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A new model for thermodynamic analysis of a drying process

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Abstract

In this paper we present a new model for thermodynamic analysis, in terms of exergy, of a drying process. Exergy efficiencies are derived as functions of heat and mass transfer parameters. An illustrative example is considered to verify the present model and to illustrate the applicability of the model to actual drying processes at different drying air temperatures, specific exergies of drying air, exergy differences of inlet and outlet products, product weights, moisture contents of drying air, and humidity ratios of drying air. As a result, this work is intended not only to demonstrate the usefulness of exergy analysis in thermodynamic assessments of drying processes, but also to provide insights into their performances and efficiencies. It is believed that the present model should be useful to people seeking (i) to optimize the design of drying systems and their components and (ii) to identify appropriate applications and optimal configurations for drying systems.

1. Introduction

Drying is widely used in a variety of thermal energy applications ranging from food drying to wood drying. Utilization of high amount of energy in the drying industry makes drying one of the most energy-intensive operations with a great industrial significance. The objective of the dryer is to supply the product with more heat than is available under ambient conditions thus sufficiently increasing the vapor pressure of the moisture held within the product to enhance moisture migration from within the product and significantly decreasing the relative humidity of the drying air to increase its moisture carrying capability and to ensure a sufficiently low equilibrium moisture content [1–3].

During the past few decades, thermodynamic analysis, particularly exergy analysis, has appeared to be an essential tool for system design, analysis and optimization of thermal systems. From a thermodynamic point of view, exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment [4,5]. Exergy is not subject to a conservation law, rather exergy is consumed or destroyed, due to irreversibilities in any process It is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment. For this reason, the state of the reference environment, or the reference state, must be specified completely. This is commonly done by specifying the temperature, pressure and chemical composition of the reference environment.

The exergy method can help further the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. Therefore, exergy analysis can reveal whether or not and by how much it is possible to design more efficient thermal systems by reducing the sources of existing inefficiencies. Increased efficiency can often contribute in a major way to achieving energy security in an environmentally acceptable way by the direct reduction of irreversibilities that might otherwise have

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Nomenclature

C_P	specific heat
e	specific exergy
$\dot{E}$	rate of exergy flow
h	specific enthalpy
$\dot{m}$	mass flow rate
P	pressure
P_v	vapor pressure
P_g	saturation pressure of water
$\dot{Q}$	rate of heat transfer
R	gas constant
s	specific entropy
T	temperature
v	specific volume
x_v	mole fraction of vapor
x_v^0	mole fraction of vapor in air at dead state

Greek symbols

η	efficiency
ω	humidity ratio of air
ω^0	humidity ratio of air at dead state
ϕ	percent relative humidity of air

Subscripts

0	dead state
a	air
av	average
d	destruction
ev	evaporation
ex	exergy
f	saturated liquid state
g	saturated vapor state
l	loss
p	product
q	heat transfer related
v	vapor
w	water

occurred. This makes exergy one of most powerful tools to provide optimum drying conditions. Exergy analysis becomes more crucial, especially for the industrial (large-scale) high-temperature drying applications.

During the past decade, many studies have been undertaken by several researchers e.g., [6–24] to investigate thermodynamic aspects of thermal systems and processes ranging from refrigeration to drying.

Of these, Sieniutycz and Kubiak [6], using irreversible thermodynamics, define and analyze dynamic limits for various traditional and work-assisted processes of sequential development with finite rates important in engineering. These dynamic limits are functions rather than numbers; they are expressed in terms of classical exergy change and a residual minimum of dissipated exergy, or some extensions including time penalty. They consider processes with heat and mass transfer that occur in a finite time and with equipment of finite dimension. Such processes include heat-mechanical and separation operations and are found in heat and mass exchangers, thermal networks, energy converters, energy recovery units, storage systems, chemical reactors, and chemical plants.

Demirel and Sandler [8] use linear-nonequilibrium thermodynamics to express the entropy generation and dissipation functions representing the true forces and flows for heat and mass transport in a multicomponent fluid. These forces and flows are introduced into the phenomenological equations to formulate the coupling phenomenon between heat and mass flows.

