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Heat and Mass Transfer Analysis of Fluidized Bed Grain Drying

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The effects of heat and mass transfer parameters on the efficiency of fluidized bed drying have been studied to optimize the input and output conditions. The analysis was carried out using two different materials, wheat and corn. Energy and exergy models based on the first and second law of thermodynamic are developed. Furthermore, some unified non-dimensional experimental correlations for predicting the efficiency of fluidized bed drying process have been proposed. The effects of hydrodynamics and thermodynamics conditions such as the inlet air temperature, the initial moisture content and well known Fourier and Reynolds numbers on energy efficiency and exergy efficiency were analyzed using the developed model. A good agreement was achieved between the model predictions, non-dimensional correlations and the available experimental results.

NOMENCLATURE

C_p	air specific heat, kJ/ kg K
d	particle diameter, m
dt	time interval, s
E	total exergy, kJ
$\dot{E}$	time rate of exergy transfer, kJ/s
e	specific exergy, kJ/kg
Fo	Fourier Number
h	specific enthalpy, kJ/kg
h_{fg}	latent heat of vaporization, kJ/kg water
k	thermal conductivity, W/m K
M^*	dimensionless moisture, defined in Eq. (24)
$\dot{m}$	mass flow rate, kg/s
$\dot{m}_w$	mass flow rates of water from surface of a particle, kg water/s
$\dot{Q}$	heat transfer rate, kJ/s
r	particle radius, m
Re	Reynolds Number, = Vd/υ
S	total entropy, kJ/K
s	specific entropy, kJ/kg K
S_{gen}	entropy generation, kJ/K
T	temperature, K
T^*	dimensionless temperature, def. in Eq. (25)
T_o	ambient air temperature, K
T_m	material temperature, K
t	time, s
V	velocity, m/s
W	mass of material, kg

Greek symbols

α	thermal diffusivity, m^2/s
η_{th}	thermal efficiency
η_e	energy efficiency
η_{ex}	exergy efficiency
υ	kinematic viscosity of air, m^2/s

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Subscripts

∘	standard state value
1	inlet
2	outlet
a	air
amb	ambient
e	equilibrium
D	destruction
g	gas
p	particle
i	initial
t	target

1. INTRODUCTION

A complex transport phenomenon takes place during drying process, including unsteady-state heat and mass transfer simultaneously. The heat and moisture transfer rates are related to drying air temperature and Reynolds number as a function of velocity of the circulating drying air. In drying process therefore different mass and energy balance mechanisms are involved.

The direct contact heat and mass transfer method has been adopted in many engineering fields by using different heat transfer media [1]. In fluidized bed drying the process is carried out in a bed fluidized by the drying medium. Fluidized bed is extensively used in particulate grain drying [2]. The developments of the regime of fluidization and subsequent design modifications have made fluidized bed drying a desirable choice among other dryers. However, the efficiency of a conventional drying system is usually low. It is, therefore, desirable to improve the efficiency of the drying process [3].

In the previous studies of direct contact heat transfer, some experimental conditions of air flow rate, inlet air temperature and humidity as a dispersion fluid were carried out by bubbling air. Although a large number of experimental and theoretical investigations of heat and mass transfer analyses of wet materials in fluidized bed have been undertaken by many researchers [e.g. 1-10], very few works have appeared on energy and exergy model of grain drying in fluidized bed [e.g. 11-14].

Exergy or availability is defined as the work available in a system due to its non-equilibrium condition with respect to environment as a reference state [15]. Exergy is based on the first and second law of thermodynamic is not subject to a conservation law, but consumed or destroyed due to irreversibility. Any discussion of the basic principles of convective heat transfer must include the second law of thermodynamics [16]. The need to understand the linkages between exergy and energy, and environmental impact has become increasingly significant. Lower exergy efficiency leads to higher environmental impact [17, 18]. Considering the importance of the cost of energy, the availability of fuel and their impact on the environment, the exergy efficiency model in the drying process becomes a very useful tool of analysis.

The main objective of this paper is to conduct an energy and exergy model to study heat and mass transfer parameter in fluidized bed drying. Differently from previous work [11-14], in this paper we propose some correlations by using non-dimensional parameters including well known Fourier and Reynolds number to estimate energy efficiency and exergy efficiency of fluidized bed drying process for wheat and corn materials. Finally, we validate the model to experimental drying data to elucidate the effects of inlet air temperature, Fourier and Reynolds numbers in different operating conditions.

2. EXPERIMENTAL SETUP AND MATERIAL PROPERTIES

A schematic of fluidized bed dryer system used in the present study is shown in Fig. 1, mainly consists of a fluidized bed column, electric heater and blower. The cylinder bed column is made of Plexiglas with a wall thickness of 7 mm, an internal diameter of 175 mm with overall length of 1200 mm. The distributor plate is constructed from Plexiglas of 6 mm thickness, with 666 holes of 2 mm diameter arranged in a triangular pattern (for details on the experimental setup see [10]). Air is supplied via a root blower and then passed through a 2.5 kW heater. The air then enters the plenum filled with rings to distribute the air flow before passing through the distributor plate.

