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Energy and exergy analyses in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system (CMCB) ☆

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ABSTRACT

This paper is concerned with the energy and exergy analyses in the drying process of non-hygroscopic porous packed bed by combined multi-feed microwave-convective air and continuous belt system (CMCB). Most importantly, this work focused on the investigation of drying phenomena under industrialized microwave processing. In this analysis, the effects of the drying time, hot-air temperature, porous structure (F-Bed and C-Bed) and location of magnetron on overall drying kinetics and energy utilization ratio (EUR) were evaluated in detail. The results showed that using the continuous microwave application technique had several advantages over the conventional method such as shorter processing times, volumetric dissipation of energy throughout a product with higher energy utilization and less exergy efficiency in drying process. The results presented here provided fundamental understanding for drying process using CMCB in industrial size.

1. Introduction

Microwave and convection heating may be applied simultaneously or at different times. It has been proven that combination drying is an effective way particularly when microwaves are introduced in the final stages of drying to reduce the product moisture below 20% [1]. Microwave application can be effectively utilized in the falling rate period where hot-air drying is too slow affecting the quality of the dried product with over exposure to hot-air conditions. Application of microwave or combination drying technique for potato [2], apple and mushroom [3–4], raisins [5–6], blueberries [7] and banana [8] has been successfully experimented. These researchers also noted the improvement in the end product quality along with the reduction of total drying time compared to hot-air only drying. This technique combines the capability of microwaves to heat the product internally (depending on the dielectric properties and interaction of the material with electromagnetic energy) and enables faster removal of the surface moisture due to conventional heating of the surroundings.

Various materials that undergo drying in industrial production require different approach to this process [9]. In many cases, the time of drying becomes important because of the production rate. In another case, the time is less important but the quality of the products, that is, their appearance and good mechanical state or the biological value in the case of food or medicine products are relevant. In all cases, important is the minimization of the energy use as drying is a big energy consuming process. To fulfill these requirements, one has to look for special methods of drying among others for the combined methods in which different sources of energy supply are used.

When drying with dielectric heating it is usual to combine hot air with the system, particularly with microwave systems. This is because it usually improves the efficiency and the economics of the drying process [10]. Hot air is, by itself, relatively efficient at removing free water at or near the surface, whereas the unique pumping action of dielectric heating provides an efficient way of removing internal free water as well as bound water. By combining these properly, it is possible to draw on the benefits of each and maximize efficiency and keep the costs of drying down. Note that drying with microwaves or dielectrics alone can be very expensive in terms of both equipment and operating costs.

The traditional thermodynamics method of assessing processes involving the physical or chemical processing of materials with accompanying transfer and transformation of energy is by the completion of an energy balance which is based on the first law of thermodynamics. The first law analysis is used to reduce heat losses or enhance heat recovery. Meanwhile, it gives no information on the degradation of the useful energy that occurs within the process equipment [11]. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential change [12]. Exergy is defined as the maximum work, which can be produced by a system or a flow of matter or energy and it comes to equilibrium with a

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specified reference environment (dead state) [13]. Unlike energy, exergy is conserved only during ideal processes and destroyed due to irreversibilities in real processes [14].

The features of exergy are identified to highlight its importance in a wide range of applications [15]. Exergy analysis has been increasingly as a useful tool in the design, assessment, optimization and improvement of energy systems. It can be applied on both system and component levels. Exergy analysis leads to a better understanding of the influence of thermodynamics phenomena on effective process, comparison of the importance of different thermodynamics factors, and the determination of the most effective ways of improving the process [16]. As regards the exergy analyses of drying processes, some work has been carried out in recent years. Kanoglua and et al. [17] analyzed a thermodynamics aspect of the fluidized bed drying process of large particles for optimizing the input and output conditions by using energy and exergy models. The effects of the hydrodynamic and thermodynamics conditions were also analyzed such as inlet air temperature, fluidization velocity and initial moisture content on EUR and exergy efficiency. Syahrul and et al. [18] and Dincer [19] used a model to analyze exergy losses of a air drying process. Their work demonstrated that the usefulness of exergy analysis in thermodynamics assessments of drying processes and providence the performances and efficiencies of these processes. Akpinar et al. [20–21] studied energy and exergy of the drying of red pepper slices in a convective type dryer, with potato slices in a cyclone type dryer and pumpkin slices in a cyclone type dryer. The type and magnitude of exergy losses during drying was calculated. Colak [22] performed an exergy analysis of thin layer drying of green olive in a tray dryer. In Colak's study the effects of the drying air temperature, the mass flow rate of drying air and olives on the system performance were discussed. Ceylan et al. [23] carried out energy and exergy analyses during the drying of two types of timber.

