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FULL LENGTH ARTICLE

Potential saving in energy using combined heat and power technology for drying agricultural products (banana slices)

Seyed Hashem Samadi, Barat Ghobadian *, Gholamhassan Najafi, Ali Motevali

Department of Mechanics of Agricultural Machinery Engineering, Agricultural Faculty, Tarbiat Modares University, Tehran, Iran

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Abstract The drying behavior of banana slices was studied in a combined heat and power dryer system at 4 engine load levels (25%, 50%, 75%, and 100%) and at three levels of drying product thickness (3, 5, and 7 mm) with the constant airflow velocity of 1 m/s. Results from the mathematical modeling showed that the Midilli et al. model gave the best fit to the experimental data. The present study confirms the importance of heat recovery to improve the system energy consumption and efficiency. Energy efficiency of this dryer was from 11% to 20% higher than that of electricity efficiency. Also, the specific energy consumption varied between 409 and 957 kWh/kgwater. The lowest value of energy consumption and highest value of energy efficiency were observed at 75% engine load and 3 mm thickness of sample.

1. Introduction

Banana is one of the most commonly consumed fruits in many countries. However, it spoils rapidly, particularly in the case of ripe banana. One of the conventional methods for long-term preservation of agricultural products, like vegetables and fruits, is drying. Drying is usually used to minimize deterioration after harvesting. Drying preserves foods by removing enough moisture from food and reduces microbiological activity and minimizes physical and chemical changes during storage to prevent decay and spoilage (Barbosa-Canovas and Vega-Mercado, 1996; Calban and Ersahan, 2003; Chen and Mujumdar, 2008; Khattab, 1996).

Hot air convection drying is one of the oldest methods and one technique performed to preserve agricultural products like banana. Over 85% of industrial dryers are of convective type with hot air. However, one of the disadvantages of these dryers is the high energy operation (Alibas, 2007; Koyuncu et al., 2007; Lewicki, 2006; Motevali et al., 2011).

Energy plays an essential role for the economic development in many countries. Using the waste heat of exhaust gas of an internal combustion engine is an alternative drying mean instead of hot air convection drying. Cogeneration or

* Corresponding author. Tel.: +98 912 1135306; fax: +98 21 44292200.
E-mail address: ghobadib@modares.ac.ir (B. Ghobadian).
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Combined Heat and Power (CHP) technology is an energy saving method that is defined as a concept of generating heat and electricity simultaneously on site from a single fuel source (De Paepe et al., 2006; Eriksson and Kjellström, 2010; Wu and Wang, 2006). This technology is based on recycling waste heat in order to significantly increase the total efficiency of the CHP system compared to conventional electricity generation systems. Therefore, this offers significant potential savings in energy costs. CHP is also more environmentally friendly than conventional generation systems. CHP is more efficient, reducing total fossil fuel consumption and thereby reducing emissions to the atmosphere (Dorer and Weber, 2009; Erdem et al., 2007; Godefroy et al., 2007; Haeseldonckx et al., 2007; Peacock and Newborough, 2005; Schicktanz et al., 2011). CHP is used for many different applications in the industrial, commercial, and residential sectors (Backlund and Karlsson, 1988; Barigozzi et al., 2011; Dentice d'Accadia et al., 2003; Kopanos et al., 2013; Oh et al., 2012; Onovwiona et al., 2007). Recovered heat from the CHP can be used for many purposes. Waste heat can be used directly for air heating, serving industrial ovens, absorption process and also to produce hot water for other uses. In some industrial applications, the exhaust from a prime mover (such as gas turbine, reciprocating engines, and Stirling engines) is directed to a process such as drying agricultural products (Gungor et al., 2011; Meckler and Hyman, 2010; Turul Oulata, 2004).

About two-thirds of the energy input in the internal combustion engine is wasted through exhaust gas and cooling system (Yun et al., 2013). Considering the high energy loss from the exhaust gas of internal combustion engines, the required energy for drying of agricultural products could be recycled from this leaving waste gas.