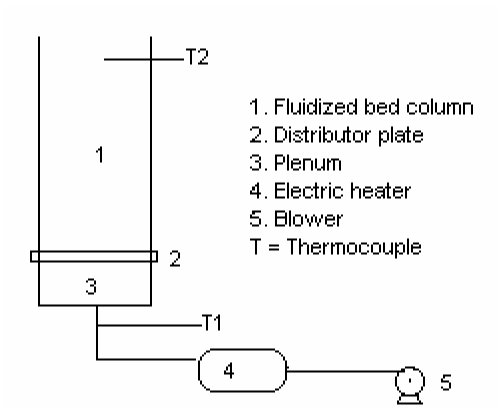

Fig. 1. Schematic of fluidized bed dryer system

Two different materials (wheat and corn) were used in the previous studies of fluidized bed drying analysis [10-12]. In this study the same materials were selected to provide a basis for comparison. Red-spring wheat was used as one of the test materials. The wheat kernel is assumed to be spherical with an average diameter of 3.66 mm and a density of 1215 kg/m^3. The specific heat of wheat is given as [19],

$$C_m = 1398.3 + 4090.2\left(\frac{M_p}{1+M_p}\right) \quad (1)$$

where M_p is moisture content of grain on a dry basis (kg water/kg solid).

The second type of material used was shelled corn. The corn kernel is found to have a shape factor close to the unity with an average diameter of 6.45 mm and a density of 1260 kg/m^3. The specific heat of corn is given as [19],

$$C_m = 1465.0 + 3560.0\left(\frac{M_p}{1+M_p}\right) \quad (2)$$

All moisture contents referred to in this work is on a dry basis. The moisture content on a dry basis is calculated by dividing the weight of water by the weight of dry material.

$$M_p = \frac{W_w}{W_d} * 100\% \quad (3)$$

where W_w is weight of water (kg) and W_d is weight of dry material (kg) or more simply

$$M_p = \frac{W_b - W_d}{W_d} \quad (4)$$

where W_b is weight of material before drying (kg), W_d is weight of material after drying (kg) and M_p is moisture content of material on a dry basis (kg water/kg solid).

3. MODELLING

Fluidized bed drying is a process of contact between the two phases. The solid phase, under fluidization conditions, assumes a "fluid like" state. When drying air is passed upward through a layer of wet material, as shown in Fig. 2, the gas will pass at low flow rates through the fixed bed of particles. As the gas velocity is increased, the pressure drop across the particle layer will increase until all particles are suspended in the upward-flowing drying air; the gas velocity at this point is called the minimum fluidization velocity, U_{mf}.

When the drying air velocity increased further above U_{mf}, the gas will pass through the particle layer as bubbles. At still higher gas velocities, a point is reached at which the drag forces are increased to a degree that the particles become entrained within the gas stream and are carried from the fluid bed as a pneumatic transport. In this work however, the region of gas fluidization as shown in Fig. 3 is in bubbling Fluidization. A comprehensive mathematical model to simulate heat and mass transfer in bubbling fluidized bed has been described in the previous studies [9, 12].

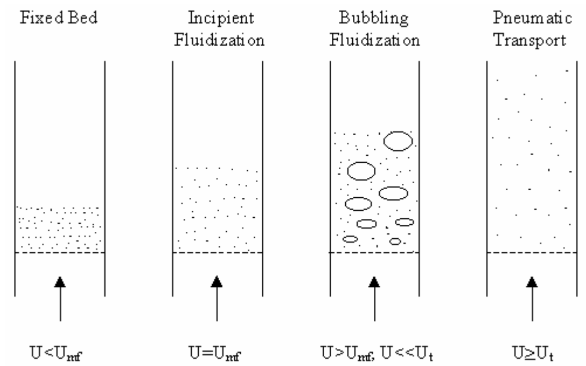

Fig. 2. Region of gas fluidization

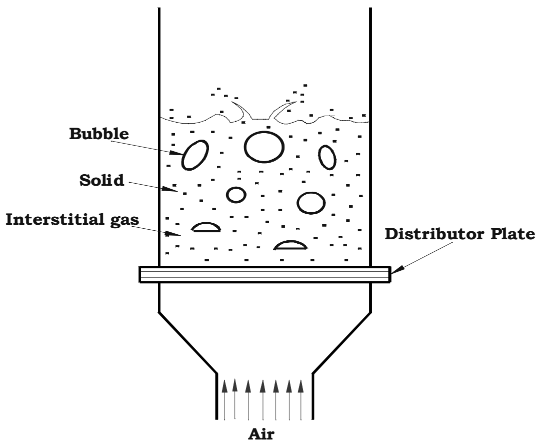

Fig. 3. Bubbling fluidization

Drying is essentially a process of simultaneous heat and mass transfer. Heat, necessary for evaporation, is supplied to the particles of the material and moisture vapor is removed from the material into the drying medium. Heat is transported by convection from the surroundings to the particle surfaces, and from there, by conduction, further into the particle. Moisture is transported in the opposite direction as a liquid or vapor on the surface it evaporates and passes on by convection to the surroundings [2] as can be seen in Fig. 4.

