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Application of Combined Heat and Power for Drying Agricultural Products (apple slices) to Save Energy

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Abstract

In this research work, the waste heat of exhaust gas of an engine-generator for the process of apple slice drying was used and tested. Drying experiments were conducted at different engine loads (25%, 50%, 75% and full load) and thickness of the samples (3, 5 and 7 mm). Experiments were conducted to evaluate the drying kinetics, comparison of energy consumption and efficiency of the combined heat and power (CHP) and electricity generation. The results showed that drying time decreased significantly with increasing the engine load and decreasing thickness of test samples. Also, the specific energy consumption (SEC) was decreased with a decrease in the thickness of the samples. The SEC varied between 518-1071kWh/kg_{water}. The lowest value of SEC of 518 kWh/kg_{water} was observed at 75% engine load and thickness of 3 mm. Energy efficiency of CHP was from 68% to 210% higher than that of electricity generation. The maximum efficiency was obtained at 75% engine load. The brake specific fuel consumption (BSFC) was from 40.7% to 67.7% lower than that of electricity generation under different engine loads. This study showed that the use of exhaust waste heat of an engine-generator for drying process in the final energy consumption is very reasonable.

***Keywords*:** Combined heat and power, Drying kinetics, Energy efficiency, Energy consumption

Nomenclature

AF	air to fuel ratio
BSFC	brake specific fuel consumption (m^3/kW.h)
CHP	combined heat and power
C_p	specific heat at constant pressure of exhausts chamber (ºC)
$\dot{m}_{ex}$	mass flow rate of exhaust gases (kg/h)
$\dot{m}_f$	fuel consumption (m^3/hr)
m_w	amount of water evaporated during the drying process (kg)
$M_{w.b}$	moisture content on a wet basis (%)
Q_{ex}	energy of exhaust gases (kWh)
Q_{LCV}	calorific value of gas fuel (MJ/m^3)
Q_t	primary energy consumption (kWh)
SEC	specific energy consumption (kWh/kg_{water})
t	engine operation time (hr)
$T_{in, ex}$	exhaust gas temperature at the inlet of drier's gases (J/kg K)
W_0	initial weight of undried product (g)
W_d	final weight of the sample after drying (g)
η_{CHP}	energy efficiency of the combined heat and power technology (%)
η_{el}	energy efficiency of the single generation (%)

INTRODUCTION

Using new method and technology for energy production that do not have the disadvantages of conventional methods is becoming widespread in the world. One of these new technologies is combined heat and power (CHP). Combined heat and power (CHP) also known as cogeneration is the sequential or simultaneous generation of multiple forms of useful energy (usually electrical and thermal) in a single, integrated system. The conventional way to provide electricity and heat is to purchase electricity from the local grid and generate heat by burning fuel in a boiler. But in a CHP system, by-product heat, which can be as much as 60–80% of total primary energy in combustion-based electricity generation, is recycled for different uses [1-4]. CHP is versatile and can be coupled with existing and planned technologies for many different applications in the industrial, commercial, and residential sectors [5-12].

CHP technologies have different heat recovery potentials. Some CHP technologies may produce low temperature hot water (LTHW) generation (less than 250°F), low-pressure steam production (15 psig or less), or medium-pressure steam. Some heat recovery systems are a part of the equipment served. For example, an exhaust gas-fired absorption chiller-boiler, which directly intakes the exhaust from the prime mover and uses the hot exhaust gases directly to drive the absorption process and also to produce hot water for other uses. Another occasional thermal use is direct heating or drying, which can be highly efficient as exhaust gas transfers its energy as it cools to ambient temperature. In some industrial applications, the exhaust from a prime mover (such as gas turbine, reciprocating engines, Stirling engines, etc.) is directed to a process such as drying agricultural products [13-15].

Apple is the pomaceous fruit of the apple tree, species Malus domestica in the rose family (Rosaceae). The apple is an important raw material for many food products. The apple plantations are cultivated all over the world in many countries. It is the fourth most important world fruit crop following all citrus types, grapes, and bananas [16]. The apple is one of the most important horticultural crops in Iran. More than 1660000 tons of apples are produced in Iran [17]. Improper storage methods cause losses of fruits and vegetables which range from 10% to 30% [18]. In many cases drying is usually used to minimize deterioration after harvesting. Drying is one of the oldest methods of food preservation and it is one of the most common processes used to improve food stability. 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. One of the biggest advantages of dried foods is that they take much less storage space than canned or frozen foods [19].

