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International Journal of Thermal Sciences 42 (2003) 691–701
International Journal of Thermal Sciences
www.elsevier.com/locate/ijts

Thermodynamic modeling of fluidized bed drying of moist particles

S. Syahrul [a], I. Dincer [b,*], F. Hamdullahpur [c]

[a] *Mechanical Engineering Department, Mataram University, Mataram, NTB 83125, Indonesia*
[b] *Mechanical Engineering Department, KFUPM, Dhahran 31261, Saudi Arabia*
[c] *Mechanical and Aerospace Engineering Department, Carleton University, Ottawa, ON K1S 5B6, Canada*

Received 14 February 2002; accepted 3 September 2002

Abstract

A thermodynamic analysis of the fluidized bed drying process of large particles is performed to optimize the input and output conditions. Energy and exergy models were used for the study. The effects of the hydrodynamic and thermodynamic conditions such as the inlet air temperature, the fluidization velocity and the initial moisture content on the energy efficiency and the exergy efficiency were analyzed. The analysis was carried out using two different materials, wheat and corn. It was observed that the thermodynamic efficiency of the fluidized bed dryer was the lowest at the end of the drying process in conjunction with the moisture removal rate. The inlet air temperature has a strong effect on thermodynamic efficiency for wheat, but for corn, where the diffusion coefficient depends on the temperature and the moisture content of particles, an increase in the drying air temperature did not result in an increase of the efficiency. Furthermore, the energy and exergy efficiencies showed higher values for particles with high initial moisture content while the effect of gas velocity varied depending on the particles. A good agreement was achieved between the model predictions and the available experimental results.

Keywords: Drying; Exergy analysis; Fluidized bed; Thermodynamic efficiency

1. Introduction

Drying can be regarded as one of the most important and most frequently applied unit operation in all sectors producing solid products. The term drying generally refers to the removal of moisture or liquid from a wet solid by bringing this moisture into a gaseous state. In most drying operations, water is the liquid evaporated and air is the normally employed drying gas. Gas-solid fluidization is a process of contact between the two phases. The solid phase, under fluidization conditions, assumes a "fluid like" state. In *fluidized bed drying* the process is carried out in a bed fluidized by the drying medium.

In order to achieve the optimum performance of a dryer, it is important that the operational conditions and the material to be dried are correctly specified. The operation conditions will naturally influence the quality of the dried product. Operation conditions include gas velocity, inlet gas temperature, outlet gas temperature, feed temperature, start-up and shutdown.

Significant amounts of energy are used in removing water from the intermediate or final products in a wide range of industries, and thermal drying is often one of the final stages in a process. The energy used in drying materials is significant and therefore represents an often reducible element of process cost. It is possible to identify the operation conditions in which potential savings can be made using an exergy analysis. For example, in the drying industry, the goal is to use a minimum amount of energy for maximum moisture removal for the desired final conditions of the product.

From the thermodynamics point of view, exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal, or reversible, processes). Rather exergy is consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to

* Corresponding author.
E-mail addresses: syahrul_syahrul@yahoo.com (S. Syahrul), idincer@kfupm.edu.sa (I. Dincer), FeridunHamdullahpur@pigeon.carleton.ca (F. Hamdullahpur).

1290-0729/03/$ – see front matter
doi:10.1016/S1290-0729(03)00035-8

Nomenclature

A	bed cross-sectional area	m^2
c_p	specific heat of air	$kJ\cdot kg^{-1}\cdot K^{-1}$
c_m	specific heat of material	$kJ\cdot kg^{-1}\cdot K^{-1}$
D	moisture diffusivity	$m^2\cdot s^{-1}$
D_v	diffusivity of vapor	$m^2\cdot s^{-1}$
E	total exergy	kJ
$\dot{E}$	time rate of exergy transfer	$kJ\cdot s^{-1}$
e	specific exergy	$kJ\cdot kg^{-1}$
g	gravitational acceleration	$m\cdot s^{-2}$
h	specific enthalpy	$kJ\cdot kg^{-1}$
h_{fg}	latent heat of vaporization	$kJ\cdot kg_{water}^{-1}$
M_f	final moisture content of particle, dry basis	$kg_{water}\cdot kg_{solid}^{-1}$
M_p	moisture content of particle, dry basis	$kg_{water}\cdot kg_{solid}^{-1}$
M_{pi}	initial moisture content of particle, dry basis	$kg_{water}\cdot kg_{solid}^{-1}$
$\dot{m}$	mass flow rate	$kg\cdot s^{-1}$
$\dot{m}_w$	mass flow rates of water from surface of a particle	$kg_{water}\cdot s^{-1}$
P	pressure	Pa
P_v	vapor pressure of air	Pa
PE	potential energy	kJ
$\dot{Q}$	heat transfer rate	kW
$\dot{Q}_{evap.}$	heat transfer rate due to water evaporation	kW
R	gas constant	$J\cdot kg^{-1}\cdot K^{-1}$
RH	relative humidity	%
S	total entropy	$kW\cdot K^{-1}$
s	specific entropy	$kJ\cdot kg^{-1}\cdot K^{-1}$
S_{gen}	entropy generation	$kW\cdot K^{-1}$
T	temperature	K
T_o	ambient air temperature	K
T_m	material temperature	K
T_{pf}	final particle temperature	K
T_{pi}	initial particle temperature	K
t	time	s or min
u	superficial gas velocity	$m\cdot s^{-1}$
u_{mf}	superficial gas velocity at minimum fluidization conditions	$m\cdot s^{-1}$
W	work	kJ
$\dot{W}$	work rate	kW
W_d	weight of dry material	kg
W_b	bulk weight of grain before drying	kg
X	absolute humidity or humidity ratio	$kg_{water\ vapor}\cdot kg_{dry\ air}^{-1}$