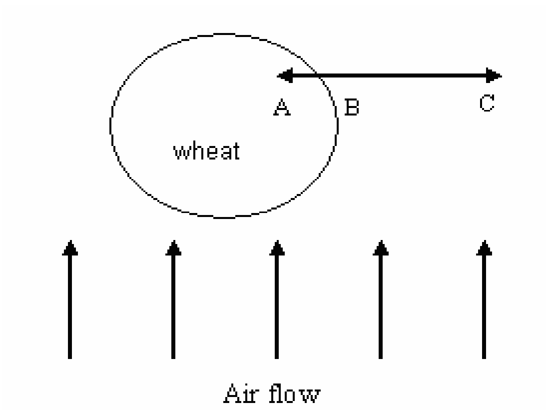

Fig. 4. Heat and mass transfer in drying of material

3.1. Heat and mass transfer analysis

The fluidized bed drying system is divided into the following subsystems: the blower, the heater and the drying column. For fluidized bed drying, the most significant component is the drying column. Therefore, the thermal balance is derived by applying mass, energy and entropy balances to the drying column in batch fluidization shown in Fig. 1. The drying process in a batch-fluidized bed is modeled by assuming a perfect mixing of particles. The process occurs during an isobaric process due to simultaneous heat and mass transfer between gas and solid. The thermodynamic state of the particle is described by enthalpy h_m, entropy s_m, and moisture content M_p. As there is a single inlet and a single exit, the mass rate balance reduces to:

$$\frac{dm_{cv}}{dt} = \dot{m}_{g1} - \dot{m}_{g2} \tag{5}$$

where $\dot{m}_{g1}$ and $\dot{m}_{g2}$ denote, respectively, the rate of mass that enters at inlet and exit in the batch dryer. Similarly, a balance of water in air flowing through the dryer column leads to:

$$W_d \frac{dM_p}{dt} = \dot{m}_a \left(X_1 - X_2\right) \tag{6}$$

where W_d represents the mass of dry solid, M_p is the moisture content of the material (uniform throughout the bed), $\dot{m}_a$ is the mass flow rate of dry air, X_1 and X_2 denote absolute humidity of inlet and exit air respectively. Equation (6) can be written as:

$$\dot{m}_w = \dot{m}_a\left(X_2 - X_1\right) \tag{7}$$

The significant heat transfer is due to the heat of evaporation between the solid and the drying air, and there is also heat transfer with the surroundings. The energy rate balance reduces with the assumption that all kinetic and potential energy effects can be ignored. The energy rate balance therefore becomes:

$$\frac{dH_{cv}}{dt} = \dot{Q}_{evap} + \dot{m}_{a1}h_1 - \dot{m}_{a2}h_2 - \dot{Q}_{loss} \tag{8}$$

where $\dot{Q}_{evap}$ = heat transfer rate due to water evaporation (kJ/s), $\dot{Q}_{loss}$ = heat loss (kJ/s), h_1 = specific enthalpy of inlet drying air (kJ/kg), h_2 = specific enthalpy of outlet drying air (kJ/kg). Since the mass flow rate of the dry air and the mass of dry material within the control volume remain constant with time, the energy rate balance can be expressed as:

$$\frac{W_d\left(h_{m2} - h_{m1}\right)}{\Delta t} = \dot{Q}_{evap} + \dot{m}_a\left(h_1 - h_2\right) - \dot{Q}_{loss} \tag{9}$$

The material enthalpy balance expression for the material flow can be written as:

$$h_{m2} - h_{m1} = c_m\left(T_{m2} - T_{m1}\right) \tag{10}$$

where c_m shows the specific heat of the material. The enthalpy of moist air can be calculated by adding the contribution of each component as it exits in the mixture; thus the enthalpy of moist air is:

$$h = h_a + X\, h_v \tag{11}$$

The heat transfer rate due to phase change is:

$$\dot{Q}_{evap.} = \dot{m}_w h_{fg} \tag{12}$$

where h_{fg} is latent heat of vaporization of water (kJ/kg) at the average temperature of the moist material.

Mass and energy are conserved quantities, but entropy is never conserved. To account for these entropy transfers, the entropy balance has to be performed. The entropy rate balance for the batch drying column becomes:

$$\frac{W_d\left(s_{m2} - s_{m1}\right)}{\Delta t} = \frac{\dot{Q}_{evap}}{T_m} + \dot{m}_a\left(s_1 - s_2\right) - \frac{\dot{Q}_{loss}}{T_b} + \dot{S}_{gen} \tag{13}$$

where $\dot{S}_{gen}$ is the total amount of entropy generation in the dryer column, T_b is the boundary temperature and T_m is the material average temperature.

The exergy balance for the drying column is developed by combining the energy balance Eq. (9) and the entropy balance Eq. (13). Multiplying the entropy balance by T_o and subtracting the resulting expression from the physical exergy balance gives:

$$\frac{W_d\left(E_{m2}-E_{m1}\right)}{\Delta t}=\dot{m}_a\left(h_1-h_2\right)+\left(1-\frac{T_0}{T_m}\right)\dot{Q}_{evap}$$
$$-\left(1-\frac{T_0}{T_b}\right)\dot{Q}_{loss}-T_0\dot{m}_a\left(s_1-s_2\right)-T_0\dot{S}_{gen}$$
$$\dot{E}_{m2}-\dot{E}_{m1}=\dot{E}_{da1}-\dot{E}_{da2}+\dot{E}_{evap}-\dot{E}_{loss}-\dot{E}_D \tag{14}$$

