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FULL LENGTH ARTICLE

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

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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

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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-

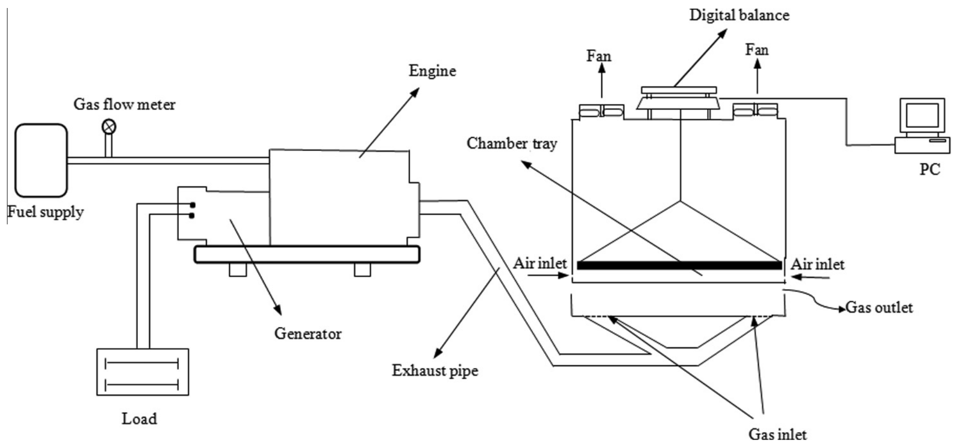

Figure 1 Schematic diagram of the CHP dryer system.

Table 1 Mathematical models given for drying curves.

No.	Model name	Model	Reference
1	Newton	$\mathrm{MR} = \exp(-kt)$	Motevali et al. (2010)
2	Page	$\mathrm{MR} = \exp(-kt^n)$	Motevali et al. (2010)
3	Wang and Singh	$\mathrm{MR} = 1 + a.t + bt^2$	Wang and Singh (1978)
4	Henderson and Pabis	$\mathrm{MR} = a.\exp(-kt)$	Chhinnan (1984)
5	Logaritmic	$\mathrm{MR} = a.\exp(-kt) + c$	Dandamrongrak et al. (2002)
6	Midili et al.	$\mathrm{MR} = a.\exp(-\mathrm{kt}^{\mathrm{n}}) + b.t$	Midilli et al. (2002)

pared to M_t and M_0, hence the error involved in the simplification by assuming that M_e is equal to zero is negligible (Akgun and Doymaz, 2005), then the equation could be simplified as follows:

$$\mathrm{MR} = \frac{M_t}{M_0} \tag{2}$$

Statistical test using the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were calculated to evaluate the goodness of fit of each model. The χ^2, RMSE and R^2 were calculated according to the following equations (Ertekin and Yaldiz, 2004):

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}})^2}{N - z} \tag{3}$$

$$\mathrm{RMSE} = \left(\frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp},i})^2}{N}\right)^{\frac{1}{2}} \tag{4}$$

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - \overline{MR}_{\exp})(MR_{pre,i} - \overline{MR}_{pre})}{\sqrt{\sum_{i=1}^{N}(MR_{\exp,i} - \overline{MR}_{\exp})^2 \sum (MR_{pre,i} - \overline{MR}_{pre})^2}} \tag{5}$$

where $\mathrm{MR}_{\mathrm{exp}}$ is the experimental dimensionless moisture ratio, $\mathrm{MR}_{\mathrm{pre}}$ is the predicted dimensionless moisture ratio by model, N is the number of experimental data points, and z is the number of parameters in model. The model is said to be good if R^2 value is high and, χ^2 and RMSE values are low.

Drying rate was defined as (Akpinar et al., 2003):

$$\mathrm{DR} = \frac{M_{t+\Delta t} - M_t}{t} \tag{6}$$

where $M_t + \Delta t$ is moisture content at time $t + \Delta_t$ (kg [H_2O]/kg dry mater), M_t is moisture content at time t (kg water/kg dry matter), t is the time (min) and DR is the drying rate (kg [H_2O]/kg dry mater. min).

2.4. Energy and efficiency analysis

For obtain the energy consumption and efficiency of the drying process, it is necessary primary energy consumption in fuel and available energy of the waste exhaust gases, were concluded.