Greek symbols

α	thermal diffusivity	$m^2\cdot s^{-1}$
η_{th}	thermal efficiency	
η_e	energy efficiency	
η_E	exergy efficiency	
ρ_a	air density	$kg\cdot m^{-3}$
ρ_g	gas density	$kg\cdot m^{-3}$
ρ_p	dry particle density	$kg\cdot m^{-3}$
v	specific volume	$m^3\cdot kg^{-1}$

Subscripts

o	standard state value
1	inlet
2	outlet
a	air
b	bed
cv	control volume
d	dry material
da	drying air
D	destruction
e	outlet stream
F	fuel
g	gas
i	inlet stream
j	stream of matter
L	loss
m	material
mf	minimum fluidization
P	product
p	particle
tot	total
v	vapor
w	water
wa	wet air

the entropy created due to irreversibilities associated with the process. Summaries of the evolution of exergy analysis through the late 1980s are provided by Kotas [1], Szargut et al. [2], Moran and Sciubba [3], Bejan et al. [4], Rosen [5], and Dincer [6]. A review of literature reveals that the exergy analysis method overcomes the limitation of the first law of thermodynamics and it is based on the first and second laws of thermodynamics. The use of exergy principles enhances understanding of thermal and chemical processes and allows sources of inefficiency to be quantified. Lower exergy efficiency leads in general to higher environmental impact [7]. Considering the importance of the cost of energy, the availability of fuel and an impact on the environment, the efficiency of energy availability (exergy) in the drying process becomes a very useful tool of analysis.

The objective of this study is to conduct an energy and exergy analysis as a thermodynamic consideration to better understand and to compare the influence of thermodynamic and hydrodynamic parameters on the process effectiveness; to develop a thermodynamic modeling of a fluidized bed dryer; and to determine the most effective ways of improving the drying process.

2. Fluidized bed drying aspects

Krokida and Kiranoudis [8] stated that industrial fluidized bed dryers are the most popular family of dryers for drying agricultural and chemical products in dispersion or multi-dispersion state. Gas-solid fluidization is a process of contact between the two phases. The solid phase, under fluidization conditions, assumes a “fluid like” state. Fluidizing with hot air is an attractive means for drying many moist powder and granular products. The first commercial unit was installed in the USA in 1948 [9] to dry dolomite rock.

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. During the past two decades various experimental and theoretical works have been undertaken by several investigators, e.g., [8,10–13] to study particularly heat, mass and fluid flow aspects of fluidized bed drying.

2.1. The hydrodynamics of fluidized beds

The fluidization gas velocity dominates the behavior of fluidized beds. DiMattia et al. [14] investigated the effect of fluidization velocity on the slugging behavior of large particles (i.e., red spring wheat, long grain rice, and whole peas). It was found that it is not necessary to operate the bed at a high fluidization velocity. Fluidized bed drying retains high efficiencies at low fluidization velocity, drying times are shortened, thus requiring less energy.

The excessive amount of moisture content of particles may affect the behavior of particles during the fluidization process. The effect of particle moisture content and relative humidity of fluidizing gas on the fluidization behavior of two different types of bed material (sand and wheat) were investigated by Hajidavalloo and Hamdullahpur [15].

The general correlation for minimum fluidization velocity, u_{mf}, is given by Kunii and Levenspiel [16]:

$$\frac{1.75}{\varepsilon_{\mathrm{mf}}^3\phi_s} Re_{\mathrm{mf}}^2 + \frac{150(1-\varepsilon_{\mathrm{mf}})}{\varepsilon_{\mathrm{mf}}^3\phi_s^2} Re_{\mathrm{mf}} = Ar \qquad (1)$$

where Re is the Reynolds number and Ar is the Archimedes number defined as:

$$Re_{\mathrm{mf}} = \frac{d_p u_{\mathrm{mf}} \rho_{\mathrm{g}}}{\mu_{\mathrm{g}}} \qquad (2)$$

$$Ar = \frac{d_{\mathrm{p}}^3 \rho_{\mathrm{g}}(\rho_{\mathrm{p}} - \rho_{\mathrm{g}}) g}{\mu_{\mathrm{g}}^2} \qquad (3)$$

Note that the minimum fluidization velocity depends on the moisture content of particles, and increasing the moisture content increases the minimum fluidization velocity.

For wet particle fluidization, the bed pressure drop after the minimum fluidization point is not constant but gradually increases with increasing gas velocity [15]. In the beginning of fluidization, not all particles are fluidized because of the adhesive forces in the bed. Usually, the top layers of the bed start fluidizing when the bottom layers are still stationary. Thus the bed pressure drop is slightly less than the pressure dropping equivalent to the weight of bed material.

Increasing the gas velocity further, the drag force exerted on the particle increases, which can then break apart more contact points between particles, thus bringing them to the fluidized state. Consequently, the pressure drop increases with increasing the gas velocity, as more particles require to be suspended. At a certain velocity, all particles will eventually be suspended and full fluidization will take place. At this point the pressure drop would be higher than the weight of bed pressure drop because of the effect of the adhesive force. Further increase in the gas velocity may not necessarily cause the pressure drop to increase linearly.

2.2. Material properties

The thermophysical properties (e.g., specific heat) of the particles to be dried in the fluidized bed are dependent strongly upon the moisture content of the particles. In this regard, there many correlations developed for different particles are available in the literature.

