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Energy and exergy analysis of an indirect solar cabinet dryer based on mathematical modeling results

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ABSTRACT

In the present study, using a previously developed dynamic mathematical model for performance analysis of an indirect cabinet solar dryer [1], a microscopic energy and exergy analysis for an indirect solar cabinet dryer is carried out. To this end, appropriate energy and exergy models are developed and using the predicted values for temperature and enthalpy of gas stream and the temperature, enthalpy and moisture content of the drying solid, the energy and exergy efficiencies are estimated. The validity of the model for predicting variations in gas and solid characteristics along the time and the length of the solar collector and/or dryer length was examined against some existing experimental data. The results show that in spite of high energy efficiency, the indirect solar cabinet dryer has relatively low exergy efficiency. Results show that the maximum exergy losses are in midday. Also the minimums of total exergy efficiency are 32.3% and 47.2% on the first and second days, respectively. Furthermore, the effect of some operating parameters, including length of the collector, its surface, and air flow rate was investigated on the exergy destruction and efficiency.

1. Introduction

Drying is a process which requires high energy input because of the high latent heat of water evaporation and the relatively low energy efficiency of industrial dryers. It can be regarded as one of the most important and widely-used unit operations in all sectors producing solid products [2].

From economical and environmental viewpoints, in the drying industry, the aim is to using a minimum amount of energy for maximum moisture removal for the desired final conditions of the product. In this regard, the use of the solar energy for drying solid products saves conventional fuels and also offers the advantage of less pollution. Solar drying in enclosed structures is also an attractive way of lowering post-harvest losses and the low quality associated with traditional sun-drying methods.

Solar dryers with enclosed structures are of different types. The indirect solar cabinet dryer is a usual mode used in food industries. In this system, the solid product is not directly exposed to solar radiation to minimize discoloration and cracking on the surface of the solid product. After passing through the glass cover, solar radiation is directed toward an absorber plate. Then, some heat radiation is transferred from the absorber plate to the flowing air above it by convective mechanism. The heated air passes through a bed of drying solid placed in the drying chamber.

Energy analysis of solar dryers has been an interesting subject for researchers but, it should be noted that the energy analysis does not just show the quality of energy destruction. In the recent years, a new concept has been introduced and used in order to measure the ability of several types of energies to work, known as Exergy.

Exergy is the property of the system, which gives the maximum power that can be distracted from the system when it is brought to a thermodynamic equilibrium state from a reference state. Using exergy analysis, based on the first and second laws of thermodynamics, it is possible to infer the true potential of different kinds of energies. Due to thermodynamic irreversibilities, the exergy efficiency of a process is often low in spite of high energy efficiency [3].

Exergy analysis, as is known, evaluates the available energy at different points in a system. In the design of a system, the exergy method provides the useful information to choose the appropriate component design and operation procedure. Exergy is not subject to a conservation law; rather, exergy is consumed or destroyed due to the irreversibility in any process. It is the measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment.

Many studies, covering mathematical modeling and kinetics of the drying process, have been undertaken by several researchers

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recently [4–7]. Many experimental and theoretical studies on the solar drying process could be found in the literature, but there are few studies on the energy and exergy analysis of this process.

Kim and Favrat [8] presented energy and exergy analyses of a micro-CAES (Compressed Air Energy Storage) system, and to improve the efficiency of the system, some innovative ideas have been introduced. Fadare et al. [9] estimated energy requirements and exergy inefficiencies for processing of malt drink for a Nigerian brewery. The exergy analysis revealed that the packaging house operation was responsible for most of the inefficiency (92.16%) followed by brew house operation (7.17%) and the silo house and filter room operations with less than 1% of the total exergy lost. Karamarkovic and Karamarkovic [10] focused on air gasification of biomass with different degrees moisture at different gasification temperatures. A chemical equilibrium model is developed with analyses being carried out at different pressures. Lohani [11] considered the energy and exergy analysis of a fossil plant and ground and air source heat pump building heating system at two different dead-state temperatures. A zone model of a building with natural ventilation is considered and heat is being supplied by condensing boiler. The same zone model is applied for heat pump building heating system. Corzo et al. [12] in their experimental study considered energy and exergy of the drying of coroba slices at different conditions. The energy and exergy analysis of a single layer drying process of potato slices via a cyclone type dryer was considered by Akpinar et al. [13]. As mentioned before, no study has been reported on exergy analysis of a solar cabinet dryer.