Miguel [9] presents a theoretical and experimental research in the field of mass transport through porous media and employs a thermodynamic model for the change of mass inside porous media and the fluid flow through porous media. An experimental study is carried out to provide a thermodynamic chart of a porous medium and to infer the parameters required by the theoretical approach. The effect of the moisture content and temperature on fluid transport properties is also investigated.

Topic [10] presents a mathematical model for exergy analysis of an industrial system for high-temperature forage drying. It allows qualitative analysis of the individual components as well as the entire system using a software package. It also presents, as an example, the application of the model and the software, for forage drying, the changes of exergy and the basic elements and system operation quality indicators depending on the significant parameters.

Syahrul et al. [11–14] conduct a thermodynamic analysis of the fluidized bed drying process of moist particles to optimize the input and output conditions. They use energy and exergy models and 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. The analysis is carried out for different materials. A good agreement is achieved between the model predictions and the experimental data.

The primary objective of this work is to develop a new thermodynamic model for exergy analysis of the drying process of moist solids and define exergy efficiency as a function of heat and mass transfer parameters. An illustrative example is presented to highlight the importance of the present model and show how it is important for the drying process analysis and optimization. To the best of the authors' knowledge, the present work is the first study incorporating heat and mass transfer parameters into the exergy model and exergy efficiency.

2. Modeling

Here, in this section, we introduce a new model for energy and exergy analysis of drying processes. The schematic presentation of the systems with input and output terms is shown in Fig. 1. As clearly seen in the figure, we have four major components to take into consideration as follows:

- Point 1. Referring to the input of drying air to the drying chamber to dry the products.
- Point 2. Referring to the input of moist products to be dried in the chamber.
- Point 3. Referring to the output of the moist air after taking the evaporated moisture from the products.
- Point 4. Referring to the output of the dried products. In fact, their moisture contents are reduced to a certain level required for each commodity of the product.

Here we now write the mass, energy, and exergy balance equations for the above system, as a control volume system, shown in Fig. 1 since writing the balance equations correctly is an essential way of solution to such systems.

2.1. Mass balance equations

In order to write the mass balance equations for the dryer shown in Fig. 1, we consider three components such as product itself, air and the water which exits in the drying air and product. Therefore, we write the mass balance equations for these three elements as follows:

$$\text{Product}: \ (\dot{m}_\text{p})_2 = (\dot{m}_\text{p})_4 = \dot{m}_\text{p}, \tag{1}$$

$$\text{Air}: \ (\dot{m}_\text{a})_1 = (\dot{m}_\text{a})_3 = \dot{m}_\text{a}, \tag{2}$$

$$\text{Water}: \ \omega_1 \dot{m}_\text{a} + (\dot{m}_\text{w})_2 = \omega_3 \dot{m}_\text{a} + (\dot{m}_\text{w})_4. \tag{3}$$

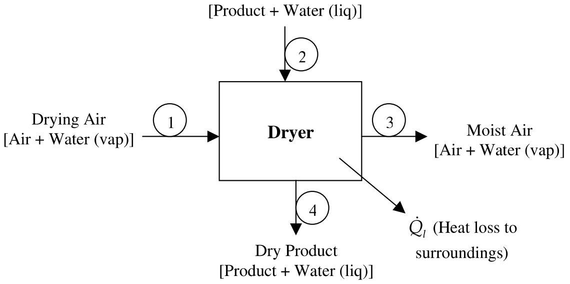

Fig. 1. Schematic of drying process with input and output terms.

2.2. Energy balance equations

The energy balance equation can be written for the entire system in the following manner, by taking input energy terms equal to output energy terms:

$$\dot{m}_\text{a} h_1 + \dot{m}_\text{p}(h_\text{p})_2 + (\dot{m}_\text{w})_2 (h_\text{w})_2 = \dot{m}_\text{a} h_3 + \dot{m}_\text{p}(h_\text{p})_4 + (\dot{m}_\text{w})_4 (h_\text{w})_4 + \dot{Q}_\text{l}, \tag{4}$$

where

$$h_1 = (h_\text{a})_1 + \omega_1 (h_\text{v})_1 \simeq (h_\text{a})_1 + \omega_1 (h_\text{g})_1, \tag{5}$$

$$h_3 = (h_\text{a})_3 + \omega_3 (h_\text{g})_3. \tag{6}$$

Note that here the values of h_1 and h_3 can directly be obtained from psychrometric chart.