In this study the same materials used in the experimental study of Hajidavalloo and Hamdullahpur [15] were selected to provide a basis for comparison and to validate the present model. 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 $\mathrm{kg \cdot m^{-3}}$. The specific heat of wheat is given by Kazarian and Hall [17] as

$$c_{\mathrm{m}} = 1398.3 + 4090.2\left(\frac{M_{\mathrm{p}}}{1+M_{\mathrm{p}}}\right) \qquad (4)$$

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 $\mathrm{kg \cdot m^{-3}}$. The specific heat of corn is given as [17]:

$$c_{\mathrm{m}} = 1465.0 + 3560.0\left(\frac{M_{\mathrm{p}}}{1+M_{\mathrm{p}}}\right) \qquad (5)$$

All moisture content data used in the present analysis are on a dry basis. The normalized moisture content (M_{n}) is then calculated by dividing the moisture content of material at any time by its initial moisture content.

$$M_{\mathrm{n}} = \frac{M_{\mathrm{p}}}{M_{\mathrm{i}}} \qquad (6)$$

3. Thermodynamic modeling

A comprehensive thermodynamic model applied to the fluidized bed dryer system is developed in order to compare

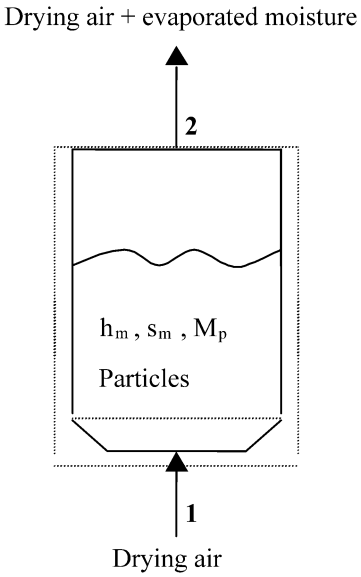

Fig. 1. Schematic of batch fluidization.

and analyze the effect of air temperature entering the dryer column, fluidization velocity of drying air and initial moisture content of the material on energy and exergy efficiencies. The fluidized bed drying system is divided into three essential subsystems; the blower, the heater and the drying column. In this section, the exergy 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 is isobaric while simultaneous energy and mass transfer between gas and solid takes place. As can be seen from Fig. 1, the control volume is defined by the dashed line, the thermodynamic state of the particle is described by enthalpy h_m, entropy s_m, and moisture content M_p.

3.1. Mass balance for the drying column

The control volume system of the drying column is shown in Fig. 1, and the following mass balance equation can then be written for a single inlet and exit:

$$\frac{dm_{cv}}{dt} = \dot{m}_{g1} - \dot{m}_{g2} \tag{7}$$

Here, Eq. (7) is the mass rate balance for the control volume where $\dot{m}_{g1}$ and $\dot{m}_{g2}$ denote, respectively, the rate of mass that enters at inlet (1) and exit at (2). Similarly, a balance of water in air flowing through the dryer column leads to:

$$W_d \frac{dM_p}{dt} = \dot{m}_a (X_1 - X_2) \tag{8}$$

where W_d is 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, respectively, absolute humidities of inlet and exit air. The left-hand side of the mass balance equation, Eq. (8), is the mass flow rate of water $\dot{m}_w$ in the air flowing out of the bed. Eq. (8) can be written as:

$$\dot{m}_w = \dot{m}_a (X_2 - X_1) \tag{9}$$

3.2. Energy balance for the drying column

For the drying processes, we apply the First Law of Thermodynamics (the law of conservation of energy) for the control volume shown in Fig. 1. The significant heat transfer is due to the heat of evaporation between the solid and the drying air, and there is also heat rejection to the surroundings. The energy rate balance is simplified by ignoring kinetic and potential energies. 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:

$$\frac{W_d (h_{m2} - h_{m1})}{\Delta t} = \dot{Q}_{evap} + \dot{m}_a (h_1 - h_2) - \dot{Q}_{loss} \tag{10}$$

The differences in specific enthalpy are given by:

$$h_{m1} - h_o = c_m (T_{m1} - T_o) \tag{11}$$

$$h_{m2} - h_o = c_m (T_{m2} - T_o) \tag{12}$$

The energy balance equation for the material can be expressed as:

$$h_{m2} - h_{m1} = c_m (T_{m2} - T_{m1}) \tag{13}$$

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:

$$h = h_a + X h_v \tag{14}$$

3.3. Entropy balance for the drying column

Mass and energy are conserved quantities while entropy is not. The entropy rate balance for the control volume shown in Fig. 1 is expressed:

$$\frac{W_d (s_{m2} - s_{m1})}{\Delta t} = \frac{\dot{Q}_{evap}}{T_m} + \dot{m}_a (s_1 - s_2) - \frac{\dot{Q}_{loss}}{T_b} + \dot{S}_{gen} \tag{15}$$

The specific entropies of the material are given by:

$$s_{m1} - s_o = c_m \ln(T_{m1}/T_o) \tag{16}$$

$$s_{m2} - s_o = c_m \ln(T_{m2}/T_o) \tag{17}$$

The entropy balance equation for the material can be expressed as:

$$s_{m2} - s_{m1} = c_m \ln(T_{m2}/T_{m1}) \tag{18}$$

To evaluate the entropy of moist air, the contribution of each component in the mixture is determined at the mixture temperature and the partial pressure of the component:

$$s_{wa} = s_a - R_a \ln \frac{p_a}{p_0} + X \left(s_v - R_v \ln \frac{p_v}{p_0} \right) \tag{19}$$

3.4. Exergy balance for the drying column

Combining the energy and entropy balance equations one defines the exergy balance for the drying column. Multiplying the entropy balance by T_o and subtracting the resulting expression from the energy balance gives:

$$\frac{W_d(E_{m2}-E_{m1})}{\Delta t} = \dot{m}_a(h_1-h_2) + \left(1-\frac{T_0}{T_m}\right)\dot{Q}_{evap} - \left(1-\frac{T_0}{T_b}\right)\dot{Q}_{loss} - T_0\dot{m}_a(s_1-s_2) - T_0\dot{S}_{gen} \quad (20)$$

or more simply:

$$\dot{E}_{m2}-\dot{E}_{m1} = \dot{E}_{da1}-\dot{E}_{da2}+\dot{E}_{evap}-\dot{E}_{loss}-\dot{E}_D \quad (21)$$

where $\dot{E}_m$ represents the exergy transfer rate of the material, $\dot{E}_{da}$ the exergy transfer rate of the drying air, $\dot{E}_{evap}$ the exergy evaporation rate of the dryer, $\dot{E}_{loss}$ the rate of exergy loss to the surrounding, $\dot{E}_D$ the rate of exergy destruction in the dryer column.