$\dot{E}_m$ and $\dot{E}_{da}$ are the exergy transfer rate of the material and drying air, respectively; $\dot{E}_{evap}$ is the exergy evaporation rate, $\dot{E}_{loss}$ is the rate of exergy loss to the surrounding and $\dot{E}_D$ is the exergy destruction rate in the batch drying. The specific exergies at inlets (e_{m1}) and outlets (e_{m2}) of the material are given by:

$$e_{m1}=\left(h_{m1}-h_o\right)-T_o\left(s_{m1}-s_o\right) \tag{15}$$

$$e_{m2}=\left(h_{m2}-h_o\right)-T_o\left(s_{m2}-s_o\right) \tag{16}$$

The specific exergies associated with a stream of drying air entering and leaving the column are:

$$e_{da1}=\left(h_1-h_o\right)-T_o\left(s_1-s_o\right) \tag{17}$$

$$e_{da2}=\left(h_2-h_o\right)-T_o\left(s_2-s_o\right) \tag{18}$$

where e_{da1} and e_{da2} are the specific exergy transfers at inlets and outlets, respectively; h_o, s_o denote the specific enthalpy and specific entropy at the temperature of dead state (T_o) respectively; h_1 and s_1 denote the specific enthalpy and the specific entropy at the temperature of drying air entering the column (T_{da1}); h_2 and s_2 denote the specific enthalpy and the specific entropy of drying air at the temperature of the drying air exiting the column, respectively. The potential and kinetic exergies are negligible.

The following equation is the rate of exergy transfer due to evaporation of the dryer and the rate of exergy loss to the surrounding, where T_b is the boundary temperature.

$$\dot{E}_{evap}=\left[1-\frac{T_o}{T_m}\right]\dot{m}_w\ h_{fg} \tag{19}$$

$$\dot{E}_{loss}=\left(1-\frac{T_0}{T_b}\right)\dot{Q}_{loss} \tag{20}$$

3.2 Efficiency of fluidized bed drying

The potential for using fluidized bed dryers is strongly dependent on an efficient use of energy. In this section, two methods to determine the efficiency of fluidized bed drying are described. These are energy efficiency based on the First Law of Thermodynamics and exergy efficiency based on the First Law and the Second Law of Thermodynamics.

(a) Energy efficiency

Energy efficiency of the dryer column based on the First Law of Thermodynamics can be derived by using the energy balance equation. The thermal efficiency of the drying process can be defined as [20]:

$$\eta_{th}=\frac{Energy\,transmitted\ to\ the\ solid}{Energy\,incorporated\ in\ the\ drying\ air} \tag{21}$$

The thermal efficiency can be expressed in terms of energy efficiency using the energy rate balance equation as:

$$\eta_e=\frac{W_d\left[h_{fg}\left(M_{p1}-M_{p2}\right)+c_m\left(T_{m2}-T_{m1}\right)\right]}{\dot{m}_{da}\left(h_1-h_0\right)\Delta t} \tag{22}$$

(b) Exergy efficiency

Exergy efficiency of the dryer column based on the First Law and the Second Law of Thermodynamics can be derived using the exergy rate balance equation. The exergy efficiency provides a true measure of the performance of the drying system from the thermodynamic viewpoint. In defining the exergy efficiency it is necessary to identify both the product and the fuel. In this study, the product is the rate of exergy evaporation and the fuel is the rate of exergy drying air entering the dryer column. The exergy efficiency of the dryer is the ratio between product and fuel. Where the product is only the rate of exergy evaporation process and the fuel is the rate of exergy drying air enters the dryer column, the exergy efficiency on the basis of the exergy rate balance is given as [13]:

$$\eta_{ex}=\frac{\dot{E}_{evap}}{\dot{E}_{da1}} \tag{23}$$

where $\dot{E}_{evap}$ is the rate of exergy evaporation (kJ/s) and $\dot{E}_{da1}$ is the rate of exergy drying air entering the drying column (kJ/s).

3.3 Non-dimensional correlation

Since the initial moisture content of grain (M_{pi}) used in the experiment at various inlet air conditions is different, comparison of drying time and efficiency in terms of absolute moisture content may be misleading. Therefore, the non-dimensional moisture content M^* is used for analyzing the data.

$$M^* = \frac{M_{pt} - M_{pe}}{M_{pi} - M_{pe}} \quad (24)$$

where M_{pt} and M_{pe} are the moisture content of grain as a target and equilibrium respectively.

In order to provide optimum operation conditions and energy saving in the drying process, without making any experimental measurement for practical applications. We proposed the non-dimensional parameter for determining efficiency of fluidized bed drying by using non-dimensional moisture content Eq. (24), non-dimensional temperature Eq. (25), and also well known Fourier and Reynolds correlations in Eq. (26) and Eq. (27) respectively.

$$T^* = \frac{T_{ai} - T_{amb}}{T_{pi} - T_{amb}} \quad (25)$$

$$Fo = \frac{\alpha t}{r^2} \quad (26)$$

$$Re = \frac{Vd}{\upsilon} \quad (27)$$

4. RESULTS AND DISCUSSION

In this work the analysis was done for two different materials, namely wheat and corn. As reported by Hajidavalloo [3], wheat and corn are among the main commodities of agriculture and have extensive applications in drying systems. Although wheat and corn are both hygroscopic materials, the corn grains are many times bigger than the wheat grains. This difference may cause a different pattern of drying as well as energy efficiency and exergy efficiency of the fluidized bed drying of these particles.

In order to get an understanding of the effects of heat and mass transfer parameters in drying process, energy and exergy efficiencies are analyzed using the model developed. The experimental inlet temperature and moisture content data were taken from the previous studies [3, 9-11] to determine actual energy and exergy efficiencies for the fluidized bed drying of wheat and corn at different drying conditions.