The heat loss rate from the chamber becomes

$$\dot{Q}_\text{l} = \dot{m}_\text{a} q_\text{l}. \tag{7}$$

2.3. Exergy balance equations

In this section we now write the exergy balance equation for the entire system in the way we did it for energy balance equation for the input and output terms. Therefore, it can be written as follows:

$$\dot{m}_\text{a} e_1 + \dot{m}_\text{p}(e_\text{p})_2 + (\dot{m}_\text{w})_2 (e_\text{w})_2 = \dot{m}_\text{a} e_3 + \dot{m}_\text{p}(e_\text{p})_4 + (\dot{m}_\text{w})_4 (e_\text{w})_4 + \dot{E}_q + \dot{E}_\text{d}, \tag{8}$$

where the specific exergy for point 1 can be obtained as

$$\begin{aligned} e_1 = {} & [(C_P)_\text{a} + \omega_1 (C_P)_\text{v}](T_1 - T_0) \\ & - T_0 \left\{ [(C_P)_\text{a} + \omega_1 (C_P)_\text{v}] \ln\left(\frac{T_1}{T_0}\right) - (R_\text{a} + \omega_1 R_\text{v}) \ln\left(\frac{P_1}{P_0}\right) \right\} \\ & + T_0 \left\{ (R_\text{a} + \omega_1 R_\text{v}) \ln\left(\frac{1 + 1.6078\omega^0}{1 + 1.6078\omega_1}\right) + 1.6078\omega_1 R_\text{a} \ln\left(\frac{\omega_1}{\omega^0}\right) \right\}. \end{aligned} \tag{9}$$

The specific exergy for point 3 can be obtained as

$$\begin{aligned} e_3 = {} & \left[(C_P)_\mathrm{a} + \omega_3 (C_P)_\mathrm{v}\right](T_3 - T_0) \\ & - T_0\left\{\left[(C_P)_\mathrm{a} + \omega_3 (C_P)_\mathrm{v}\right]\ln\left(\frac{T_3}{T_0}\right) \right. \\ & \left. - (R_\mathrm{a} + \omega_3 R_\mathrm{v})\ln\left(\frac{P_3}{P_0}\right)\right\} \\ & + T_0\left\{(R_\mathrm{a} + \omega_3 R_\mathrm{v})\ln\left(\frac{1 + 1.6078\omega^0}{1 + 1.6078\omega_3}\right) \right. \\ & \left. + 1.6078\omega_3 R_\mathrm{a}\ln\left(\frac{\omega_3}{\omega^0}\right)\right\}. \end{aligned} \tag{10}$$

The specific exergy for the moist products results in

$$e_\mathrm{p} = [h_\mathrm{p}(T, P) - h_\mathrm{p}(T_0, P_0)] - T_0[s_\mathrm{p}(T, P) - s_\mathrm{p}(T_0, P_0)] \tag{11}$$

and the specific exergy for water content results in

$$\begin{aligned} e_\mathrm{w} = {} & [h_\mathrm{f}(T) - h_\mathrm{g}(T_0)] + v_\mathrm{f}[P - P_\mathrm{g}(T)] \\ & - T_0[s_\mathrm{f}(T) - s_\mathrm{g}(T_0)] + T_0 R_\mathrm{v}\ln\left[\frac{P_\mathrm{g}(T_0)}{x_\mathrm{v}^0 P_0}\right]. \end{aligned} \tag{12}$$

In addition, exergy flow due to heat loss can be identified as follows:

$$\dot{E}_q = \dot{m}_\mathrm{a} e_q = \dot{m}_\mathrm{a}\left(1 - \frac{T_0}{T_\mathrm{av}}\right) q_1 = \left(1 - \frac{T_0}{T_\mathrm{av}}\right) Q_1, \tag{13}$$

where T_av is the average dryer's outer surface temperature.