Fuel energy consumption for an IC engine is obtained with a calorific value and consumption of the fuel. Energy consumption was calculated using Eq. 7:

$$Q_t = \left(\frac{\dot{m}_f Q_{LCV}}{3.6}\right) \times t \tag{7}$$

where, Q_t is the fuel energy consumption in kWh, $\dot{m}_f$ is the fuel consumption in m^3/hr which is obtained by a gas flow meter, Q_{LCV} is the lower calorific value of gas fuel in MJ/m^3 and t is the engine time of operation in hours.

Energy of the waste exhaust gases includes a significant portion of the fuel energy in the IC engine (Özcan and Söylemez, 2006). With having mass flow rate and temperature of the exhaust gases, available energy of the exhaust gases is achieved using Eq. 8:

$$Q_{\mathrm{ex}} = [\dot{m}_{\mathrm{ex}} C_p (T_{\mathrm{in,ex}} - T_{\mathrm{out,ex}}) \times t]/3600 \tag{8}$$

where, Q_{ex} is the energy of exhaust gases in kWh, $T_{\mathrm{in,ex}}$ and $T_{\mathrm{out,ex}}$ are the exhaust gas temperature at the inlet and outlet of dryer chamber in °C respectively, C_p is the specific heat at constant pressure of exhaust gases in J/kg K, $\dot{m}_{ex}$ is the mass flow rate of exhaust gases in kg/h which is obtained using Eq. 9:

$$\dot{m}_{\mathrm{ex}} = \dot{m}_f(1 + \mathrm{AF}) \tag{9}$$

where, $\dot{m}_f$ is the mass flow rate of fuel in m^3/h and AF is the air to fuel ratio.

The system can be observed as two subsystems, the power system, which is an IC engine that produces electricity and the heat recovery system, which is a dryer for drying process.

The system efficiency when the engine only produces electricity (single generation) is given by:

$$\eta_{s.g} = \frac{P_{\mathrm{el}} \times 3.6}{\dot{m}_f \mathrm{Q}_{\mathrm{LCV}}} \times 100 \tag{10}$$

where, P_{el} is the electric power generation (kW) and $\eta_{s.g}$ is the efficiency of single generation.

The overall efficiency of the system (CHP efficiency) is defined as the heating capacity of the dryer (kW) divided by the energy input to the engine from the fuel plus the efficiency of single generation.

$$\eta_{\mathrm{CHP}} = \eta_{s.g} + \frac{\dot{m}_{\mathrm{ex}} C_p (T_{\mathrm{in,ex}} - T_{\mathrm{out,ex}})}{3600 \times \dot{m}_f Q_{\mathrm{LCV}}} \times 100 \tag{11}$$

Also the parameter of specific energy consumption is used to evaluate the energy consumption of the dryers. The specific energy consumption (SEC) was calculated as the energy needed to evaporate a unit mass of water from the product in kWh/kg [H_2O] from Eq. 12: (Sharma and Prasad, 2006)

$$\mathrm{SEC} = \frac{Q_t}{m_w} \tag{12}$$

where, SEC is the specific energy consumption in $\mathrm{kWh/kg_{water}}$, m_w is the amount of water evaporated during the drying process in kg.

3. Results and discussion

3.1. Drying kinetic and mathematical modeling

The moisture content versus drying time curves for CHP drying of banana samples as affected by various engine loads are shown in Fig. 2. Engine loads had an important effect on drying time. The time required to dry banana samples from initial moisture content of 68.3 ± 1.5% (w.b.) to the final moisture content of 4 ± 1% (w.b.) decreased significantly with increasing engine loads.

According to Fig. 2, the minimum drying time of banana slices occurred at full engine load (temperature of 95 °C) and 3 mm thickness while its maximum was at 25% of engine load (temperature of 50 °C) and 7 mm thickness. This is because; at higher loads of engine the gas temperature and mass flow rate of exhaust are increased. Therefore, the available energy of exhaust gases for drying of banana slices is increased. Also the mass transfer within the sample was more rapid in higher engine loads (temperatures) because there was an increase in thermal gradient inside the samples and the evaporation rate of the product. The temperature in the dryer chamber at 25%, 50%, 75% and full load of engine was approximately 50, 65, 80 and 95, respectively. Additionally, it could be found, when the slice thickness increased at fixed engine loads, drying time increased. Thinly sliced products dried faster due to faster moisture transfer from the body to the surface and hence, the increased surface area for the same amount of the product (Ertekin and Yaldiz, 2004). On the other hand, since the drying occurs initially at the outer layer, hardened layer is created on the outer surface of product. This hardened layer imposes a