Hot air convection drying is one of the oldest methods and the most widely used methods of drying. Over 85% of industrial dryers are of convective type with hot air. One of the disadvantages of these dryers is high energy consumption [20, 21]. Also, this energy could be supplied from the solar energy; however, issues with using solar energy led to replace the traditional drying processes with the industrial operations. In turn, using these industrial operations requires high amounts of energy and turns the drying of agricultural products into an energy-intensive process [22]. Some research works have been carried out in drying of agriculture products with waste heat from the engine such as: [23-26], biomass drying [27, 28], pulp and paper mill [29], clay minerals [30] and grand composite [31]. However, there is no extensive and complete research on the drying of agricultural products using the exhaust's hot leaving gas.

In this study, it is tried to supply this energy demand using the outlet heat of an engine generation set exhaust. Cogeneration or the Combined Heat and Power (CHP) method is an energy saving method where the mechanical power and heat are produced simultaneously. As applied to drying, heat from a cogeneration system can be taken from an engine cooling liquid and/or engine exhaust gases. Direct use of the exhaust gases as a heat and momentum carrier in convective dryers is technically feasible. In this study, the waste heat of exhaust gas of an internal combustion engine was used for the process of apple slice drying. The aim of this study is to investigate drying kinetics, comparison of energy consumption and efficiency with and without CHP application.

MATERIALS AND METHODS

Materials

Cultivar of Golab apple was used in the present study which was purchased from the local market in Tehran and was stored in a refrigerator at 4 ºC. Initial moisture content of the apple slices was determined by drying in an air convection oven. About 40 g sample was placed in an oven at 105± 1° C for 4 h until a constant weight was achieved. After drying, moisture content of 86.2% on a wet basis was achieved. Moisture content on a wet basis was calculated as follows [32]:

$$M_{w.b} = \left(\frac{W_o - W_d}{W_o} \right) \times 100 \qquad (1)$$

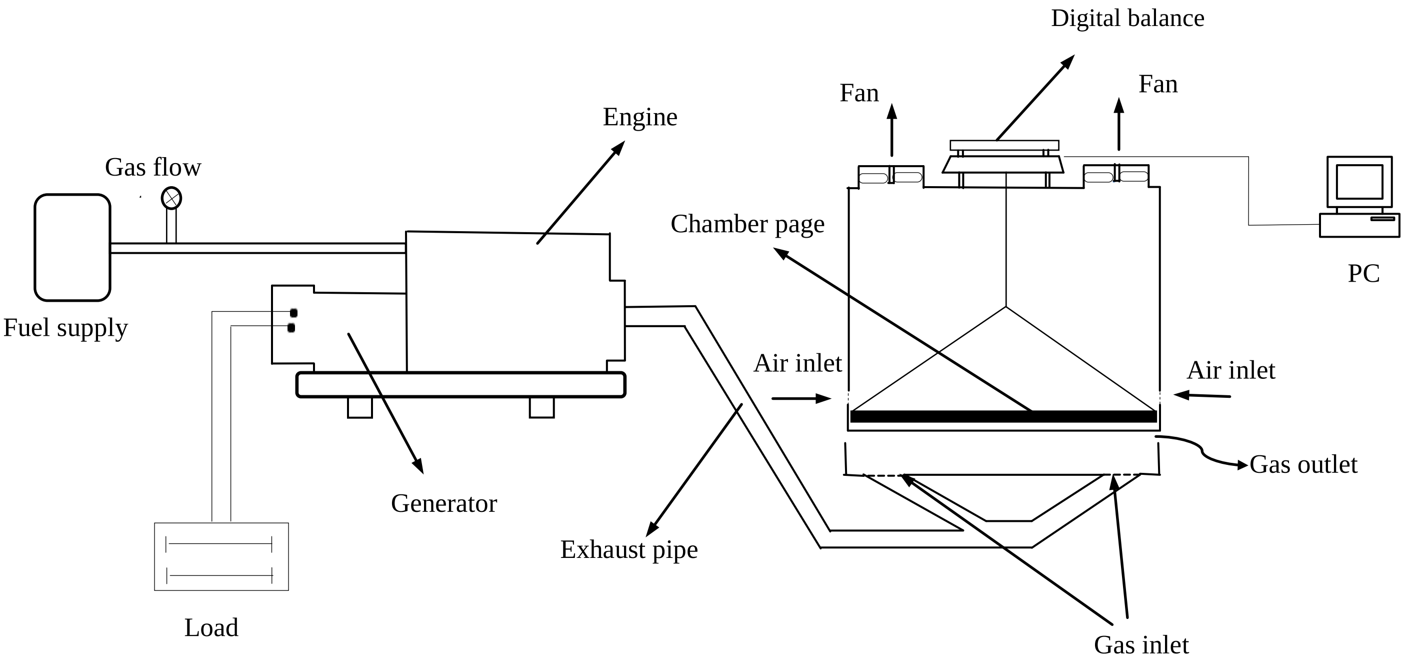
where, $M_{w.b}$ is the moisture content on a wet basis in %, W_o is the initial weight of undried product in g, W_d the final weight of the sample after drying in g.