The specific inlet and outlet exergies of the material are given by:

$$e_{m1} = (h_{m1}-h_o) - T_o(s_{m1}-s_o) \quad (22)$$

$$e_{m2} = (h_{m2}-h_o) - T_o(s_{m2}-s_o) \quad (23)$$

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

$$e_{da1} = (h_1-h_o) - T_o(s_1-s_o) \quad (24)$$

$$e_{da2} = (h_2-h_o) - T_o(s_2-s_o) \quad (25)$$

where e_{da1} and e_{da2} are the specific exergy transfers at inlet and outlet, 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 fluidized bed column (T_{da1}), respectively; 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 heat transfer rate due to phase change is:

$$\dot{Q}_{evap.} = \dot{m}_w h_{fg} \quad (26)$$

where h_{fg} is latent heat of vaporization of water $kJ\cdot kg^{-1}$ at the average temperature of the wet material and at the atmospheric pressure, while the rate of exergy transfer due to evaporation of the dryer is:

$$\dot{E}_{evap} = \left[1-\frac{T_o}{T_m}\right]\dot{m}_w h_{fg} \quad (27)$$

3.5. Thermodynamic efficiency of fluidized bed drying

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

Energy efficiency of the dryer column based on the First Law of Thermodynamics can be derived by using the energy balance equation as Giner and Calvelo [18] did earlier. The thermal efficiency (so-called "energy efficiency") of the drying process can be defined as:

$$\eta_{th} = \frac{\text{Energy transmitted to the solid}}{\text{Energy incorporated in the drying air}} \quad (28)$$

Therefore, energy efficiency from energy balance equations becomes:

$$\eta_e = \frac{W_d[h_{fg}(M_{p1}-M_{p2}) + c_m(T_{m2}-T_{m1})]}{\dot{m}_{da}(h_1-h_0)\Delta t} \quad (29)$$

The exergy efficiency of the dryer column based on 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 a "product" and a "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. In conjunction with this, the exergy efficiency of the dryer is considered as the ratio between product and fuel as outlined earlier by Topic [19]. Where the product is only the rate of exergy evaporation process and the fuel is the rate of exergy drying air enter the dryer column, the exergy efficiency for the particle based on the exergy rate balance can be given as:

$$\eta_E = \frac{\dot{E}_{evap}}{\dot{E}_{da1}} \quad (30)$$

The following input parameters are selected to analyze the thermodynamic efficiencies of fluidized bed drying process:

- Temperature of drying air entering the dryer column, T_1;
- Relative humidity of drying air, RH_1;
- Velocity of drying air, u;
- Temperature of the material entering the dryer, T_{pi};
- Initial moisture content of the material, M_{pi};
- Weight of the material, W_b;
- Ambient temperature, T_a.

The following additional thermal parameters are obtained from Hajidavalloo and Hamdullahpur [15] and used as inputs in the model:

- Temperature of drying air leaving the dryer column, T_2;
- Relative humidity of drying air leaving the dryer, RH_2;

– Absolute humidity of drying air leaving the dryer, X_2;
– Moisture content of the material after drying process, M_{pf};
– Temperature of the material after drying process, T_{pf};
– Drying time, Δt.

The thermodynamic data are obtained from thermodynamic tables for both vapor and dry air:

– Enthalpy of dry air, h_a and enthalpy of water vapor, h_v entering the dryer column;
– Enthalpy of dry air, h_0 and enthalpy of water vapor, h_v at the ambient temperature;
– Enthalpy evaporation, h_{fg} at the material temperature, T_m;
– Entropy of dry air, s_a and entropy of water vapor, s_v entering the dryer;
– Entropy of dry air, s_0 and entropy of water vapor, s_{v0} at the ambient temperature.

Here, it is important to highlight the following points for clearer presentation before the discussion of the results:

- The solution methodology is not of differential form due to fact that in practice practitioners prefer simple, accurate methods or models for system analysis and design over the complicated and complex solution techniques. In this regard, a practical thermodynamic analysis is presented based on mass, energy, entropy and exergy balance equations, and is validated with the experimental data available from [15].
- The thermodynamic modelling is undertaken from a macroscopic point of view, dealing with the mass, energy, entropy and exergy aspects of the system.
- The spatial variation of the physical and thermophysical quantities is considered negligible to provide simpler solution methodology. This is in fact consistent with the results of an earlier work [15], studying the changes in heat and mass transfer parameters and physical quantities.
- The quantities T_0, h_0 and s_0 represent the thermodynamic properties of dead state or reference environment which are the ambient external conditions.

4. Results and discussion

In this section, the effects of the inlet air temperature, the fluidization velocity and the initial moisture content on thermodynamic efficiency are analyzed using the model developed. The experimental data of Hajidavalloo and Hamdullahpur [15] are used as the input parameters here in the model, particularly for model verification and comparison. In the experimental investigation he studied various parameters, by changing one variable and keeping the other variables almost constant in order to compare and analyze the effect of the variables listed on the drying rate for wheat and corn material. Different types of data were collected during each drying experiment for the wheat and corn particles. These are the temperature and relative humidity of drying air and moisture content of material in the bed at different times.

In this work the analysis was done for two different materials, namely wheat and corn. As reported by Syahrul et al. [20], 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 nature of their moisture diffusivity is very different. The moisture diffusion coefficient of wheat is dependent only on temperature [9]; but for corn, it is a function of both the temperature and the moisture content of particles [21]. The other difference is in the size of materials. The corn grains are usually many times bigger than the wheat grains. These differences may cause a different pattern of drying as well as thermodynamic efficiency of the fluidized bed drying of these particles.

