

Numerical study of heat transfer in fluidized bed dryers by volume of fluid method

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Abstract

The purpose of this study is numerical modeling of temperature variation of phases in a two phase regime in fluidized bed dryers including particles belonging to Group D of geldart classification. The mass transfer between phases is not taken into consideration in this modeling which has been assumed in three-dimensional, unsteady, and two-phase regime. To verify the modeling we consider the domain so that we will be able to compare the results with the experimental study has done by khorshidi et al [1]. At first we choose the governing equations according to problem physics and solving method. Then by designing an appropriate grid, we solved the governing equation by the volume of fluid (VOF) method, a suitable method to solve multi-phase problems; finally we obtained thermal variations of gas and solid phase, the contours of temperature, pressure, and volume fraction. The comparison of numerical and experimental study results revealed that there was an appropriate adaptation between them. Also, the temperature contours proved that perfect mixing hypothesis that has been introduced by some researchers is a true one and has adaptation with this research results.

Keywords : Volume of fluid (VOF) method; Heat transfer; Fluidized bed; Two phase flow.

1 Introduction

For the centuries, drying has been used throughout the world in order to keep the industrial products, food and agricultural products. Drying process is currently one of the principal methods of storage of perishable materials or those which are reactive to high humidity. Moreover, this method is one of the most important operational units for use in a wide range of industries, particularly the food industry.

Drying process is complicated process involving heat, mass and momentum transfer. This process causes destructive and nondestructive irreversible changes in physical, chemical and apparent properties such as color, viscosity and breakdown of hydrocarbons which may reduce the quality of the product. For this reason, it is important to use the best method to dry each product in order to establish minimum quality loss and the operations be performed in minimum time.

One of the most commonly used types of dryers in the industry, are fluidized bed dryers in which solid particles are suspended and floated in warm air flow. Due to the high capacity, low manufacturing cost, easy operation and high efficiency (high heat and mass transfer coefficients) fluidized bed dryers are used in a wide range of industries. These dryers could be used for ev-

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ery moist solid particle which has the Capability of becoming fluidized by means of warm air flow. Some of the main reasons of the use of this method, specifically in food and pharmaceutical industries, are high drying speed, high quality of dried product, and appropriate homogeneity.

A lot of studies have been done for modeling heat transfer in these dryers; many researchers who conducted these studies have used equations of equilibrium between phases which are famous for two-phase and three-phase methods. A few numbers of those researchers have done direct solution of equation by 3-d modeling and numerical methods because solving this equation in a three-phase, unsteady, and porous domain is very complicated. Wildhagen et al [5] used a three-phase model to study heat and mass transfer in a fluidized bed dryer consisted of porous alumina. The solid phase assume perfectly mixed and the bubble phase and interstitial gas phase assume one dimensional. Vitor et al [4] investigated drying process of tapioca belong to Geldart group D particles. Like the previous study, they used three-phase model.

Rizzi et al [3] performed a numerical and experimental modeling of a fluidized bed dryer containing low moisture grass seeds which belonged to group D of Geldart classification. In this study Rizzi also considered the heat transfer from bed surfaces. They ignored mass transfer between phases because there was a low percentage of seed moisture. With modification of three-phase model, Khorshidi et al [1] presented a correlation for heat transfer coefficient between solid phase and interstitial gas phase for colza seeds belonging to group D of geldart classification. The aim of this research is numerical study of two phase flow regime in fluidized bed dryer using direct solution of equations by volume of fluid method. At first, we solve the governing equations of volume of fluid (VOF) method according to initial and boundary conditions and geometry, and then we calculate temperature variation of each phase, pressure, temperature, and volume fraction contours. To ensure the correctness of modeling, we consider the conditions and calculating domain such as khorshidi et al. [1] experimental study.