Apples were cut into slices of thickness approximately 3, 5 and 7 mm. For presses drying, 50 g samples were used in each experiment. Drying process was done until the moisture content about 5% on a wet basis was achieved. Each experiment was done in triplicate.

System Description

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

Waste heat from the engine exhaust was directed into the dryer chamber. The heat is approached directly under the



Figur1. Schematic diagram of the drying equipment

chamber page and the drier's chamber is warmed. Hot air is circulated inside the chamber and is removed from the chamber by a fan. Engine was run for a few minutes to reach steady state conditions. The drying experiments were performed at constant speed and four load levels, 25%, 50%, 75% and full load. About 50g samples with a thickness of 3, 5 and 7 mm were placed dryer chamber and were dried. Samples were weighted automatically by the digital balance with ±0.01 accuracy for 5 min.

Energy Consumption

Energy consumption in heating and drying process, are the important parameter. The engine chemical energy in the fuel is converted into mechanical energy of the engine shaft. Only a portion of fuel energy is available for useful work in the engine. The rest of the energy is wasted through heat losses. Energy consumption for an engine is obtained with calorific value and consumption of the fuel. Energy consumption is calculated by following formula:

$$Q_t = \left(\frac{\dot{m}_f Q_{LCV}}{3.6} \right) \times t \qquad (2)$$

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

Exhaust waste heat includes a significant portion of the fuel energy in the engine [33, 34]. With having mass flow rate and temperature of the exhaust gases, available energy of the exhaust gases is achieved by:

$$Q_{ex} = \left[\dot{m}_{ex} C_p (T_{in,ex} - T_{out,ex}) \times t \right] / 3600 \qquad (3)$$

where, Q_{ex} is the energy of exhaust gases in kWh, $T_{in,ex}$ and $T_{out,ex}$ is the exhaust gas temperature at the inlet and outlet of dryer chamber in ºC 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 by using:

$$\dot{m}_{ex} = \dot{m}_f (1 + AF) \qquad (4)$$

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

The parameter of specific energy consumption is used to evaluate the energy consumption of the dryers [35].

$$SEC = \frac{Q_t}{m_w} \qquad (5)$$

Where, SEC is the specific energy consumption in kWh/kg, m_w is the amount of water evaporated during the drying process in kg.

RESULTS AND DISCUSSION

Drying Kinetics

Figure 2 shows the change of moisture content (dry basis) with drying time at different engine loads for thickness of 3 mm. It is clearly seen from Fig. 2 that drying time decreased significantly with increasing the engine loads. Drying duration at 25% engine load is approximately twice at full load. This is because; exhaust gas temperature and flow rate is increased with increasing the engine load. Therefore, more energy is available for the drying process. Also, the temperature gradients between the air drying and the products in higher temperatures are higher than lower temperatures. Thus, the temperature increase causes a decrease in relative moisture of sample and increases the vapor pressure of produce inside. The temperature in the dryer chamber at 25%, 50%, 75% and full load is approximately 50, 65, 80 and 95, respectively.