4.1. Results for wheat material

The conditions of inlet air and the material for each drying test are given in Tables 1–3. Figs. 2–8 show the results obtained from the model for the wheat material. They show the effects of the inlet drying air temperature, the fluidization velocity and the initial moisture content, which are discussed in more detail in subsequent sections. It was observed that, as a general trend, the energy efficiency was found to be higher than the exergy efficiency. Furthermore, at the beginning of the drying process, the energy and the exergy efficiencies were observed to be higher than at the final stage. The exergy of evaporation increases at the initial stage due to rapid evaporation of surface moisture. But it decreases exponentially as the surface moisture evaporates until the end of the drying process.

Both the energy and exergy efficiencies for the drying of wheat particles were found to be very low at the end of drying process (i.e., less than 10% for the energy efficiency and about 5% for the exergy efficiency). 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. This is due to fact that the drying rate is very high at the initial stage of the drying process, but it decreases exponentially when all the surface moisture evaporates and the drying front diffuses inside the material.

In order to compare and analyze the different trends of energy efficiency and exergy efficiency, both energy efficiency and exergy efficiency are presented in the graph. Figs. 3 and 4 present the effect of inlet air temperature on energy efficiency and exergy efficiency versus drying time and normalized moisture content. It can be seen that the energy efficiency is found to be higher than the exergy efficiency. Furthermore, the temperature of inlet air (drying medium) influences the energy and exergy efficiencies, though they are not linear. For an increase of about 25 °C in

Table 1
Experimental conditions for investigating the effect of temperature

	T [°C]	M_{pi} [d.b]	W_b [kg]	RH [%]	U [m·s^{-1}]	T_a [°C]	T_{pi} [°C]
Run 8	40.2	0.326	2.5	21.1	1.95	22.0	7.0
Run 11	65.0	0.317	2.5	18.5	1.95	22.0	6.0

Table 2
Experimental conditions for investigating the effect of gas velocity

	T [°C]	M_{pi} [d.b]	W_b [kg]	RH [%]	U [m·s^{-1}]	T_a [°C]	T_{pi} [°C]
Run 6	49.5	0.300	2.5	13.5	1.95	18.0	6.0
Run 12	50.0	0.323	2.5	15.7	1.63	23.0	6.0

Table 3
Experimental conditions for investigating the effect of initial moisture content

	T [°C]	M_{pi} [d.b]	W_b [kg]	RH [%]	U [m·s^{-1}]	T_a [°C]	T_{pi} [°C]
Run 2	54.5	0.409	2.54	17.0	1.91	20.5	7.0
Run 4	54.0	0.307	2.48	14.7	1.93	20.0	7.0

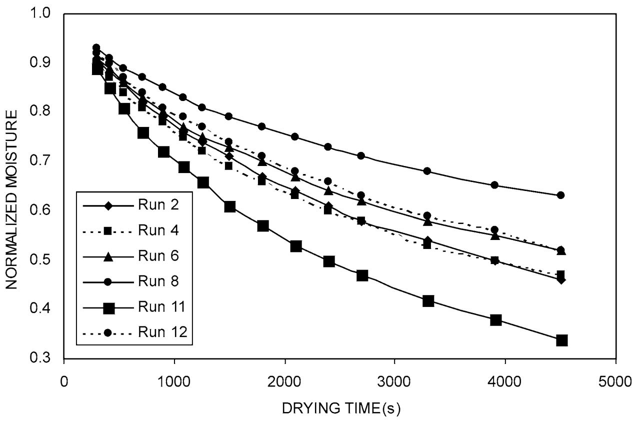

Fig. 2. Normalized experimental moisture content profiles of wheat versus drying time at different runs.

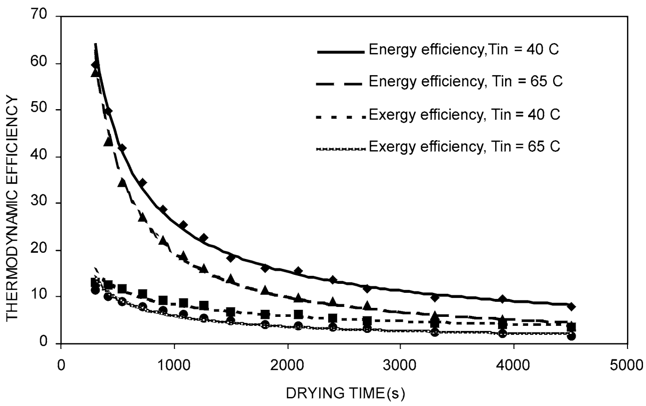

Fig. 3. Effect of inlet air temperature on the thermodynamic efficiencies versus drying time for wheat.

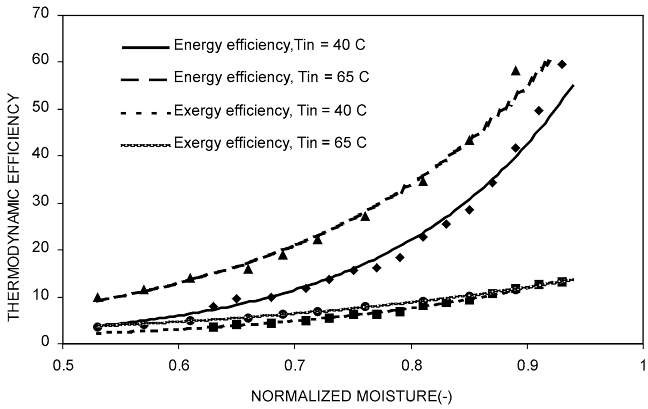

Fig. 4. Effect of inlet air temperature on the thermodynamic efficiencies versus normalized moisture for wheat.