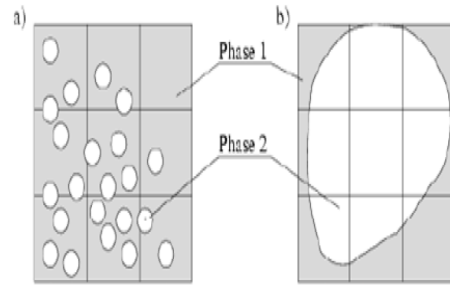


Figure 1: Locating each phase in cells in VOF method

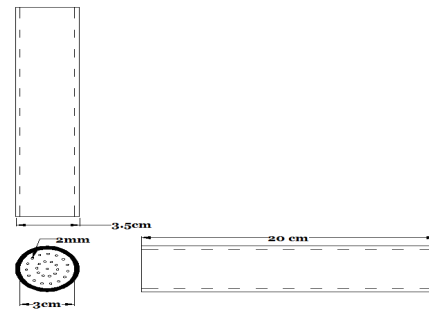


Figure 2: Dimensions of bed

2 Materials and methods

Symptoms:

P : Pressure

V : velocity

E : Energy

T : Temperature

u : Inlet gas velocity

$T_{g^{\circ}}$: Inlet gas temperature

$T_{s^{\circ}}$: Solid particles temperature.

M : mass of particles

L : Fluidization height

F and a_q : Locating of each phase in the cells function

k_{eff} : Effective heat conductivity

μ : Dynamic viscosity

V : Cell volume

U_f : Volume flux inputs

\dot{m}_{pq} : Mass transfer rate from phase q to phase p

s_{a_q} : Energy source term

2.1 Introducing volume of fluid (VOF) method

With a review on previous studies such as this one, volume of fluid (VOF) is one of the newest methods in solving multi-phase problems. This method first was introduced by Hirt and Nichols [2] which soon attracted the attention of re-

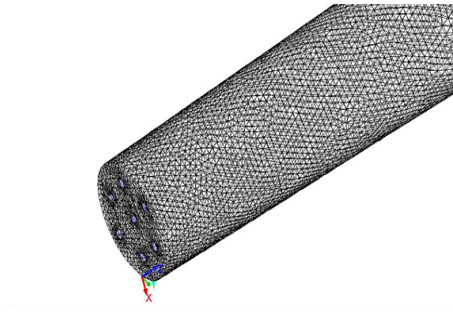


Figure 3: Generated mesh.

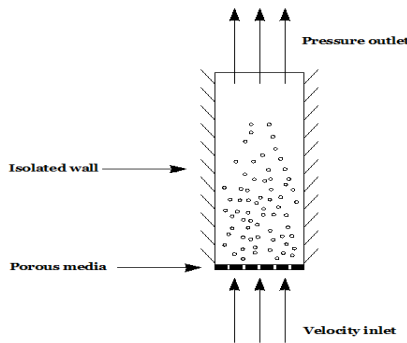


Figure 4: Boundary conditions

searchers to study the multi-phase problems. This method is mostly applicable to free boundaries problems; besides, volume fraction of each phase in the grids is an effective factor in this method. To this end, a function F is generated for each cell that at any time has one of the values listed in Table 1:

Table 1: Locating of each phase in the cells

$F = 0$	Cell only contain phase 1
$F = 1$	Cell only contain phase 2
$0 < F < 1$	Cell contain mixture of two phases

The correct form of locating phases in cells in VOF method is shown in Fig 1.

Volume fraction limit: Volume fraction cut-off is a factor to control volume fraction in modeling. So that if volume fraction of one phase in one cell is less than the amount of volume fraction cut-off, the amount of that phase in that cell will be considered zero. In this study we consider this factor as equal as 1-6 less amounts will diverge the solution.

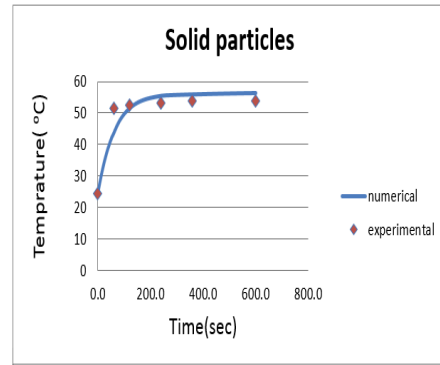


Figure 5: Solid particles temperature comparison (test no.1)

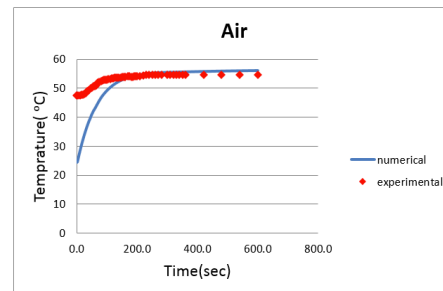


Figure 6: Output air temperature comparison (test no.1)

2.2 Governing equations

Next, we will introduce the governing equation related to VOF method which includes continuity, momentum, and energy equations.