Also the variation of moisture content with drying time at different engine loads for thickness of 5 and 7 mm are shown in Figs. 3 and 4, respectively. With increasing thickness of the sample, increases drying time. For instance, drying time at 50% load and thickness of 3, 5 and 7 mm were about 125, 210 and 260 min, respectively. Thinner samples 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 [36]. On the other hand, since the drying occurs initially at the outer layer, the product is then dried and its permeability is therefore decreased (hardening phenomenon). This hardened layer imposes a barrier against the dissipation of moisture across the product's surface and prolongs its departure from the product. Similar results were reported in other research works for drying of pomegranate seeds [21, 37, 38].

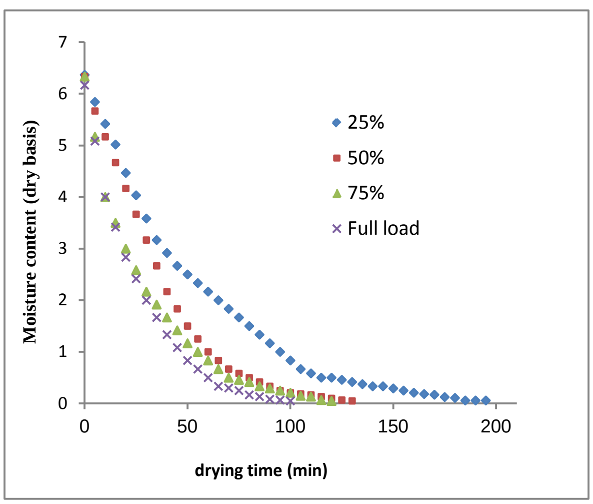


Figure 2. Variation of moisture content with drying time at different engine loads when sample thickness is 3 mm.

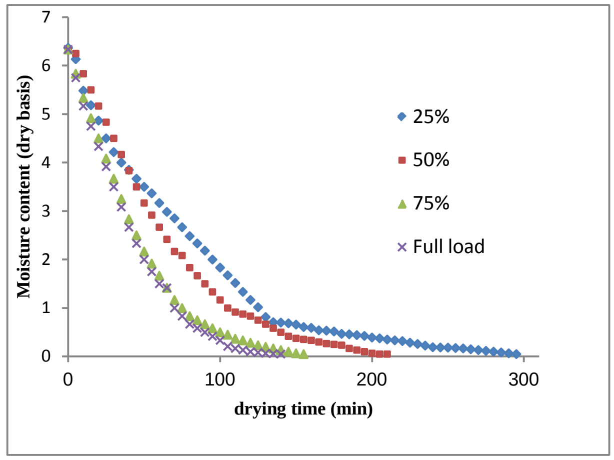


Figure 3. Variation of moisture content with drying time at different engine loads when sample thickness is 5 mm.

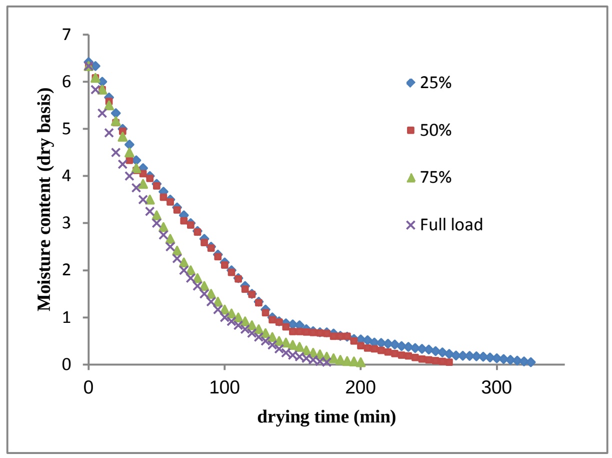


Figure 4. Variation of moisture content with drying time at different engine loads when sample thickness is 7 mm.