Here are some example data for the reference dead state (i.e., the environment): $T_0 = 32$ °C, $P_0 = 1$ atm, $\omega^0 = 0.0153$, $x_\mathrm{v}^0 = 0.024$ (mole fraction of water vapor in air).

2.4. Exergetic efficiency of drying process

Since we deal with exergy analysis of a drying process, we can go one step ahead and define the exergy efficiency for this drying process as the ratio of exergy use (investment) in the drying of the product to exergy of the drying air supplied to the system:

$$\eta_\mathrm{ex} = \frac{\text{Exergy investment in the evaporation of moisture in the product}}{\text{Exergy of drying air supplied}}$$

or

$$\eta_\mathrm{ex} = \frac{(\dot{m}_\mathrm{w})_\mathrm{ev}[(e_\mathrm{w})_3 - (e_\mathrm{w})_2]}{\dot{m}_\mathrm{a} e_1}, \tag{14}$$

where

$$(\dot{m}_\mathrm{w})_\mathrm{ev} = (\dot{m}_\mathrm{w})_2 - (\dot{m}_\mathrm{w})_4, \tag{15}$$

$$\begin{aligned} (e_\mathrm{w})_3 = {} & [h(T_3, P_{\mathrm{v}3}) - h_\mathrm{g}(T_0)] \\ & - T_0[s(T_3, P_{\mathrm{v}3}) - s_\mathrm{g}(T_0)] + T_0 R_\mathrm{v}\ln\left[\frac{P_\mathrm{g}(T_0)}{x_\mathrm{v}^0 P_0}\right] \end{aligned} \tag{16}$$

and

$$P_{\mathrm{v}3} = (x_\mathrm{v})_3 P_3. \tag{17}$$

3. Illustrative example

In this example we will show how to conduct an exergy analysis of the dryer and investigate the changes in exergy efficiencies versus various system parameters such as mass flow rate of the drying air, temperature of the drying air, the amount of products coming in, the initial moisture content of the product, the final moisture content of the product, specific inlet exergy, humidity ratio, and net exergy use for drying the products.

The following is the procedure to conduct the exergy analysis to determine the exergy efficiency of the drying process:

- Provide $\dot{m}_\mathrm{a}$, $\dot{m}_\mathrm{p}$, $(\dot{m}_\mathrm{w})_2$, $(\dot{m}_\mathrm{w})_4$ and $\omega_1 \rightarrow$ calculate ω_3.
- Provide T_1, P_1, T_2, P_2, T_3, P_3, T_4 and $P_4 \rightarrow$ determine $\dot{Q}_1$.
- Provide $(C_P)_\mathrm{a}$, $(C_P)_\mathrm{v}$, R_a, R_v, T_av and $(x_\mathrm{v})_3 \rightarrow$ determine $\dot{E}_\mathrm{d}$ and η_ex.
- Use steam tables, the psychrometric chart and the dead state properties accordingly.

In the solution one may consider the following parameters as inputs or known parameters to proceed for the solution:

- $\dot{m}_\mathrm{a}$, $\dot{m}_\mathrm{p}$, $(\dot{m}_\mathrm{w})_2$, $(\dot{m}_\mathrm{w})_4$, ω_1, T_1 and T_2.

In the following Table 1, we list the thermal data related to products and drying air that are used in the calculations to obtain exergy efficiency change with mass flow rate of air, temperature of drying air, specific exergy, specific exergy difference, moisture content of the product, and humidity ratio of drying air.

4. Results and discussion

Fig. 2 shows exergy efficiency with inlet air mass flow rate as product mass is variable. Increasing mass flow rate reduces the exergy efficiency, provided that further increase in the mass flow rate of air does not affect considerably the exergy efficiency. This occurs because

Table 1
Thermal data used in the example

Thermophysical properties	State 1	State 2	State 3	State 4
Panel A				
Temperature (°C)	55–100	25	25–70	50–95
ϕ (%)	10–35	55–85	60–95	15–30
Panel B				
$(C_P)_a$	1.004 kJ/kg K			
$(C_P)_v$	1.872 kJ/kg K			
R_a	0.287 kJ/kg K			
R_v	04615 kJ/kg K			
T_{av}	50 °C = 323.15 K			
$(x_v)_3$	0.055			
T_0	32 °C = 305.15 K			
P_0	101.3 kPa			
w_0	0.0153			
$(x_v)_0$	0.024			
$\dot{m}_a$ (kg/s)	m_p (kg)	$\dot{m}_p$ (kg/s)		
Panel C				
0	1	0.0002778		
1	5	0.0013389		
1.5	10	0.0027778		
2	15	0.0041667		
2.5	20	0.0055556		