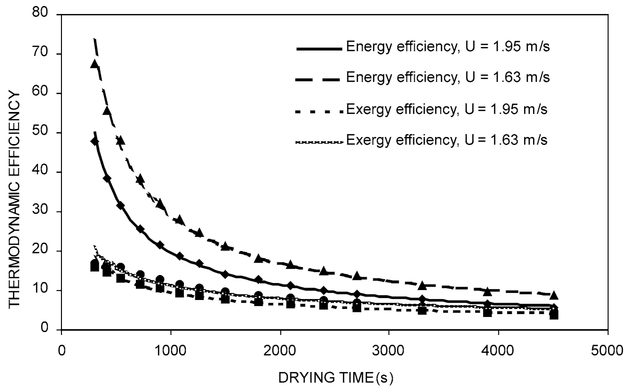

Fig. 5. Effect of gas velocity on the thermodynamic efficiencies versus drying time for wheat.

the inlet air temperature, the increasing of energy efficiency is about 7% and for exergy efficiency is only about 1%. Thus, higher inlet temperatures of drying air can be used which lead to the shorter drying times. The enthalpy and the entropy of drying air also increase leading to higher energy and exergy efficiencies, although the increase of the inlet air temperature is limited due to considerable damage of the material. The final temperature of the material after long

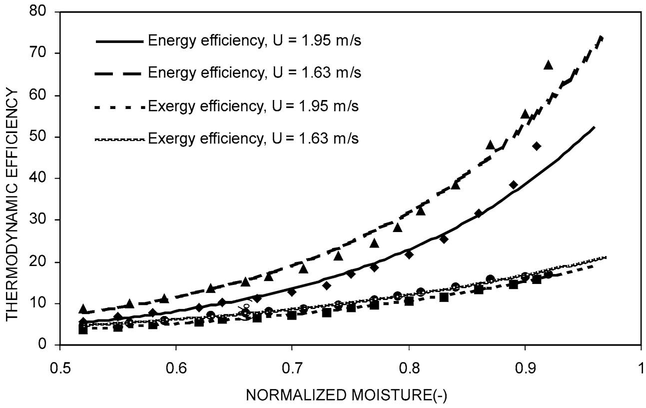

Fig. 6. Effect of gas velocity on the thermodynamic efficiencies versus normalized moisture for wheat.

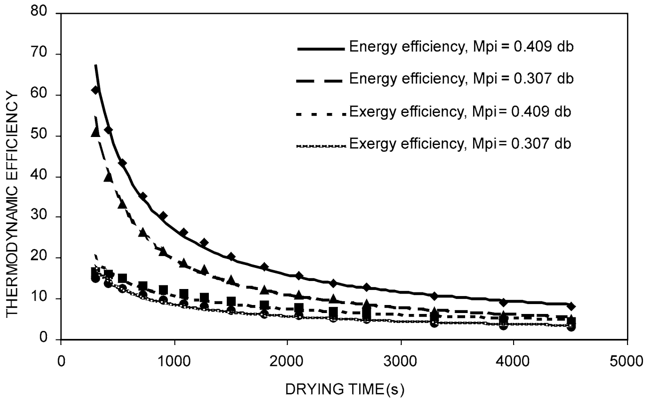

Fig. 7. Effect of initial moisture content on the thermodynamic efficiencies versus drying time for wheat.

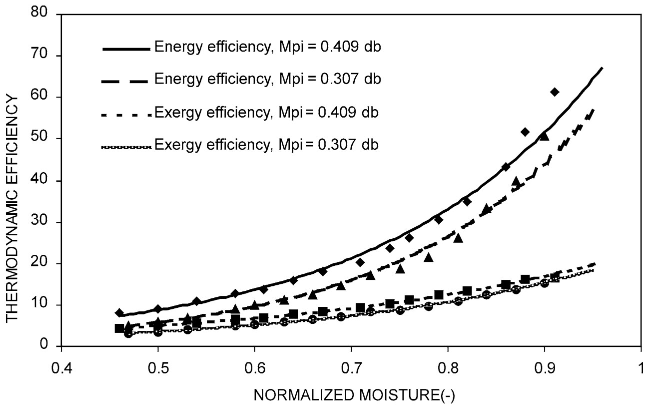

Fig. 8. Effect of initial moisture content on the thermodynamic efficiencies versus normalized moisture for wheat.

time spans becomes almost equal to the temperature of inlet drying air.

Figs. 5 and 6 present the effect of gas velocity on efficiency of dryer versus drying time and normalized moisture content of particle, respectively. It was observed that for a reduction about 15% in the air velocity, the drying time was almost the same. For this investigation, the changes in the drying properties were hardly distinguishable as agreed with an earlier work [15]. The drying process occurs at the falling rate period. The drying rate is governed by the rate of internal moisture movement, and the influence of external variables diminishes, as clearly defined by Perry [22].

Figs. 5 and 6 show that for a reduction of about 15% in the air velocity, the energy efficiency increases of about 3%, and exergy efficiency increases of about 1%. The reason for the narrow difference in velocities between the two test conditions is related to the fluidization problem. Since wet particle fluidization needs higher gas velocity, it is not possible to reduce the velocity very much. By using the equation based on the experimental data (by [15]), it was observed that the minimum fluidization for this investigation is $1.22\ \mathrm{m \cdot s^{-1}}$. It would be advantageous to use the air velocity higher than the minimum fluidization velocity at the first drying stage and to reduce it later to the specification value.

Figs. 7 and 8 present the effect of initial moisture content on efficiencies versus drying time and normalized moisture. Energy and exergy efficiencies show higher values for particles with high initial moisture content that 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 [15]. Furthermore, the exergy used to evaporate is higher for wheat material with higher moisture content. However, there are practical restrictions due to the fluidization of the bed. The amount of wet material must be fluidizable in this process.

4.2. *Results for corn material*

The second type of material used was corn; the size of the corn kernels is usually 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 thermodynamic efficiencies of the fluidized bed dryer column.