However, few works has been reported on the energy and exergy analysis in combined microwave-convective drying process of porous media. The drying of porous media has been interested by many researchers and become complex, coupled, and multiphase processes with a wide range of applications in industry. In addition, as a result of high cost of energy, an operation with a high potential for optimizing with respect to energy savings has been realized. For many years, it has been studied experimentally for measuring drying kinetics on the macro-scale.

Typical applications of non-uniform material include the tertiary oil recovery process, geothermal analysis, asphalt concrete pavements process and preservation process of food stuffs. Therefore, knowledge of heat and mass transfer that occurs during convective drying of porous materials is necessary to provide a basis for fundamental understanding of convective drying of non-uniform materials.

The fore mentioned works concerned mainly with, energy and exergy analyses of drying process. Normally, most of materials in the drying process are porous materials. In the recent works the authors were mention about porous materials structure, with are concern with energy and exergy analyses of drying process.

The objectives of this work are to evaluate (i) the exergy losses of two operations porous packed bed, (ii) the distributions of the exergy losses and exergy input of the different drying operations and (iii) the influences of operating parameters on exergy losses. The knowledge gained will provide an understanding in porous media and the parameters which can help to reduce EUR and exergy losses.

2. Experimental setup

Microwave-convective air drying was carried out using a CMCB (Fig. 1(a)).The shape of microwave cavity was rectangular with a cross sectional area of 90 cm × 45 cm × 270 cm. The drier was operated at a frequency of 2.45 GHz with maximum working temperature of 180 °C. The microwave power was generated by means of 12 compressed air-cooled magnetrons. The maximum microwave capacity was 9.6 kW with a frequency of 2.45 GHz. The power setting could be adjusted individually in 800 W steps. In the continuous processing equipment, two open ends were essential, through which the material to be heated up on the belt conveyer was put in and taken out. In this equipment, leakage of microwaves was prevented by the countermeasure in double with a combination of mechanical blocking filter (corrugate choke) and microwave absorber zone filter was provided at each of the open ends. The microwave leakage was controlled under the DHHS (US Department of Health and Human Services) standard of 5 mW/cm^2. The multiple magnetrons (12 units) were installed in an asymmetrical position on the rectangular cavity (Fig. 1(b)). The microwave power was then directly supplied into the drier by using waveguides. An infrared thermometer (located at the opening ends) was used to measure the temperature of the specimens (accurate to ±0.5 °C).

The magnetrons and transformers used in this system were cooled down by fan. In the continuous heating/drying equipment, two open ends were essential to feed in and feed out the product, through which the material to be heated up on the belt conveyer arranged in certain position, as shown, as in Fig. 1(c). The belt conveyor system consisted of a drive motor, a tension roller and a belt conveyor. During the drying process, the conveyor speed was adjusted to 0.54 m/min (at the frequency 40 Hz) and the motor speed could be controlled by the varied speed drive (vsd) of control unit. Hot air was generated using the 24 unit of electric heaters with the maximum capacity of 10.8 kW and the maximum working temperature of 240 °C. The hot air was supplied by blower fan with 0.4 kW power through the air duct into the cavity. The hot-air temperature was measured by using thermocouples.

As shown in Fig. 2, the drying samples were non-hygroscopic porous packed bed, which composed of glass beads and water (saturated porous packed bed, $s_0 = 1$). A sample container was made from polypropylene with a thickness of 2 mm (with dimension of 14.5 cm × 21 cm × 5 cm). The polypropylene did not absorb microwave energy. In this study, the voids occupied from a fraction up to 38 percent of the whole volume of packed beds. The samples were prepared in two configurations: a single-layered packed bed ($d = 0.15$ mm, $d = 0.40$ mm, and $d_p = 11.5$ mm). The sample selected for drying test was a non-hygroscopic porous packed bed with dimensions of 14.5 cm × 21 cm × 1.15 cm. The 22 porous packed beds had total weight of 11 kg which had the initial water saturation (s_0) of 1.0 and the initial temperature was equal to the ambient temperature.

The water saturations in the non-hygroscopic porous packed bed were defined as the fraction of the volume occupied by water to volume of the pores. They were obtained by weighing dry and wet mass of the sample. The water saturation formula can be described in the following form [24]:

$$s' = \frac{M_p \cdot \rho_s \cdot (1-\varphi)}{\rho_w \cdot \varphi \cdot 100} \tag{1}$$

Where s' is water saturation; ρ_s is density of solid; ρ_w is density of water; φ is porosity and M_p is particle moisture content dry basis. During the experimental microwave-drying processes, the uncertainty of the experimental data might be generated by the variations of humidity, room temperature and human errors. The uncertainty in drying kinetics was assumed to be a result of errors in the measured weight of the sample. The calculated drying kinetic uncertainties in all tests were less than 3%. The uncertainly in temperature was assumed to be a result of errors in measured input power, ambient temperature and ambient humidity. The calculated uncertainty associated with temperature was less than 2.85%.The different drying cases were then carried out in each test run (see details in Table (1)).