4.1 Non-dimensional correlation for wheat material

In order to validate the present model, in this study, Red-spring type wheat is chosen based on the actual moisture content data. These samples were dried with air temperatures of 40 °C to 65 °C and velocities of 1.63 m/s to 1.95 m/s. As explained in previous study [3], the reason for the narrow range of air velocity is regarding to fluidization velocity, since the region of gas for bubbling fluidization need higher value than minimum fluidization velocity but lower than transport velocity as can be seen in the region of gas fluidization, Fig. 2.

The data of some non-dimensional parameter including Reynolds number which expresses the non-dimensional drying air velocity and Fourier number which expresses the non-dimensional drying time, against energy and exergy efficiency are plotted in Fig. 5 for energy efficiency correlation and Fig. 6 for exergy efficiency correlation.

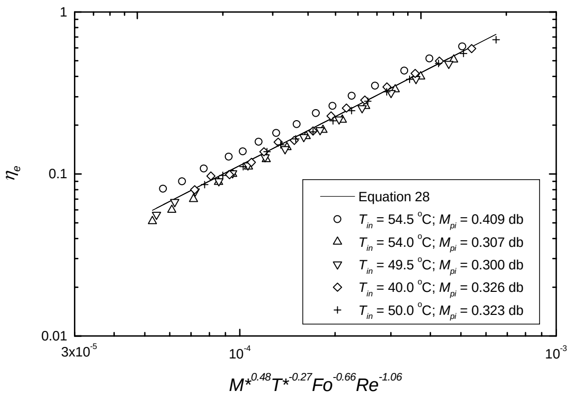

Fig. 5. Relationship between non-dimensional parameters and energy efficiency for wheat material

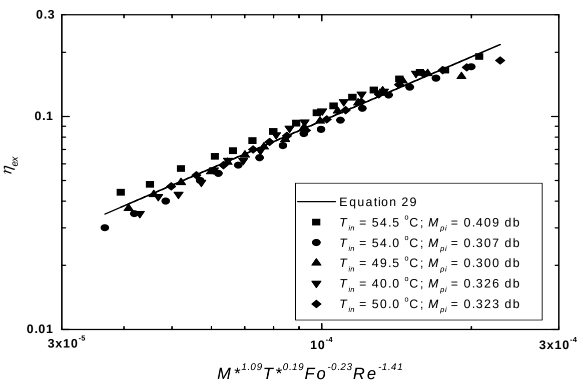

Fig. 6. Relationship between non-dimensional parameters and exergy efficiency for wheat material

The maximum difference between the experimental and estimated values is within the ± 16 %. The results of these experimental correlation Eq. 28 and Eq. 29 show that there is a remarkably good agreement between non-dimensional correlations and the available experimental results. The comparison has been performed with the following parameters: non-dimensional moisture content 0.4 < M^* < 0.9, non-dimensional temperature 1.25 < T^* < 2.75, Reynolds number Re = 250 – 450, and the Fourier number Fo = 3 – 70.

$$\eta_e = 1128\, M^{*\,0.48}\, T^{*\,-0.27}\, Fo^{-0.66}\, Re^{-1.06} \quad (28)$$

$$\eta_{ex} = 953\, M^{*\,1.09}\, T^{*\,0.19}\, Fo^{-0.23}\, Re^{-1.41} \quad (29)$$

4.2 Non-dimensional correlation for corn material

The second type of material used was corn; the size of the corn kernels is many times larger than wheat kernels. The other difference is that moisture diffusivity of corn is a function of temperature and moisture content of particles but that of wheat is dependent only on temperature. Since the mass diffusion is controlling the rate of drying process, it is possible that corn will have a different pattern in the drying process as well as energy and exergy efficiencies of the fluidized bed dryer.

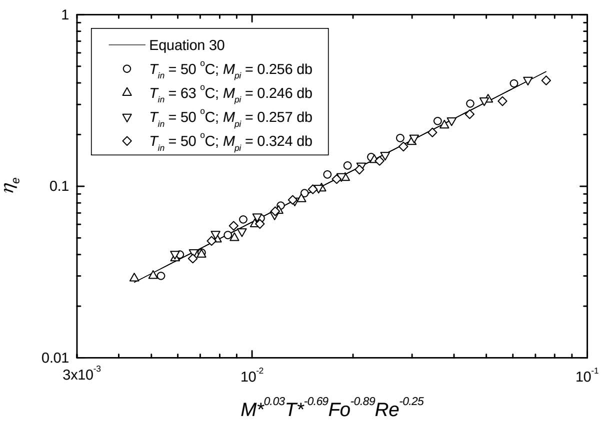

Fig. 7. Relationship between non-dimensional parameters and energy efficiency for corn material

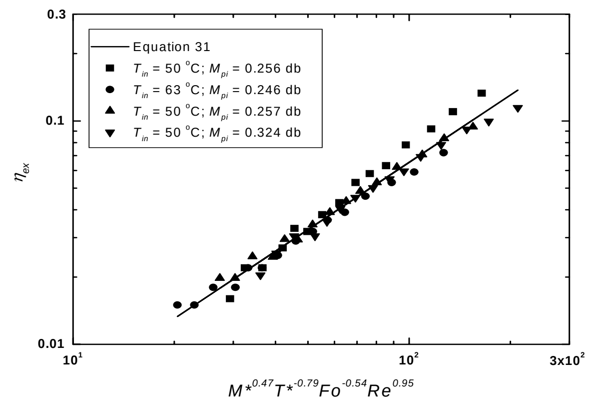

Fig. 8. Relationship between non-dimensional parameters and exergy efficiency for corn material

Figures 7 and 8 show the results for the corn material. These samples were dried with air at temperatures of 50 °C to 63 °C and velocities of 1.88 m/s to 2.24 m/s of initial moisture content very between 0.246 and 0.324 in dry basis. As explained earlier, the reason for the narrow range of air velocity is regarding to the fluidization velocity.