The test conditions are listed in Tables 4–6. The input and output data of the model are shown in Figs. 9–15 for the corn material. 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 and exergy efficiencies 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 in subsequent sections.

Figs. 10 and 11 show the effect of inlet air temperature on thermodynamic efficiencies. Curves are provided for different inlet air temperatures within the range 50 °C and

Table 4
Experimental conditions for investigating the effect of temperature

	T [°C]	M_{pi} [d.b]	W_b [kg]	RH [%]	U [m·s^{-1}]	T_a [°C]	T_{pi} [°C]
Run C1	50.0	0.256	2.5	15.2	2.22	17.0	7.0
Run C3	63.0	0.246	2.5	17.5	2.24	17.5	7.0

Table 5
Experimental conditions for investigating the effect of velocity

	T [°C]	M_{pi} [d.b]	W_b [kg]	RH [%]	U [m·s^{-1}]	T_a [°C]	T_{pi} [°C]
Run C1	50.0	0.256	2.5	15.2	2.22	17.0	7.0
Run C4	50.0	0.257	2.5	17.5	1.88	17.6	7.0

Table 6
Experimental conditions for investigating the effect of initial moisture content

	T [°C]	M_{pi} [d.b]	W_b [kg]	RH [%]	U [m·s^{-1}]	T_a [°C]	T_{pi} [°C]
Run C1	50.0	0.256	2.5	15.2	2.22	17.0	7.0
Run C5	50.0	0.324	2.5	17.0	2.21	18.2	6.0

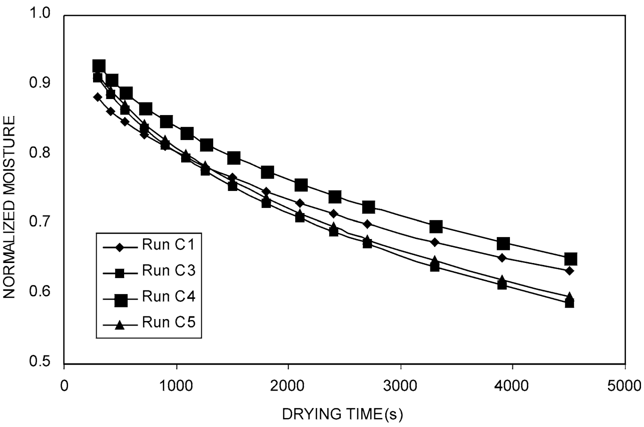

Fig. 9. Normalized experimental moisture content profiles of corn versus drying time at different runs.

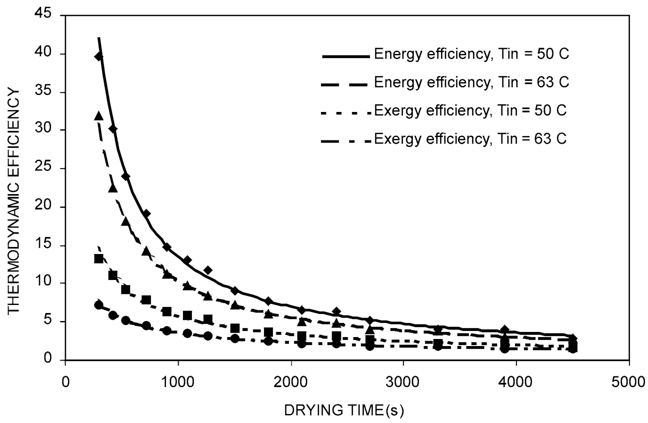

Fig. 10. Effect of inlet air temperature on the thermodynamic efficiencies versus drying time for corn.

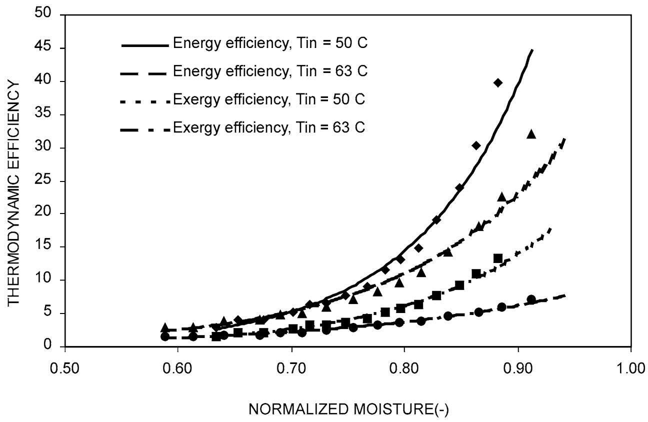

Fig. 11. Effect of inlet air temperature on the thermodynamic efficiencies versus normalized moisture for corn.

63 °C. It can be seen that energy and exergy efficiencies do not show any significant difference at the end of drying process. Since the initial moisture content of the material is below the critical moisture content, the effect of external variables may not be important. The drying rate is now governed by the rate of internal moisture movement. Unlike wheat material, the moisture diffusion coefficient of corn is a function of temperature and moisture content. The increase of temperature does not increase the efficiency automatically for corn material in the falling rate period.