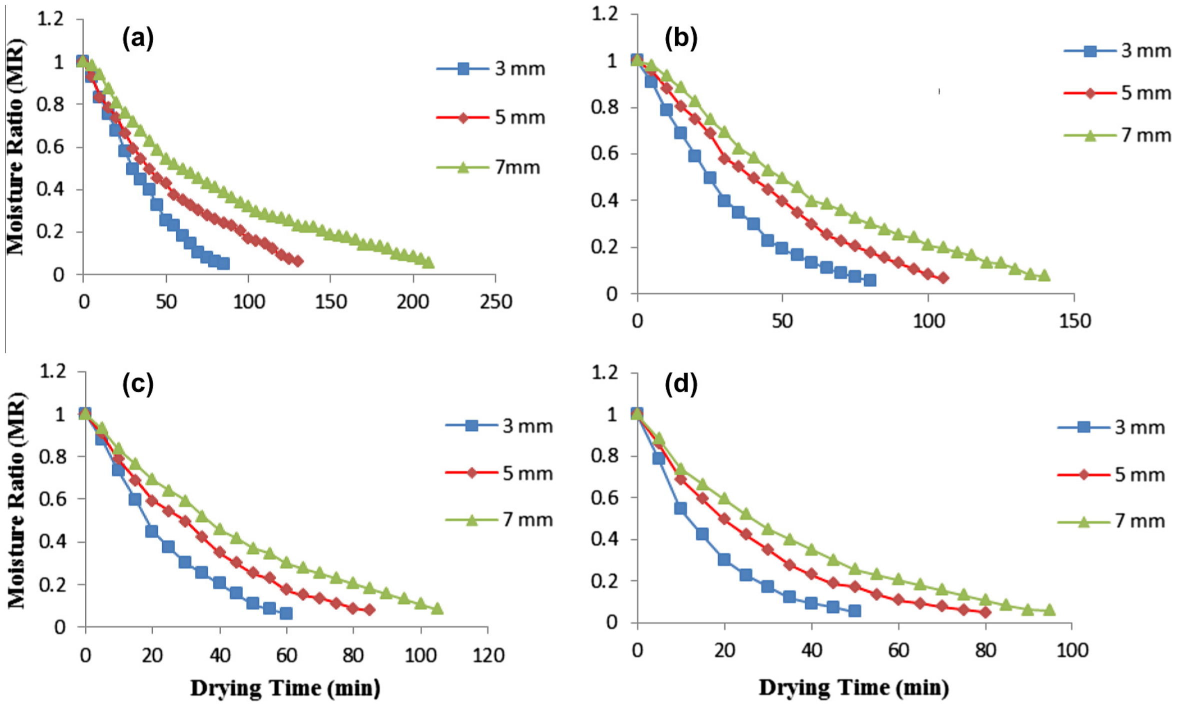

Figure 2 The variation of the moisture content with drying time at various engine loads (a) 25%, (b) 50% (c) 75% and (d) 100%.

Table 2 Results of statistical analysis on the modeling of moisture content and drying time in CHP dryer system.