Continuity equation:

The relation between phases is obtained by solving continuity equation of volume fraction of phases.

$$\frac{1}{\rho_q} \left[\frac{\partial}{\partial t} (a_q \rho_q) + \nabla \cdot (a_q \rho_q \vec{v}_q) \right] = s_{a_q} + \sum_{p=1}^n (\dot{m}_{pq} - \dot{m}_{qp}) \quad (1)$$

In which \dot{m}_{qp} indicates mass transfer from phase q to p and \dot{m}_{pq} mass transfer from p to q . Also indicates mass source; all of this terms in this study are zero. Discretized form of this equation is presented below:

$$\frac{a_q^{n+1} \rho_q^{n+1} - a_q^n \rho_q^n}{\Delta t} V + \sum_f (\rho_a^{n+1} U_f^{n+1} a_{qf}^{n+1}) = [s_{a_q} + \sum_{p=1}^n (\dot{m}_{pq} - \dot{m}_{qp})] V \quad (2)$$

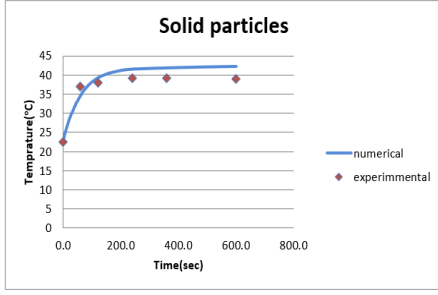


Figure 7: Solid particles temperature comparison (test no.2)

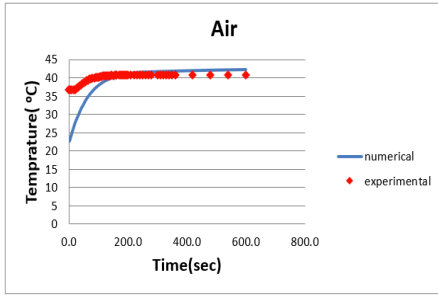


Figure 8: Output air temperature comparison (test no.2)

In which a_q is F function, V is cell volume and U_f^{n+1} is volume flux inputs for each cell depending on normal velocity.

Momentum equation (Navier-stokes):

Only one equation will be solved for the whole domain and obtained velocity field which is common to all phases. The following equation depends on volume fraction, viscosity, and density.

$$\frac{1}{\rho \vec{v}} + \nabla \cdot (\rho \vec{v} \vec{v}) = \nabla_p + \nabla \cdot [\mu (\nabla \vec{v} + \nabla \vec{v}^T) + \rho \vec{g} + \vec{F}] \quad (3)$$

Energy equation:

Energy equation for each phase is as follows:

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\vec{v} (\rho E + \rho)) = \nabla \cdot (k_{eff} \nabla T) + S_h \quad (4)$$

k_{eff} is effective thermal conductivity for each phase and his the source term.

In volume fluid method, energy and temperature are calculated in mass average form by Eq. 5:

$$E = \frac{\sum_{q=1}^n \alpha_q \rho_q E_q}{\sum_{q=1}^n \alpha_q \rho_q} \quad (5)$$

Material property:

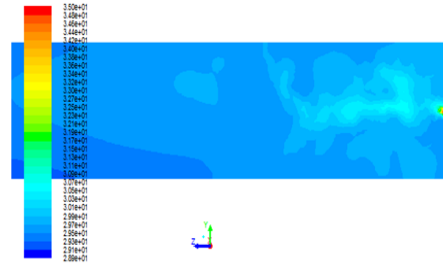


Figure 9: Mixture phase temperature for test no.1 at 10 second

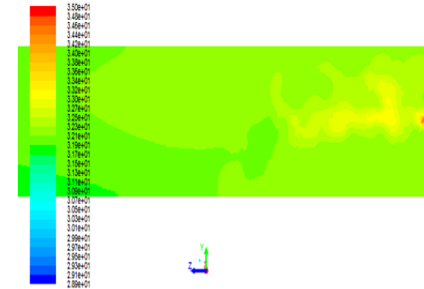


Figure 10: Mixture phase temperature for test no.1 at 30 second

To achieved properties of each phase such as velocity, density, etc. we use following correlation which calculates properties of each phase in a cell as a function of volume fraction of phase in that cell. For example, for density we use subsequent equation:

$$\rho = a_2 \rho_2 + (1 + a_2) \rho_1 \quad (6)$$

2.3 Modeling process

2.3.1 Grid generation

At first, we design the fluidized bed by GAMBIT. Next, we generate the grid by this piece of software. Physical properties and geometry considered in this study are just like the properties and geometry of experimental apparatus used by khorshidi et al [1]. This bed contains a glass cylinder which is completely isolated; also, there are several two millimeters diameter holes to increase the turbulence of inlet air flow at the bottom of it (Fig. 2). To solve the problem, we used an octahedral, unstructured mesh; the characteristics have been shown in Table 2. In Fig. 3 also, you can see a view of generated mesh.

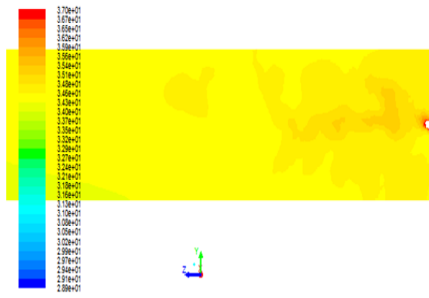


Figure 11: mixture phase temperature for test no.1 at 30 second

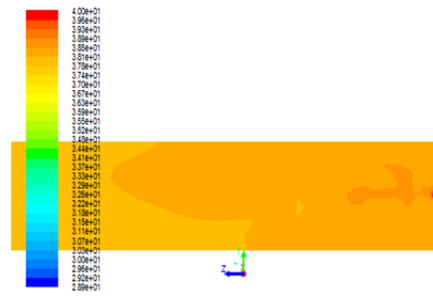


Figure 13: Mixture phase temperature for test no.1 at 70 second

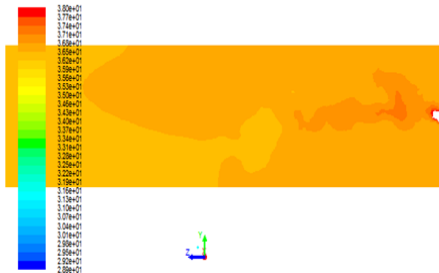


Figure 12: mixture phase temperature for test no.1 at 50 second

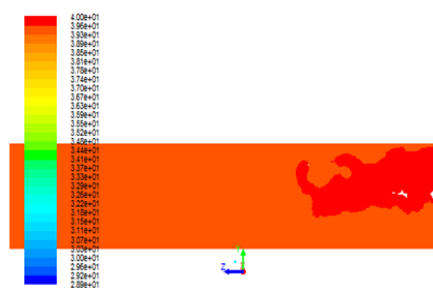


Figure 14: Mixture phase temperature for test no.1 at 70 second

Table 2: generated mesh characteristics

Number of cells	324043
Number of plains	658156
Number of nodes	59207
Number of partitions	4

2.3.2 Flow regime characteristics

At first, it is necessary to specify characteristics of flow passed from the bed. According to average velocity of air flow through the bed and its initial dimensions, the Reynolds number is in laminar flow range. Since the temperature changes from system start up moment to the moment that flow become steady, we model this problem an unsteady one. Turbulence is one of the most effective factors of heat transfer, that increase the contact surface between gas and solid phase, in this apparatus also, small holes has been created in bed inlet to increase flow turbulence.