Two non-dimensional correlations based on experimental data (Eq. (30) and Eq. (31)) we proposed to calculate energy and exergy efficiencies for drying corn material by using non-dimensional moisture content Eq. (24), non-dimensional temperature Eq. (25), and also well known Fourier and Reynolds correlations in Eq. (26) and Eq. (27) respectively.. The maximum difference between the experimental and estimated values is within the ± 11 % for energy efficiency correlation and ± 20 % for exergy efficiency correlation. These show that there is a remarkably good agreement as can be seen in Fig. 7 for effect of non-dimensional parameter on energy efficiency and Fig. 8 for the exergy efficiency correlation. The comparison has been performed for corn material with the following parameters: non-dimensional moisture content 0.4 < M^* < 0.9, non-dimensional temperature 2.5 < T^* < 5, Reynolds number Re = 600 – 800, and the Fourier number Fo = 1.3 – 25.

$$\eta_e = 6.2\, M^{*\,0.03}\, T^{*\,-0.69}\, Fo^{-0.89}\, Re^{-0.25} \quad (30)$$

$$\eta_{ex} = 0.00065\, M^{*\,0.47}\, T^{*\,-0.79}\, Fo^{-0.54}\, Re^{0.95} \quad (31)$$

4.3 Effect of heat and mass transfer parameter

It was observed that as a general trend, the results obtained for corn materials are similar to the results obtained for wheat materials. Energy efficiency was found to be higher than exergy efficiency. Furthermore, at the beginning of the drying process, energy and exergy efficiencies were observed to be higher than at the final stage. Both the energy and exergy efficiencies of the fluidized bed dryer column were found to be very low at the end of the drying process. Furthermore, both energy efficiency and exergy efficiency for corn materials were found to be lower than that for wheat materials. In the following, a more comprehensive analysis of the results is given.

The effect of Fourier number on non-dimensional moisture for wheat and corn can be seen in Fig. 9. A clear difference was observed between the non-dimensional curves at different Fourier number for two different material used in this study. Thermal diffusivity as well as diameter of the material to be dried significantly influences the shape of drying curve.

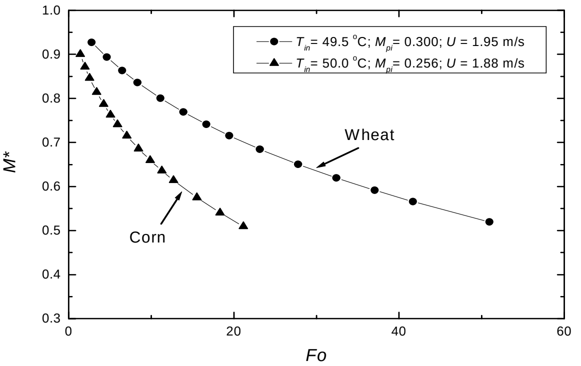

Fig. 9. The effect of Fourier number on non-dimensional moisture for wheat and corn

Fig. 10 shows the effect of Fourier number on efficiency and Fig. 11 shows the effect of non-dimensional moisture on efficiency. The experimental conditions for this study were inlet drying air temperature of 49.5 °C, gas velocity of 1.95 m/s^{-1}. The mass of wheat material was 2.5 kg with initial moisture content of 0.3 in dry basis. It can be seen that at the beginning of the drying process, the energy and exergy efficiencies were observed to be higher than at the final stage and were found to be very low at the end of drying process (i.e. less than 0.1 for energy efficiency and 0.05 for exergy efficiency) to reach non-dimensional moisture equals to 0.5. As illustrated by Topic [13], for the nominal mode of operation the changes of exergy efficiency of the dryer vary between 10 % at the beginning of the drying process and about 3 % at the end of the process.

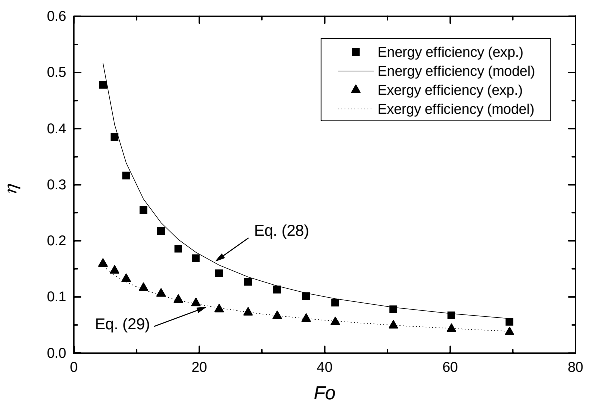

Fig. 10. The effect of Fourier number on energy and exergy efficiency

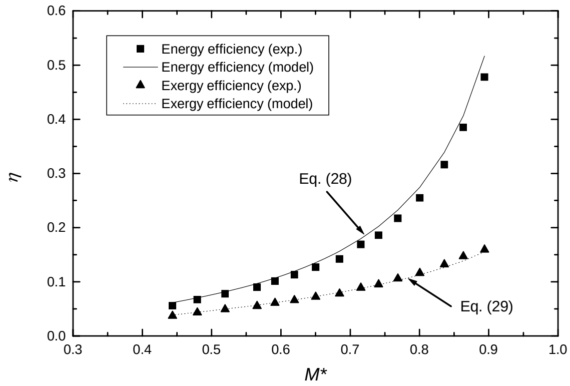

Fig. 11. The effect of non-dimensional moisture on energy and exergy efficiency

Furthermore, both the efficiencies decrease exponentially as the surface moisture evaporates until the end of the drying process. This can be explained by the fact that the surface moisture evaporates very quickly due to high heat and mass transfer coefficients in fluidized bed systems. The drying rate is very high at the initial stage of the drying process, but it decreases exponentially, leading to the transient moisture transfer, when all the surface moisture evaporates.