No.	Load-thickness			Constance	R^2	X^2	*RMSE*
1	25%-3 mm	$k = 0.02515$			0.9715	0.00281	0.05286
	25%-5 mm	$k = 0.01703$			0.9971	2.04×10^{-4}	0.01434
	25%-7 mm	$k = 0.01132$			0.9966	2.41×10^{-4}	0.01554
	50%-3 mm	$k = 0.03019$			0.9900	9.18×10^{-4}	0.03037
	50%-5 mm	$k = 0.01880$			0.9589	0.0041	0.06341
	50%-7 mm	$k = 0.01474$			0.9847	0.00123	0.03523
	75%-3 mm	$k = 0.03923$			0.9898	9.93×10^{-4}	0.03152
	75%-5 mm	$k = 0.02594$			0.9972	0.002286	0.01500
	75%-7 mm	$k = 0.02000$			0.9932	5.43×10^{-4}	0.02332
	100%-3 mm	$k = 0.05999$			0.9947	5.41×10^{-4}	0.02327
	100%-5 mm	$k = 0.03116$			0.9857	0.00101	0.03181
	100%-7 mm	$k = 0.02703$			0.9981	1.52×10^{-4}	0.01236
2	25%-3 mm	$k = 0.00686$	$n = 1.347$		0.9976	2.33×10^{-4}	0.01574
	25%-5 mm	$k = 0.01483$	$n = 1.034$		0.9976	1.75×10^{-4}	0.01352
	25%-7 mm	$k = 0.01037$	$n = 1.019$		0.9968	2.31×10^{-4}	0.01539
	50%-3 mm	$k = 0.01573$	$n = 1.182$		0.9986	1.25×10^{-4}	0.01158
	50%-5 mm	$k = 0.00335$	$n = 1.434$		0.9974	2.47×10^{-4}	0.01625
	50%-7 mm	$k = 0.00773$	$n = 1.152$		0.9920	6.71×10^{-4}	0.02588
	75%-3 mm	$k = 0.02139$	$n = 1.182$		0.9983	1.71×10^{-4}	0.01350
	75%-5 mm	$k = 0.02025$	$n = 1.066$		0.9986	1.15×10^{-4}	0.01103
	75%-7 mm	$k = 0.01292$	$n = 1.110$		0.9971	2.23×10^{-4}	0.01572
	100%-3 mm	$k = 0.04428$	$n = 1.106$		0.9975	2.53×10^{-4}	0.01719
	100%-5 mm	$k = 0.05138$	$n = 0.860$		0.9945	3.87×10^{-4}	0.02030
	100%-7 mm	$k = 0.02540$	$n = 1.017$		0.9982	1.45×10^{-4}	0.01238
3	25%-3 mm	$a = -0.01872$	$b = 8.687 \times 10^{-5}$		0.9977	2.30×10^{-4}	0.01564
	25%-5 mm	$a = -0.01404$	$b = 5.66 \times 10^{-5}$		0.9927	5.26×10^{-4}	0.02340
	25%-7 mm	$a = -0.00916$	$b = 2.374 \times 10^{-5}$		0.9879	8.71×10^{-4}	0.02989
	50%-3 mm	$a = -0.02380$	$b = 0.0001545$		0.9973	2.56×10^{-4}	0.01635
	50%-5 mm	$a = -0.01410$	$b = 4.822 \times 10^{-5}$		0.9887	0.0011	0.03399
	50%-7 mm	$a = -0.01188$	$b = 3.940 \times 10^{-5}$		0.9886	9.25×10^{-4}	0.03102
	75%-3 mm	$a = -0.03071$	$b = 0.0002560$		0.9962	3.66×10^{-4}	0.02001
	75%-5 mm	$a = -0.02053$	$b = 0.0001159$		0.9954	3.37×10^{-4}	0.01994
	75%-7 mm	$a = -0.01593$	$b = 7.020 \times 10^{-5}$		0.9946	4.36×10^{-4}	0.02138
	100%-3 mm	$a = -0.04799$	$b = 0.0006412$		0.9952	4.86×10^{-4}	0.02382
	100%-5 mm	$a = -0.02523$	$b = 0.0001801$		0.9604	0.002812	0.05466
	100%-7 mm	$a = -0.02116$	$b = 0.0001228$		0.9888	8.92×10^{-4}	0.03069
4	25%-3 mm	$a = 1.0800$	$k = 0.02725$		0.9807	0.00190	0.04488
	25%-5 mm	$a = 1.0100$	$k = 0.01724$		0.9973	1.91×10^{-4}	0.01413
	25%-7 mm	$a = 1.0200$	$k = 0.01157$		0.9972	1.92×10^{-4}	0.01427
	50%-3 mm	$a = 1.0520$	$k = 0.03182$		0.9939	5.56×10^{-4}	0.02455
	50%-5 mm	$a = 1.1100$	$k = 0.02105$		0.9762	0.0023	0.04942
	50%-7 mm	$a = 1.0660$	$k = 0.01584$		0.9915	6.89×10^{-4}	0.02673
	75%-3 mm	$a = 1.0480$	$k = 0.04119$		0.9933	6.5×10^{-4}	0.02664
	75%-5 mm	$a = 1.0230$	$k = 0.02655$		0.9980	1.65×10^{-4}	0.01332
	75%-7 mm	$a = 1.0330$	$k = 0.02072$		0.9949	4.04×10^{-4}	0.02066
	100%-3 mm	$a = 1.0200$	$k = 0.06126$		0.9955	4.64×10^{-4}	0.02327
	100%-5 mm	$a = 0.9621$	$k = 0.02984$		0.9882	8.41×10^{-4}	0.02988
	100%-7 mm	$a = 1.0010$	$k = 0.02706$		0.9981	1.52×10^{-4}	0.01269
5	25%-3 mm	$a = 1.3470$	$c = -0.31740$	$k = 0.01610$	0.9972	2.45×10^{-4}	0.01773
	25%-5 mm	$a = 1.0400$	$c = -0.03934$	$k = 0.01580$	0.9978	0.000154	0.01299
	25%-7 mm	$a = 1.0190$	$c = 0.000967$	$k = 0.01160$	0.9972	1.98×10^{-4}	0.01445
	50%-3 mm	$a = 1.1060$	$c = -0.07331$	$k = 0.02708$	0.9964	0.000331	0.01948
	50%-5 mm	$a = 1.3790$	$c = -0.31860$	$k = 0.01269$	0.9908	8.95×10^{-4}	0.03152
	50%-7 mm	$a = 1.1120$	$c = -0.06206$	$k = 0.01392$	0.9927	6.09×10^{-4}	0.02534
	75%-3 mm	$a = 1.1190$	$c = -0.09133$	$k = 0.03394$	0.9967	3.23×10^{-4}	0.01969
	75%-5 mm	$a = 1.0370$	$c = -0.02128$	$k = 0.02518$	0.9983	1.43×10^{-4}	0.01263
	75%-7 mm	$a = 1.1030$	$c = -0.09338$	$k = 0.01703$	0.9976	1.93×10^{-4}	0.01457
	100%-3 mm	$a = 1.0970$	$c = -0.09135$	$k = 0.05100$	0.9978	2.28×10^{-4}	0.01790
	100%-5 mm	$a = 0.9180$	$c = 0.076870$	$k = 0.03772$	0.9940	4.23×10^{-4}	0.02191
	100%-7 mm	$a = 1.0260$	$c = -0.03553$	$k = 0.02479$	0.9988	9.55×10^{-5}	0.01033