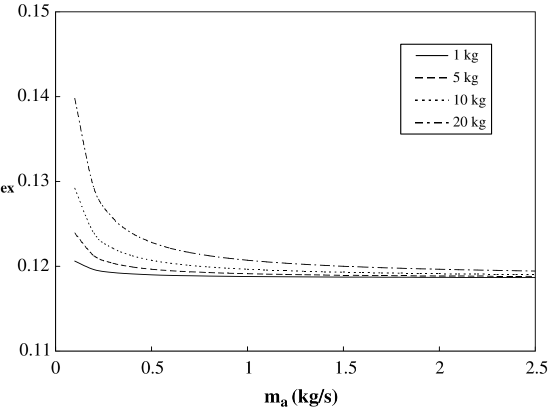

Fig. 2. The variation of process exergy efficiency with mass flow rate of drying air at different product weights.

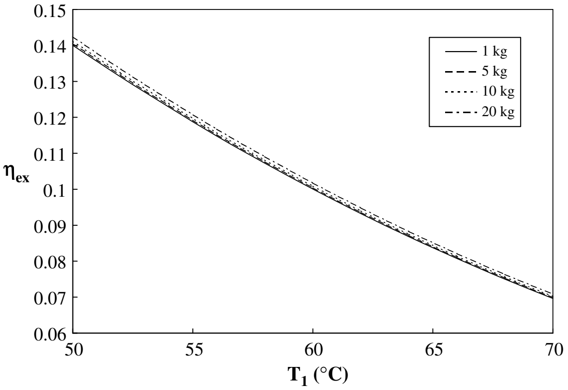

Fig. 3. The variation of process exergy efficiency with temperature of drying air at different product weights.

of increasing mass flow rate enhances the exergy into the system, which in turn lowers the exergy efficiency, based on Eq. (14). Moreover, increasing the weight (mass) of product considerably influences the exergy efficiency, i.e., exergy efficiency increases with increasing product mass. In this case, exergy used to dry the product increases with increasing product mass. Consequently, this enhances the exergy efficiency.

Fig. 3 shows the variation of exergy efficiency with the inlet drying air temperature as product mass is variable. The behavior of the curves is similar to those shown in Fig. 2. Increasing drying air temperature reduces the exergy efficiency, since exergy efficiency is inversely proportional to the exergy rate of drying air. As one may expect, the exergy efficiency changes monolithically as drying air temperature increases further. Moreover, the magnitude of exergy efficiency increases considerably with increasing product mass.

Fig. 4 exhibits the variation of exergy efficiency of the dryer versus specific exergy content of the drying air