We now compare both energy and exergy efficiency and analyzed their trends. Therefore, both energy and exergy efficiency are compared in Figures. 10 and 11. It can be seen that the energy efficiency is found to be higher than the exergy efficiency. As mentioned before, exergy is not subject to a conservation law; exergy is consumed or destroyed due to irreversibility in drying process [14].

Fourier number (Eq. 26) as a non-dimensional drying time is used for investigating the effect of initial moisture on exergy efficiency. The test conditions is wheat at initial moisture vary of 0.307 and 0.409 d.b. Fig. 12 shows the effect of initial moisture content of particle on Fourier number versus efficiency. The figure shows that although the initial moisture content is different, the figure does not show any significant difference in drying time between two curves. Exergy efficiencies show higher values for particles with high initial moisture content which is mostly due to the time lag of drying rate. Increasing the moisture content causes a time lag in the maximum drying rate in the initial stage of drying [3]. Furthermore, the exergy used for evaporation is higher for wheat material with higher moisture content.

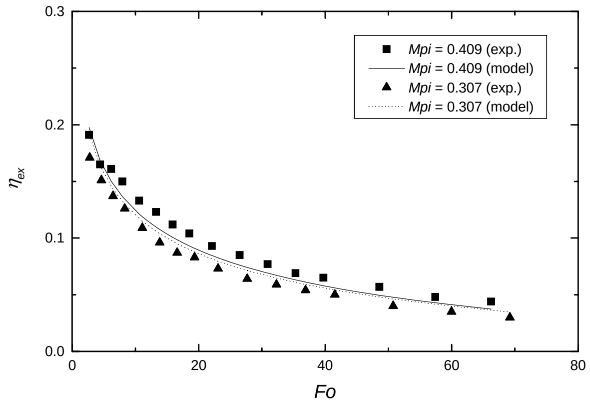

Fig. 12. The effect of initial moisture content of particle on Fourier number versus efficiency

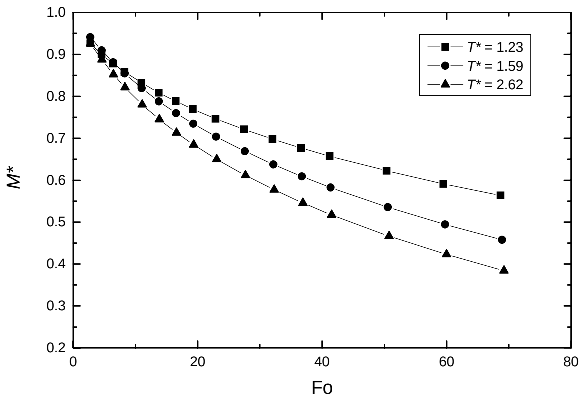

Fig. 13. The effect of non-dimensional temperature on Fourier number vs. non-dimensional moisture content

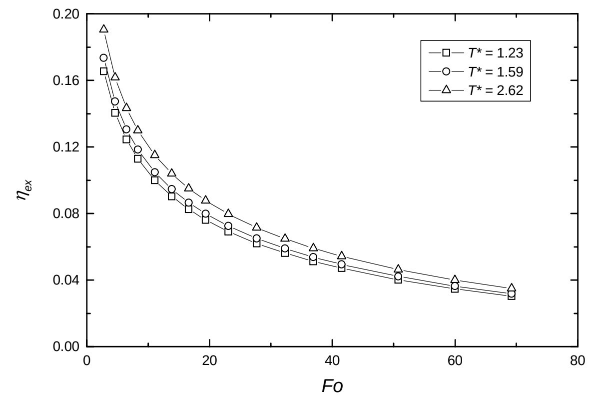

Fig. 14. The effect of non-dimensional temperature on Fourier number versus efficiency

Fig. 13 shows the effect of non-dimensional temperature on Fourier number versus non-dimensional moisture content. It can be seen that the temperature of drying air significantly influences the drying time of material. Increasing the temperature effectively reduces the moisture content of particles for the same Fourier number. The temperature of drying air significantly influences the shape of drying curve. It is a clear difference was observed between the drying rate curves at different temperatures. These differences at the initial stage of drying are higher than at the final stage [10].

The effect of non-dimensional temperature on Fourier number versus efficiency can be seen in Fig. 14. The temperature of inlet air (drying medium) influences the exergy efficiencies, though they are not linear. For the increase about 15 ^{o}C in the inlet air temperature from 40 ^{o}C to 54 ^{o}C or from 1.23 to 2.62 in non-dimensional temperature the increasing of exergy efficiency is about 0.03 (3 %) in the first stage of drying process but at the final stage of drying process the difference inlet air temperature do not show significance difference in drying efficiency. This can be explained by the fact that as the moisture content of material is reduced, the inlet drying air should be reduced. Increasing the inlet air temperature, the enthalpy and the entropy of drying air also increase leading to higher exergy efficiency.