(*continued on next page*)

Table 2 *(continued)*

No.	Load-thickness			Constance		R^2	X^2	*RMSE*
6*	25%-3 mm	$a = 0.9985$	$b = -0.0007371$	$k = 0.00893$	$n = 1.246$	0.9988	1.11 × 10–4	0.01198
	25%-5 mm	$a = 1.0080$	$b = -0.0003492$	$k = 0.01859$	$n = 0.962$	0.9980	1.41×10^{-4}	0.01289
	25%-7 mm	$a = 1.0360$	$b = -0.0001331$	$k = 0.01546$	$n = 0.930$	0.9976	1.75×10^{-4}	0.01375
	50%-3 mm	$a = 0.9999$	$b = -0.0002874$	$k = 0.0140$	$n = 1.225$	0.9989	1.01×10^{-4}	0.01119
	50%-5 mm	$a = 0.9994$	$b = -0.0002461$	$k = 0.00287$	$n = 1.484$	0.9977	2.28×10^{-4}	0.01635
	50%-7 mm	$a = 1.0360$	$b = -5.540 \times 10^{-5}$	$k = 0.01077$	$n = 1.081$	0.9931	5.06×10^{-4}	0.02508
	75%-3 mm	$a = 1.0070$	$b = -5.260 \times 10^{-5}$	$k = 0.02211$	$n = 1.176$	0.9984	1.58×10^{-4}	0.01465
	75%-5 mm	$a = 1$	$b = -0.0001125$	$k = 0.01923$	$n = 1.085$	0.9987	1.10×10^{-4}	0.01138
	75%-7 mm	$a = 1.0070$	$b = -0.0004649$	$k = 0.01682$	$n = 1.024$	0.9977	1.86×10^{-4}	0.01470
	100%-3 mm	$a = 1.0040$	$b = -0.0011380$	$k = 0.05030$	$n = 1.038$	0.9979	2.17×10^{-4}	0.01949
	100%-5 mm	$a = 1.0130$	$b = -0.0001872$	$k = 0.05165$	$n = 0.870$	0.9949	3.64×10^{-4}	0.02105
	100%-7 mm	$a = 1.0030$	$b = -0.0005574$	$k = 0.03195$	$n = 0.932$	0.9992	6.65×10^{-5}	0.00889

barrier against the dissipation of moisture across the product's surface and prolongs its departure from the product (Doymaz and Ismail, 2011).