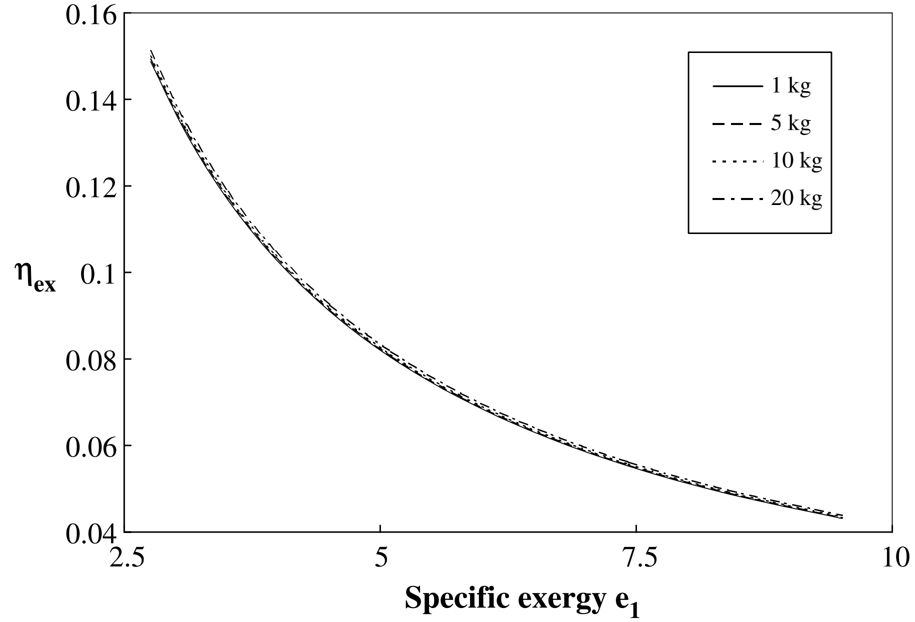

Fig. 4. The variation of process exergy efficiency with specific exergy of inlet drying air at different product weights.

entering the dryer as the amount of products changes from 1 to 20 kg, respectively. As expected, the exergy efficiency decrease with increasing the specific exergy at point 1 for the same amount of products since there will be more exergy loss in the system, resulting smaller exergy efficiency.

Note that exergy efficiency of the dryer varies with the difference in specific evaporation exergies of water content at different mass flow rates of drying air in the dryer. In conjunction with this, increasing the specific exergy difference results in decreasing exergy efficiency. For the same magnitude of the specific exergy difference, greater mass flow rate of drying air results in smaller exergy efficiency, due to fact that higher mass flow rates of drying air consume higher energy and hence causing greater exergy losses.

Fig. 5 shows the exergy efficiency with product mass as the mass flow rate of drying air is variable. The exergy efficiency therefore increases linearly with product mass. The increase in the exergy efficiency signifies as the mass flow rate of drying air reduces. This is because of the fact that the exergy efficiency is inversely proportional to the mass flow rate of drying air. Moreover, this linear increase of exergy efficiency with product mass indicates that the specific exergy difference between the product and the exergy exiting over exergy of the drying air remains constant for the given product mass.

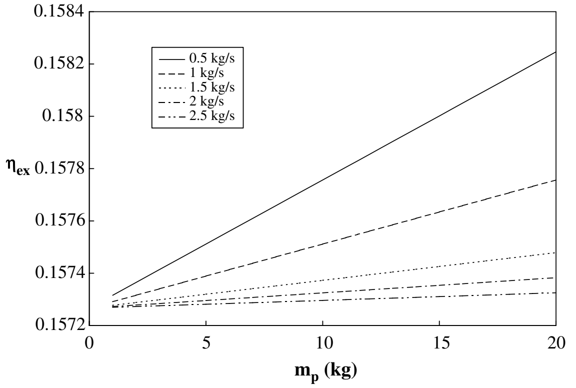

Fig. 5. The variation of process exergy efficiency with product weight at different mass flow rates of air.

Fig. 6 depicts the exergy efficiency with the moisture content of the incoming products as the mass flow rate of evaporated water is variable. The exergy efficiency increases with increasing moisture content of the products. This is more pronounced as evaporation rate increases. In this case, energy utilized for drying the product increases when moisture content of the products increases. Consequently, for given air inlet conditions, energy utilized in the system enhances. This, in turn, improves the exergy efficiency of the system.

Finally, Fig. 7 exhibits the variation of the exergy efficiency of the drying process against the humidity ratio of drying air entering the dryer at different mass flow rates of drying air. As is clearly seen in the figure, there is a linear relationship between the exergy efficiency and the humidity ratio. Interestingly we note that exergy efficiency changes considerably small (decreas-

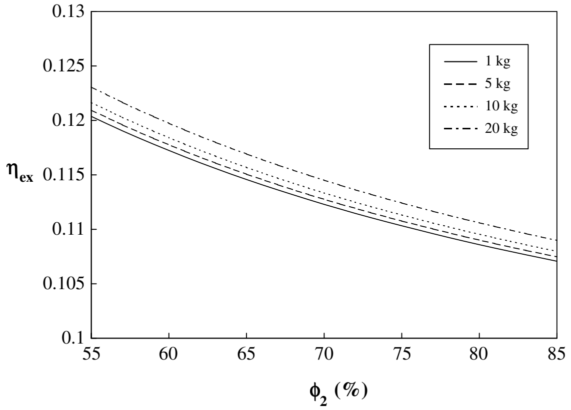

Fig. 6. The variation of process exergy efficiency with moisture content of the product at different moisture evaporation rates.

ing slightly) with increasing humidity ratio of the drying air.