Some research works have been carried out in drying of different material with waste heat from the internal combustion engine such as: drying of paddy (Basunia and Abe, 2008), biomass drying (Li et al., 2012; Nguyen and Steinbrecht, 2008), pulp and paper mill (Holmberg and Ahtila, 2005), clay minerals (Fath, 1991) and grand composite (Kemp, 2005).

However, there is no complete research on the drying of agricultural products using waste heat of exhaust gas in different engine conditions. In this research work, the waste heat of exhaust gas of an internal combustion engine was used for the process of banana slice drying. The objectives of this study are to investigate drying kinetics, suggest a mathematical model for thin layer drying of banana, and evaluate energy consumption and efficiency with and without CHP application.

2. Materials and methods

2.1. Experimental materials

In this study, banana slices were used to conduct the experiments. The study samples were freshly provided and were stored in the refrigerator at temperature of 4 ± 1 °C until the experiments were carried out. The initial moisture content of the samples was found to be 68.3 ± 1.5% (w.b.), and was determined by drying in an air convection oven at 105 ± 1 °C till the weight did not change any more (Wang et al., 2007). Banana slices were placed on the drying bed after preparing and setting the CHP dryer for different experimental levels. An engine and a generator with the following specification were used.

Engine Type: single cylinder- 4-stroke Air-cooled, power: 6.5 hp @ 1200 rpm, *Displacement*: 196 CC, Bore × Stroke: 68 × 54 mm, Fuel Types: Natural gas (N), LPG (L), Ignition system: Transistor Coil Ignition (T.C.I).

Generator Type: Single-Phase AC Synchronous, Frequency: 50 HZ, Current (A)/DC voltage (V): 12 V/8A, Maximum power: 2.3 kW, Power rating: 2 kW.

Air parameters were adjusted by measuring temperature and velocity using a thermometer (Lutron, TM-925, Taiwan) and anemometer (Anemometer, Lutron-YK, 80 AM, Taiwan). During the drying experiments, the variation range of ambient temperature was 23 ± 3 °C and of ambient relative humidity was 24 ± 4%. Drying process was done until the moisture content of about 5% on a wet basis was achieved. All experiments were carried out in triplicate.

2.2. System description

In this research work waste heat from the exhaust of an engine-generator was used for drying process. Equipments used in this dryer consist of a single cylinder IC engine that works with natural gas fuel, a generator that produces 2 kW of electricity, a gas flow meter for measuring fuel consumption, a dryer chamber which dries the samples placed in it, two fans to remove hot air of the dryer chamber, a digital balance for weighing samples, a temperature sensor for measuring temperature and a PC to record hot air temperature and sample weight. The schematic diagram of this CHP dryer system is shown in Fig. 1.

Waste heat from the engine exhaust was directed into the dryer chamber. The produced heat is directed under the chamber tray directly and the dryer chamber is warmed. Hot air is circulated inside the chamber and is removed from the chamber by a fan. Engine was kept running for a few minutes to reach a steady state condition. For each experiment, samples (about 32 ± 0.5 g with a thickness of 3, 5 and 7 mm) were placed in a dryer chamber and were dried. Experiments were performed at a constant speed and four engine load levels, 25%, 50%, 75% and full load (100%). The moisture losses of samples were recorded at 5 min intervals during the drying process by a digital balance (GF-600, A & D, Japan) and with an accuracy of ± 0.01 g.

2.3. Mathematical modeling

One of the most important aspects of drying technology is the modeling of the drying process. In this study, the experimental drying data of banana slices at different engine loads were fitted into 6 commonly used thin-layer drying models, listed in Table 1.

The moisture ratio (MR) for banana slices during the drying process was calculated using Eq. 1:

$$\mathrm{MR} = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where, MR is the moisture ratio (dimensionless); M_t, M_e and M_0 are the moisture content at any time, the equilibrium moisture content, and the initial moisture content (kg [H_2O]/kg dry mater), respectively. The values of M_e are relatively small com-