The moisture content data obtained from the drying experiments at different temperatures and thicknesses of sample were fitted to 6 thin-layer drying models (Table 1). The regression analyses were done for six different thin layer drying models by relating the drying time and moisture ratio (MR) for banana samples. The statistical results from the models such as R^2, χ^2, RMSE and drying constant values are shown in Table 2. The accuracy of different thin-layer drying models was evaluated based on R^2, χ^2 and RMSE values and the most accurate model was selected with regard to higher R^2 and lower χ^2 and RMSE. The results of fitting different models with data from banana drying showed the Midili et al. model (NO. 6) is able to estimate the moisture content reasonably over most of the drying time.

Based on the multiple regression analysis, the Midili et al. model, the constants and coefficients are as follows:

$$\mathrm{MR} = a \cdot exp(-kt^n) + b.t$$

$$\begin{aligned} a = {} & 1.057 + 0.0004668L - 0.04405S - 2.604 \times 10^{-5}L^2 \\ & + 0.0005214LS + 0.005819S^2 + 1.472 \times 10^{-7}L^3 + 4 \\ & \times 10^{-8}L^2S - 6.78 \times 10^{-5}LS^2 \\ & R^2 = 0.88 \end{aligned}$$

$$\begin{aligned} b = {} & -0.001757 + 5.409 \times 10^{-5}L - 0.0001703S - 5.736 \\ & \times 10^{-7}L^2 + 1.672 \times 10^{-6}LS + 7.042 \times 10^{-5}S^2 - 1.92 \\ & \times 10^{-9}L^3 + 1.365 \times 10^{-7}L^2S - 1.945 \times 10^{-6}LS^2 \\ & R^2 = 0.86 \end{aligned}$$

$$\begin{aligned} k = {} & 0.1095 - 0.001588L - 0.04584S + 1.638 \times 10^{-6}L^2 \\ & + 0.0006526LS + 0.004833S^2 + 5.367 \times 10^{-8}L^3 - 3.304 \\ & \times 10^{7}L^2S - 6.88e \times 10^{-5}LS^2 \\ & R^2 = 0.95 \end{aligned}$$

$$\begin{aligned} n = {} & -2.108 + 0.06246L + 1.424S - 0.0004779L^2 - 0.0166LS \\ & - 0.1547S^2 + 2.474 \times 10^{-6}L^3 - 1.251 \\ & \times 10^{-5}L^2S + 0.001879LS^2 \\ & R^2 = 0.97 \end{aligned}$$

where, L is the engine load, S is the sample thickness (mm), MR is the moisture ratio, k is the drying rate constant (min^{-1}), t is the drying time (min), a, b, n is the dimensionless drying constant and k is the drying constant (min^{-1}).

3.2. System analysis

A comparison of electric energy and available heat recovery energy in CHP dryer system at different conditions is shown in Figs. 3 and 4, respectively. In this system, overall useful en-

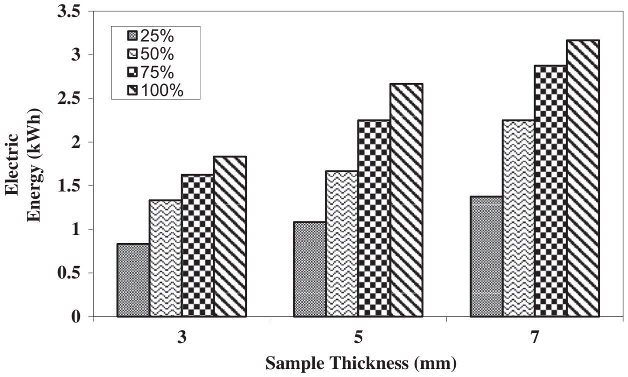

Figure 3 Electrical energy generation in the CHP dryer at different thicknesses and engine loads.

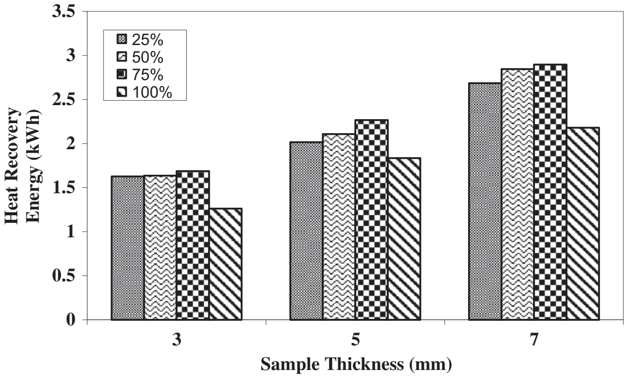

Figure 4 Heat energy recovery in the CHP dryer at different thicknesses and engine loads.