As an extension to our previous work [1], the energy and exergy analysis of an indirect cabinet solar dryer will be addressed in the present study. A new approach is illustrated for achieving the scope of work, which is using the mathematical modeling as a useful technique for energy and exergy analysis and also for determining microscopic exergy destruction characteristics of such equipment. The calculated exergy and exergy destruction are compared with the corresponding experimental ones reported by Mohanraj and Chandrasekar [14] and Dissa et al. [15].

2. Mathematical model

Fig. 1 shows the schema of an indirect cabinet solar dryer. As can be seen, the system consists of two different parts including solar collector and drying chamber. The solar collector section acts as an air heater. Thus, the conservation law of energy could be applied for the solar collector in a differential section of the collector length (Δx) and the variation equations of temperature for flowing air, glass cover, and absorber plate are derived as shown in Table 1. Moreover, the governing equations for the drying chamber are derived based on the conservation laws of mass and energy for the flowing gas and drying solid. Governing equations for the drying chamber can also be found in Table 1. More details for model assumptions, supplementary equations, required nomenclature and derivation of the equations can be found in Sami et al. [1].

In our previous work, the obtained ODEs and PDEs have been solved numerically using the finite difference and the fourth order Runge-Kutta methods. The solution of the derived governing equations under the unsteady state condition with appropriate initial and boundary conditions leads to the humidity and temperature of drying air, material temperature and moisture content of drying solid as a function of time. In addition, using appropriate pre-defined equations, the efficiency of the system was calculated and analyzed according to the first law of thermodynamics.

2.1. Energy analysis model

The energy capacities of streams flowing through the solar collector and drying chamber are calculated by the following relations. The inlet and outlet energy flow in the solar collector are determined by Eqs. (1) and (2), respectively:

$$Q_{\mathrm{col,i}} = I_{\mathrm{t}}\tau_{\mathrm{g}}\alpha_{\mathrm{p}}A + \dot{m}_{\mathrm{a}}C_{\mathrm{pm}}(T_{\mathrm{i}} - T_0) \tag{1}$$

$$Q_{\mathrm{col,o}} = \dot{m}_{\mathrm{a}}C_{\mathrm{pm}}(T_{\mathrm{o}} - T_0) \tag{2}$$

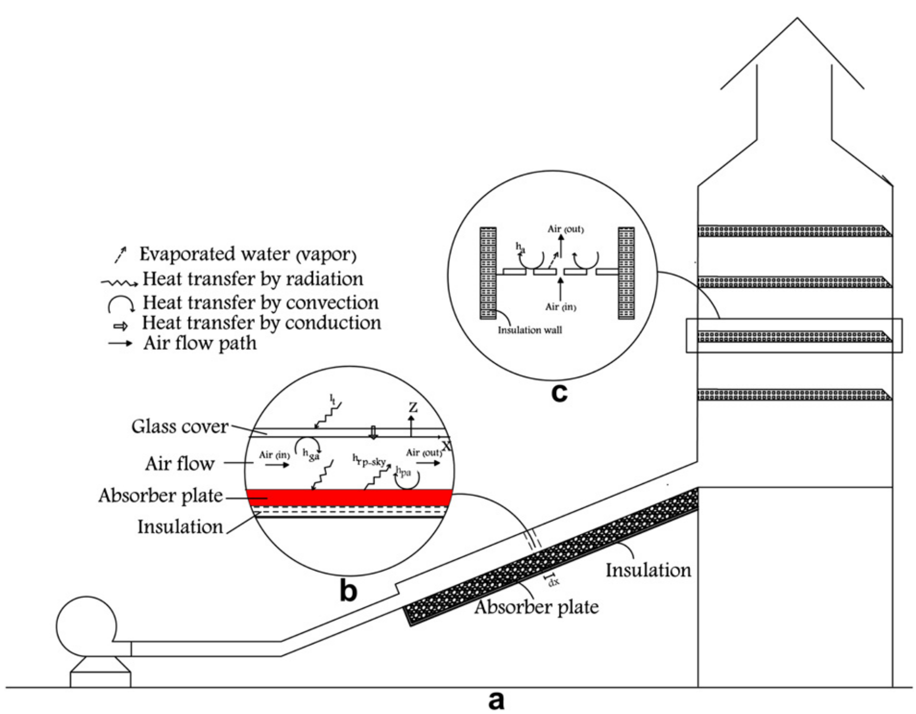

Fig. 1. (a) Schematic of an indirect solar cabinet dryer, (b) Schematic of solar collector zone, (c) Schematic of physical phenomena occurring on each tray.