.84 - 40| 17.9 - 18.01           |
The species model represented the humidity of the drying air, where mass fraction of water represents the water content of the samples (Figure 8). This Figure shows that by the time the dry air passed over the wet banana, it absorbed moisture thereby increasing in humidity. This is a better representation of the measure of the humidity of the air as it was difficult to accurately measure the air humidity with data acquisition instruments. The value 0.179 was calculated from the post process result of the Fluent Application used. However, this result represents that of a cell within the computation domain. The result for the whole domain would be got by integration of the total number of cells in the computational domain.

![Fig. 7: Contour plots of turbulent updraft airflow](image)

**Fig. 7:** Contour plots of turbulent updraft airflow

The velocity distribution within the dryer is shown in Figure 10. The air velocity tends to increase towards the outlet of the dryer. The extent of the solver performance depends on the specific values of the variable in question. Therefore, investigation of the heat transfer performances of the dryer using UDF codes of FLUENT is recommended as this will account for the mass diffusivity, thermal conductivity, density and specific heat of the product as functions of moisture content and temperature. The temperature of the drying air decreased as it flows through the dryer and passes out at the outlet.

![Fig. 8: Mass fraction of water inside the dryer](image)

**Fig. 8:** Mass fraction of water inside the dryer

![Fig. 9: Velocity magnitude of air within dryer](image)

**Fig. 9:** Velocity magnitude of air within dryer

4 CONCLUSION

The temperature, moisture and velocity of air in the dryer as well as in the banana have been characterized in this study. The temperature in this numerical simulation followed the same decreasing trend (30.1-29.4) with the experimental result of the heat pump dryer under study. Also, values were predicted for varying the positions of airflow in the dryer. Investigation of the heat transfer performances of the dryer using user-defined function (UDF) codes of FLUENT is recommended as this will account for the mass diffusivity, thermal conductivity, density and specific heat of the product as functions of moisture content and temperature. The study achieved simulation of conditions where it is not possible to take detailed measurements.

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