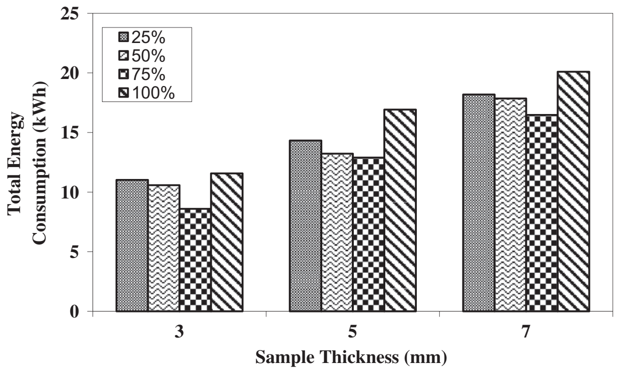

Figure 5 Total energy consumption in the CHP dryer at different thicknesses and engine loads.

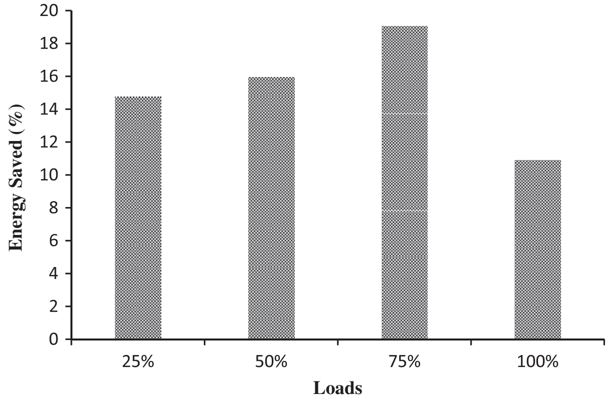

Figure 7 Energy saved at various loads of engine.

ergy includes the electric energy plus the heat recovery energy from the exhaust engine that was used for drying process. It can be seen that, for all the engine loads by increasing the thickness of sample, drying time has been increased. Therefore, overall useful energy (electrical and heat) was increased. Electric energy increases with the rise of engine loads, but the variation of heat recovery energy is quite different. For all the thicknesses, heat recovery e energy at 75% engine load is obtained. In the full load engine the drying temperature is higher as compared to other loads, but the mass flow rate of exhaust gases is lower due to the decreasing air/fuel ratio of the engine for complete combustion.

Fig. 5 shows values of energy consumption at different thicknesses and engine loads that were concluded by Eq 7. The minimum energy requirement for drying process was achieved at 75% engine load and thickness of 3 mm. Also maximum total energy consumption was obtained at 25% and full loads. More energy consumption at 25% is due to the longer drying time. Exhaust temperature at lower loads is lower. As a result, less energy was available for the same time period and hence the drying time was increased. However, at higher loads drying time was reduced, but a maximum fuel consumption is at full load. The main cause of increasing the energy consumption was reducing the air/fuel ratio for complete combustion in the engine.

Total and electrical efficiency at different thicknesses and engine loads is presented in Fig. 6. It is seen from the figure that the total and electrical efficiency increases with an increase in the load, but efficiency at full load is lower than that of 75% engine load. This is mainly because of an increase in the fuel consumption at full load. Electrical efficiency ($\eta_{s.g}$) in this work is between 7.6 and 18.9%. Maximum efficiency at 75% engine load is achieved. More energy efficiency is at 75% engine load due to reducing the primary energy consumption. It shows that utilization of waste heat in the drying process is an important factor to improve system efficiency. In this case, due to simultaneous use of heat and power (CHP), maximum energy efficiency was increased to 32%. The maximum efficiency is obtained at 75% engine load.

Also, Fig. 7 shows the energy saved due to the simultaneous use of heat and power at various load conditions. The results in this work showed that by using heat recovery methods in the exhaust of this CHP system an increase of 11–20% in system efficiency was observed. The maximum efficiency was obtained at 75% engine load.