The other important consideration in this regards is the ambient air temperature. Thus, higher inlet temperatures of drying air can be used which lead to shorter drying times. However, increasing inlet air temperature should be limited to obtain good quality dried material and consideration of drying process efficiency. It was experimentally observed that as the inlet air temperature increased the grain temperature also increases. The final temperature of the material after long time spans becomes almost equal to the temperature of inlet drying air [3]. Furthermore, since the inlet air temperature is constant by the time of drying process, in order to use the energy more effectively we can reduce the air temperature regularly until the end of drying process.

The obtained results in Fig. 15 show the effect of Reynolds number on non-dimensional moisture, for a reduction of about 15 % in the air velocity, the non-dimensional moisture content increase slightly at the same drying time. As reported by Hajidavalloo [3], the critical moisture content of wheat is between 69 % and 85 % dry basis based on temperature range of 10 ^{o}C to 90 ^{o}C, respectively. In his work the moisture content of wheat particles was below the critical moisture content. He found that, the changes in the drying properties were hardly distinguishable. This result is expected since the initial moisture content of the particle is below the critical moisture content. The drying process occurs at the falling rate period.

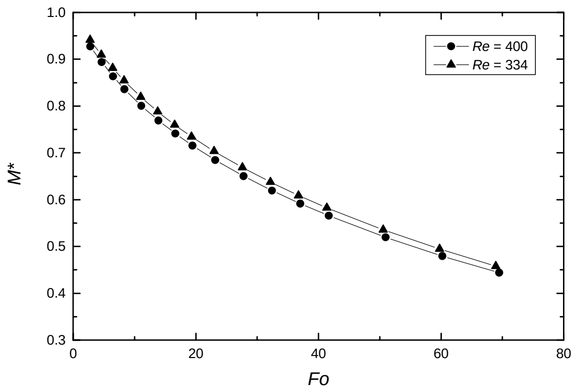

Fig. 15. The effect of Reynolds number on non-dimensional moisture with Fourier number

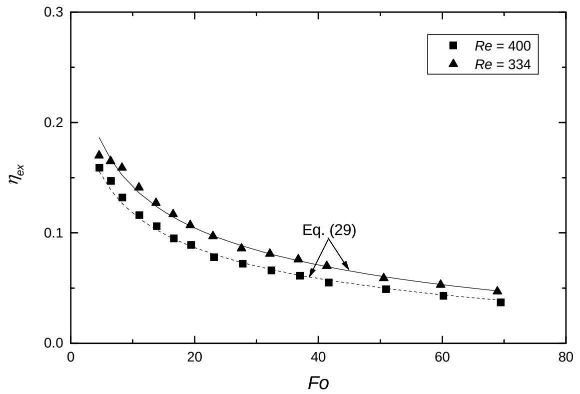

Fig. 16. The effect of Reynolds number on exergy efficiency as a function of Fourier number

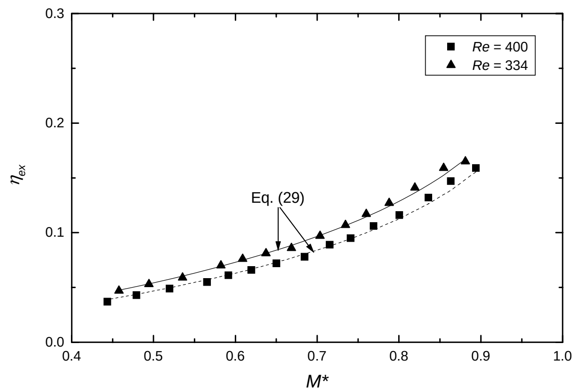

Fig. 17. The effect of Reynolds number on exergy efficiency as a function of non-dimensional moisture content of the particle

The effect of Reynolds number as a function of Fourier number and non-dimensional moisture content of the particle can be seen in Figs. 16 and 17, respectively. It can be seen that the efficiency increase is about 2% at the same Fourier number and the efficiency increase about 1% at the same normalized moisture. Thus, it would be advantageous to use a gas velocity as low as possible. However there is a practical restriction due to the onset of fluidization. It would be advantageous to use an air velocity higher than the minimum fluidization velocity at the first drying stage, and reduce it later to the required value.

5. CONCLUSIONS

The effect of some parameters on the direct contact heat and mass transfer characteristic of air bubbles in touch with the wet material has been studied by developing energy and exergy model of fluidized bed drying process. The non-dimensional correlation equations of the heat and mass transfer between air bubbles and the wet material were derived in terms of Fourier number and Reynolds number. Experimental drying data for wheat and corn were used to verify the applicability of the models. Furthermore, the following conclusions were obtained.

Energy and exergy efficiencies decrease sharply with decreasing moisture content of the material, it was seen that the heat and mass had been transferred from the drying air to the moisture for a very short time at the beginning of the drying process.

Increasing drying air temperature will increase exergy efficiencies of the drying process but there is practical limitation due to the damage of the material furthermore, the efficiency is slightly higher for the grain material with higher initial moisture content

With regard to the heat and mass transfer between air bubble and the wet material, it was clarified that reducing the Reynolds number will increase the efficiency of the drying process.

The results presented for non-dimensional correlations to estimate energy end exergy efficiency of fluidized bed drying process of wheat and corn are very useful sources for practical drying applications.

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