The work presented in this section is intended not only to demonstrate the usefulness of exergy analysis in thermodynamic assessments of drying systems, but also to provide insights into their performances and efficiencies. This work forms comprehensive part of a broader project by the investigators to examine thermodynamically the drying systems. The analysis methodologies and results presented should be useful to engineers seeking (i) to optimize the design of drying systems and their components and (ii) to identify appropriate applications and optimal configurations for drying systems in general engineering systems.

Consequently, some intuitive advantages of exergy analysis of the can be listed as follows as a core outcome of this project:

- It provides more proper accounting of the loss of availability of heat in drying system using the conservation of mass and energy principles together with the second law of thermodynamics for the goals of design and analysis.
- It gives more meaningful and useful information than energy analysis regarding the efficiency, losses and performance for drying systems.
- It is more correct reflecting the thermodynamic and economic values of the operation of drying systems.
- It is an efficient technique revealing whether or not and by how much it is possible to design more efficient drying systems by reducing the inefficiencies in the existing units.

5. Conclusions

This paper has presented a new model for thermodynamic analysis, in terms of exergy, of a drying process of moist solids subject to air drying. Mass, energy and exergy balance equations are written, and exergy

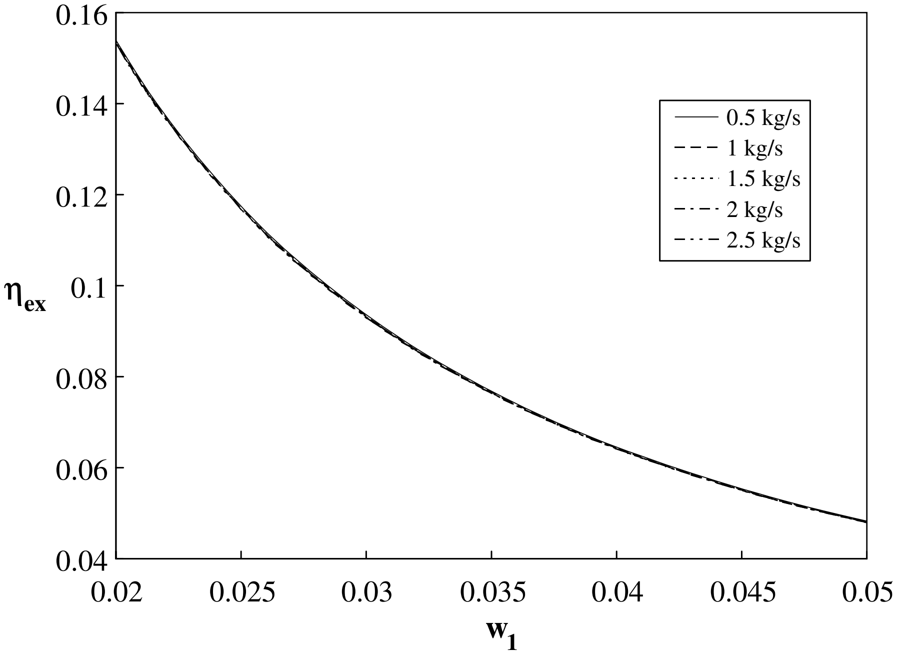

Fig. 7. The variation of process exergy efficiency with humidity ratio of drying air at different mass flow rates of air.

efficiencies are derived as functions of heat and mass transfer parameters. An illustrative example is also presented to verify the present model and to illustrate the applicability of the model to actual drying processes at different drying air temperatures, specific exergies of drying air, exergy differences of inlet and outlet products, product weights, moisture contents of drying air, and humidity ratios of drying air. It can be concluded that the present model appears to be a significant tool for design and optimization of drying processes of moist solids.