The results show that energy efficiency at the different thicknesses of the samples nearly equals each other. Thus, to compare energy drying at different thicknesses and engine loads, the parameter of the specific energy consumption (SEC) in drying process was used. Fig. 8 shows specific energy

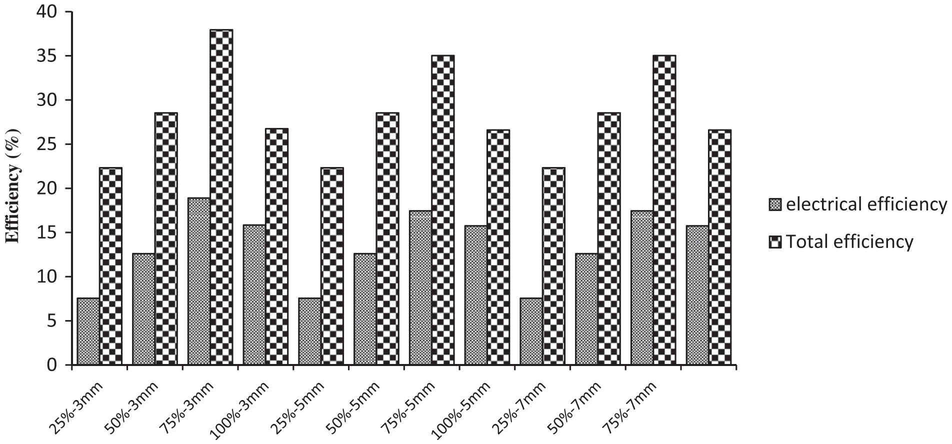

Figure 6 Total and electrical efficiency at different thickness and engine loads.

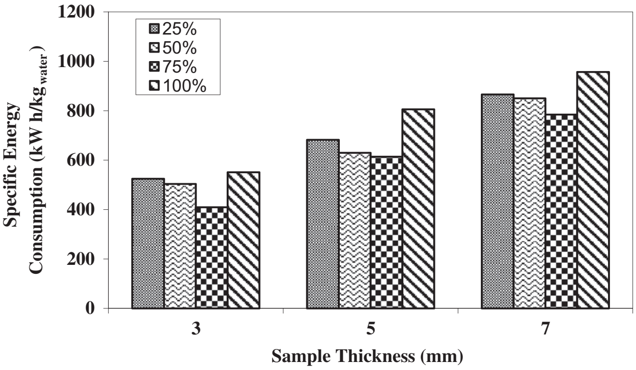

Figure 8 Specific energy consumption of drying at different thicknesses and engine loads.

consumption under various conditions of drying process. It was found that the SEC decreased with a decrease in the thickness of the sample. According to Fig. 8, the minimum specific energy consumption was observed to be 409 kWh/kg_{water} obtained at 75% engine load and 3 mm thickness of product while the maximum was 957kWh/kg_{water} at full load and thickness of 7 mm. In other words, energy consumption in the thickness of 7 mm (full load) was nearly 2.3 times that consumed in the thickness of 3 mm (75% load). This is because, at 75% engine load and thickness of 3 mm, drying time was reduced than when the drying is done at low loads. Therefore, fuel consumption and SEC were reduced. Also, at engine loads greater than 75% (full load) although the drying time was reduced, the rate of fuel consumption and hence specific energy consumption were increased.

4. Conclusions

In this research work, the heat recovery energy from the exhaust of IC engine was used for drying banana slices. The drying kinetics and energy parameters of the system have been studied. According to the result, drying time decreased significantly with increasing engine load and sample thickness. The minimum and maximum drying time was found for full loads (3 mm thickness of samples) and 25% loads (7 mm thickness of samples), respectively. Also, results from the multiple linear regression analysis showed that the Midilli et al. drying model described best the drying behavior of banana slices.

The present study confirms the importance of heat recovery to improve the system efficiency and energy consumption. Results from the CHP system showed that energy efficiency increased considerably. By using heat recovery methods in the exhaust of this CHP system an increase of 11–20% in system efficiency was observed. The maximum efficiency was obtained at 75% engine load. Also, the results showed that the specific energy consumption (SEC) decreased with a decrease in the thickness of the sample. The SEC was in the range of 409–957kWh/kg_{water}. The lowest specific energy consumption of the drying process was observed at 75% engine load and a thickness of 3 mm.

It is expected that this system will help the reduction in fuel consumption and the increasing energy efficiency. Therefore CHP dryer is a good alternative for conventional dryers in industrial applications.

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