The effect of gas velocity on efficiency in term of drying time and normalized moisture can be seen in Figs. 12 and 13. Both energy and exergy efficiencies do not show any significant difference at the final stage of the process, but the difference between the two curves is at the initial stage of the drying, when the surface moisture content is removed from the grains. Thus, it would be advantageous to use a gas velocity as low as possible. However, there is practical restriction due to the onset of fluidization. By using Hajidavalloo's model for investigating the minimum fluidization velocity, it was found in this experiment that the onset of fluidization velocity was 1.16 m·s^{-1}. DiMattia et al. [14] found

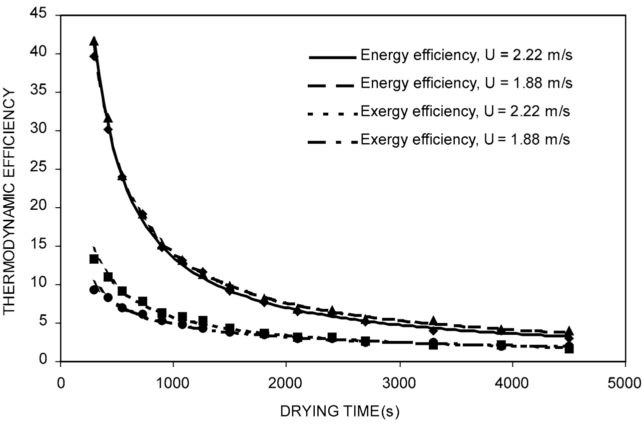

Fig. 12. Effect of gas velocity on the thermodynamic efficiencies versus drying time for corn.

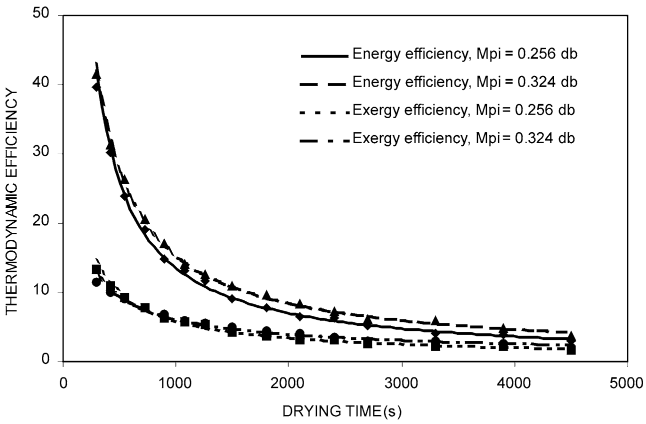

Fig. 14. Effect of initial moisture content on the thermodynamic efficiencies versus drying time for corn.

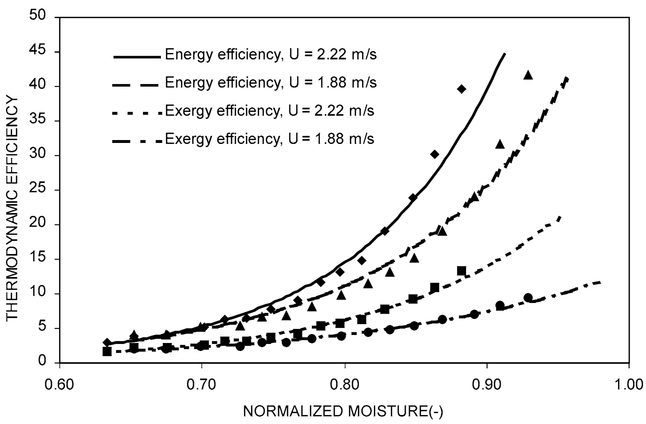

Fig. 13. Effect of gas velocity on the thermodynamic efficiencies versus normalized moisture for corn.

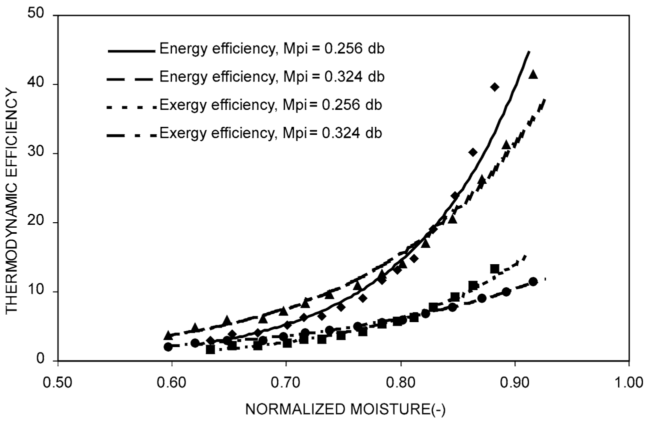

Fig. 15. Effect of initial moisture content on the thermodynamic efficiencies versus normalized moisture for corn.

that fluidized bed dryers reach their very high efficiency at low fluidization velocity.

Figs. 14 and 15 show the effect of initial moisture content on thermodynamic efficiencies versus drying time and normalized moisture. At the initial stage, the process does not show any difference between the two curves due to rapid evaporation, but as all of the surface moisture evaporates, both of them show efficiency increases as the initial moisture content of the materials increases. A clear difference is observed between the efficiency curves at the end of the drying process. As it was also indicated by Hajidavalloo and Hamdullahpur [15], the drying rate also shows a higher value for the corn, which has higher initial moisture content.

5. Conclusions

The study of the thermodynamic analysis of various aspects of the kinetics of fluidized bed drying moist particles, e.g., wheat and corn has been described and analyzed in this work. The main findings are summarized in the following and recommendations for future work are given.

- Thermodynamic efficiencies were obtained to be higher at the beginning of the process than at the final stage since the moisture removal rate from the particle is higher in the beginning.
- The inlet air temperature has an effect on the thermodynamic efficiency of the fluidized bed dryer system. This effect may vary for different particles depending on the physical properties of the materials. For wheat particles, where the diffusion coefficient is only a function of the temperature, the increase of the drying air temperature increases the efficiency though not in a linear way. For corn particles, where the diffusion coefficient depends on the temperature and the moisture content of particles, the increase of the drying air temperature does not increase the efficiency automatically.
- The effect of gas velocity on energy and exergy efficiencies may vary depending on the materials. For wheat particles, energy and exergy efficiencies increase for a reduction of about 15% in the air velocity. However, for corn particles, both energy and exergy efficiencies do not show any difference at the end of the drying process.
- The thermodynamic efficiencies show higher values for particles with high initial moisture content.

- The drying air temperature and velocity entering the dryer are constant by the drying time. The efficiency decreases accordingly.

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