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References

[1] I. Dincer, On energetic, exergetic and environmental aspects of drying systems, Int. J. Energy Res. 26 (8) (2002) 717–727.

[2] I. Dincer, M.M. Hussain, A.Z. Sahin, B.S. Yilbas, Development of a new moisture transfer (Bi–Re) correlation for food drying applications, Int. J. Heat Mass Transfer 45 (8) (2002) 1749–1755.

[3] A.Z. Sahin, I. Dincer, Graphical determination of drying process and moisture transfer parameters for solids drying, Int. J. Heat Mass Transfer 45 (16) (2002) 3267–3273.

[4] I. Dincer, Thermodynamics, exergy and environmental impact, Energy Sources 22 (8) (2000) 723–732.

[5] I. Dincer, Y.A. Cengel, Energy, entropy and exergy concepts and their roles in thermal engineering, Entropy—Int. J. 3 (3) (2001) 116–149.

[6] S. Sieniutycz, M. Kubiak, Dynamical energy limits in traditional and work-driven operations I. Heat-mechanical systems, Int. J. Heat Mass Transfer 45 (14) (2002) 2995–3012.

[7] G.S. Zhu, D.R. Rolf, A model for high-pressure vaporization of droplets of complex liquid mixtures using continuous thermodynamics, Int. J. Heat Mass Transfer 45 (3) (2002) 495–507.

[8] Y. Demirel, S.I. Sandler, Linear-nonequilibrium thermodynamics theory for coupled heat and mass transport, Int. J. Heat Mass Transfer 44 (13) (2001) 2439–2451.

[9] A.F. Miguel, Contribution to flow characterization through porous media, Int. J. Heat Mass Transfer 43 (13) (2000) 2267–2272.

[10] R. Topic, Mathematical model for exergy analysis of drying plants, Dry. Technol. 13 (1&2) (1995) 437–445.

[11] S. Syahrul, F. Hamdullahpur, I. Dincer, Energy analysis in fluidized bed drying of wet particles, Int. J. Energy Res. 26 (6) (2002) 507–525.

[12] S. Syahrul, F. Hamdullahpur, I. Dincer, Exergy analysis of fluidized bed drying of moist particles, Exergy—Int. J. 2 (2) (2002) 87–98.

[13] S. Syahrul, F. Hamdullahpur, I. Dincer, Thermal analysis in fluidized bed drying of moist particles, Appl. Thermal Eng. 22 (15) (2002) 1763–1775.

[14] S. Syahrul, I. Dincer, F. Hamdullahpur, Thermodynamic modelling of fluidized bed drying of moist particles, Int. J. Thermal Sci. 42 (7) (2003) 691–701.

[15] Y.L. Bray, M. Prat, Three-dimensional pore network simulation of drying in capillary porous media, Int. J. Heat Mass Transfer 42 (22) (1999) 4207–4224.

[16] O. Séro-Guillaume, J. Margerit, Modelling forest fires. Part I: a complete set of equations derived by extended irreversible thermodynamics, Int. J. Heat Mass Transfer 45 (8) (2002) 1705–1722.

[17] T.J. Kotas, The Exergy Method of Thermal Plant Analysis, reprint ed., Krieger, Malabar, FL, 1995.

[18] A. Bejan, Advanced Engineering Thermodynamics, John Wiley & Sons, New York, 1997.

[19] G. Wall, Exergy flows in industrial processes, Research Report, Physical resource theory group, Chalmers University of Technology and University of Göteborg, Sweden, 1983.

[20] G. Wall, Exergy—A Useful Concept, Ph.D. thesis, Chalmers University of Technology, S-412 96 Göteborg, Sweden, 1986.

[21] R.L. Cornelissen, Thermodynamics and Sustainable Development, Ph.D. thesis, University of Twente, The Netherlands, 1997.

[22] G.M. Reistad, Availability: Concepts and Applications, Ph.D. thesis, University of Wisconsin, Madison, 1970.

[23] M.A. Rosen, I. Dincer, On exergy and environmental impact, Int. J. Energy Res. 21 (1997) 643–654.

[24] J. Szargut, D.R. Morris, F.R. Steward, Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, Hemisphere Publishing Corporation, New York, 1988.