2.3.3 Initial condition and phase characteristics

Khorshidi et al [1] conducted the study with different inlet flow temperature and velocity. We

verify the study by comparing the results with khorshidi experimental study. Initial conditions of two experiments are presented in Table 3. Since colza seeds and dry air produced fluidization regime in khorshidi study, their characteristics are presented in our study (Tables 4 and 5).

Table 3: Initial conditions of khorshidi et al. experiment [1]

Test no	u (m/s)	T_{g0} °C	T_{s0} °C	M (kg)	L f(m)
1	1.96	56.5	24.1	0.012	0.050
2	1.57	47.5	23	0.012	0.040

2.3.4 Boundary conditions

In this problem we have three different boundaries (Fig 4). First is bed inlet with determined velocity and temperature air flow. The second is bed outlet with determined pressure air flow. Finally, the third one is bed wall that is completely isolated and has no heat transfer.

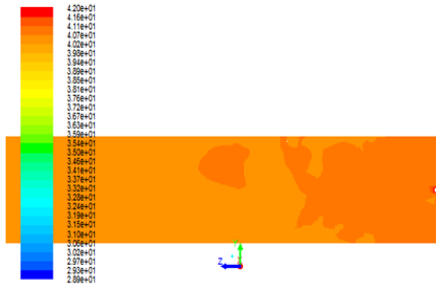


Figure 15: Mixture phase temperature for test no.1 at 70 second

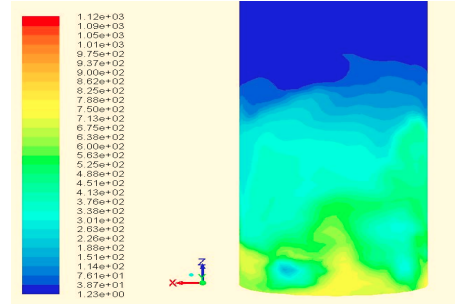


Figure 17: Density contour for test no.1 (kg/m3)

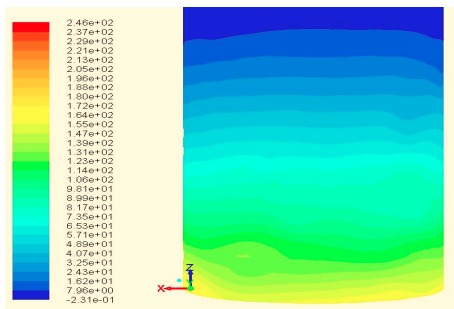


Figure 16: Static pressure contour for test no.1 (Pascal)

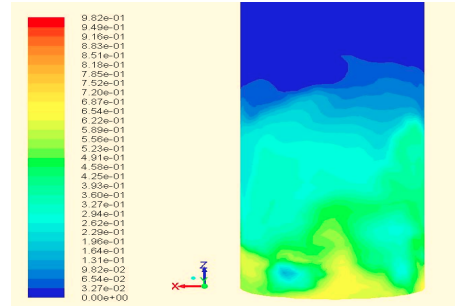


Figure 18: Volume fraction of solid phase contour for test no.1

Table 4: Characteristics of solid phase (colza)

(kg/m ³)Density	1145.77
(J/kg.K)Specific heat-Cp	20000
(w/m.K)Thermal conductivity	0.0242
(kg/kmol)Molecular	18.0152
(m)Seeds diameter	0.00178
Sphericity coefficient	0.91
Seed humidity content	0.06

Table 5: Gas phase (air) characteristics

(kg/m ³)Density	1.225
(J/kg.K) Heat capacity	1006.43
(w/m.K)Thermal conductivity	0.6
(kg/m.sec)Viscosity	1.78×10^{-5}
(kg/kmol)Molecular mass	28.966

2.3.5 controlling the solution

To solve this problem by VOF method according to the problem conditions and required time for converging the result; further, because we have

a two-phase model and the number of equations is double, the solution last very much. Time interval between steps considered 0.001 second. Discretizing methods of equations which are chosen according to previous experiments and similar studies are presented in Table 6. Under re-

Table 6: Discretization methods

Equation	Method
Pressure velocity	Simple
Gradient	Least square cell
Pressure	Presto
Momentum	Second order upwind
Volume fraction	First order upwind
Energy	Second order upwind
Transient formulation	First order implicit

laxation factors: To control solution convergence we must use appropriate under relaxation factors which are shown in Table 7.

2.3.6 Solution process

After almost eight hundred iterations and solving six equations at each iterate (triple equations for each size) the solution was converged. We solved this problem for three different cases with dif-

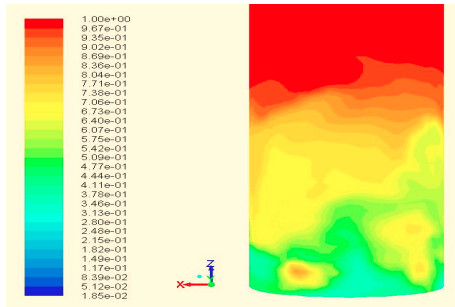


Figure 19: Volume fraction of gas phase contour for test no.1

Table 7: Under relaxation factors

Variables	Under relaxation factor
Pressure	0.3
Density	1
Body force	1
Momentum	0.7
Volume fraction	0.5
Energy	1

ferent internal air temperature and for each case the iteration last almost ten days. Because of high number of iterations, the results were saved every 0.1 seconds. Experimental apparatus in khorshidi study is presented in a way that the outlet gas temperature has been recorded at 12 cm above bottom of bed during the process and the solid particles temperature also measured by perfect mixing assumption; its mean score is a function of time and is constant all over the bed. In this study to validate the solution we measured the gas phase temperature at 12 cm height above the bed bottom and the solid phase temperature also is average of solid particles temperature throughout the bed, in next section the results are presented.

3 Results and discussion

3.1 Grid independence surveying

To study this model we generate three different grids and recognize the answers are grid independence. At last, grid that was generated by 324043 cells has been studied.

3.2 Diagram of solid particles and output gas temperature

The main purpose of modeling is studying the process of two phase's temperatures changes and comparison with experimental results that are presented in Figs 5-8.

According to Figs 5-8 there is a good adaptation between experimental and numerical results which shows that VOF method is reliable for modeling this kind of problems; also, the temperature changes slope at the beginning of the process was very high which showed the high heat transfer between phases in this kind of dryers which is as a result of high contact area between them.

3.3 Contours

In Figs 9-15 temperature of mixture of phases has been shown from the start moment to the moment that temperature become almost steady at test no.1. These contours have been saved at 20 seconds time steps. Because of higher molecular mass of solid phase in the bed this phase is lower than gas phase. As one can see the upper and lower section of the contours of bed are almost homochromatic which indicates that at each moment solid particles have the same temperature. It designates the good adaptation with perfect mixing assumption. Also, temperature of bed was constant at each moment and the difference between maximum and minimum temperature is lower than centigrade degree indicating good thermal Equilibrium.

In the following, contours of density, static pressure and volume fraction for test no.1 at the moment that temperature become steady have been presented.

4 Conclusion

In this study we analyzed heat transfer in two-phase fluid flow regime by volume of fluid method. In order to maximize the validation of the results, the results of the simulation were compared with experimental results obtained by Khorshidi et al [1]. By considering the charts and results it is obvious that there is an acceptable adaptation between numerical and experimental results. Moreover, after a while two phases of

temperature (gas and solid) converges which indicate perfect heat transfer between phases. Furthermore, by considering the charts it can be concluded that because of perfect heat transfer between phases at the beginning, output gas temperature drops sharply and reaches the temperature of solid particles. By examining pressure contour, it is clear that the more we get to the top of the bed, the static pressure decreases sharply which is as a result of the flow porosity and the existence of the particles. As it was expected, the bed density was higher at the lower part of the bed which was as a result of the high weight of solid particles mass; moreover, the volume fraction of each phase is different at the lower and upper part of the bed. The volume fraction of solid phase is zero at the top of the bed. As it can be seen in the experiment, solid phase rises only to 5 centimeters height above bottom of the bed. By considering the contours of temperature of solid particles it is obvious that Perfect Mixing Hypothesis which is used to simplify equations in three-phase modeling has a good adaptation with the results of this study. By comparing the results it can be concluded that modeling of this system by Volume of Method (VOF) is a suitable method for solving Problems of these sorts.

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