Energy usage and efficiency

Figure 5 presents a comparison of the total and useful energy consumption. Overall useful energy includes electrical energy and heat recovery energy from the exhaust engine that was used for drying process. It is seen from the results that, the minimum of total energy consumed by engine –generator was achieved at 75% engine load and thickness of 3 mm. Also maximum total energy consumption is obtained in 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 of 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.

Energy efficiency with and without heat recovery are shown in figs. 6 and 7, respectively. The values at different engine loads and thickness of the sample are obtained. The conditions without heat recovery, system efficiency is between 7 to 16%. Maximum efficiency at 75% engine load is obtained. More energy efficiency at 75% engine load is due to reducing the primary energy consumption. When the exhaust waste heat was used for drying process, the system performance was increased significantly. In this case, simultaneous use of heat and power (CHP), maximum energy efficiency was increased to 32%. Similar to Previous case, the maximum efficiency is obtained at 75% engine load.

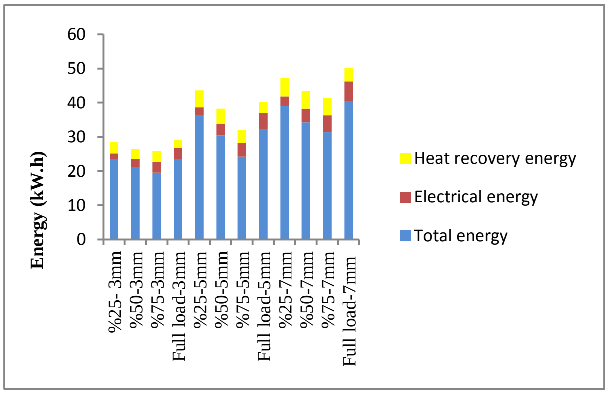


Figure 5. Total and useful energy consumption at different thickness and engine loads.

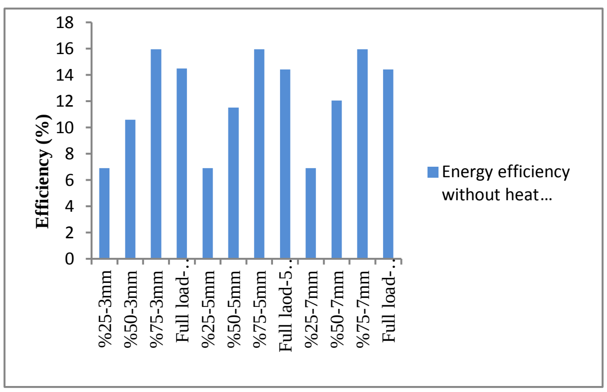


Figure 6. Energy efficiency without heat recovery at different thickness and engine loads.

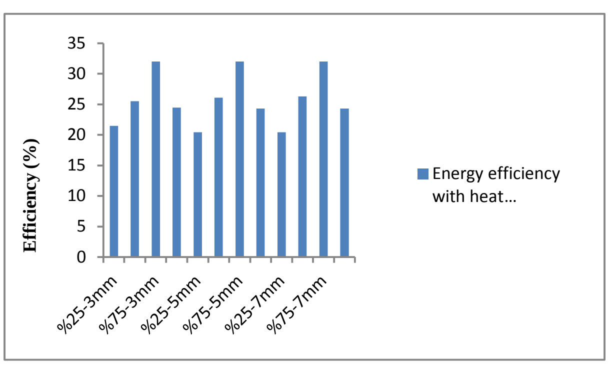


Figure 7. Energy efficiency with heat recovery at different thickness and engine.

The results show that energy efficiency at the different thickness of the samples nearly equal each other. Thus, to compare energy drying at different thickness and engine loads, the parameter of the specific energy consumption (SEC) in drying process were used. Figure 8 presents specific energy consumption under various conditions of drying process. It was found that the SEC decreased with decreasing in the thickness of the sample. This is expected because a higher thickness of the sample led to a lower rate of drying process. The SEC was in the range of 518-1071kWh/kg_{water}. The lowest value of SEC of 518 kWh/kg_{water} was observed at 75% engine load and thickness of 3 mm, which was about 100.5% lower than that at which the experiments were conducted at thickness of 7 mm and full 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 was reduced. Also, at engine loads greater than 75% (full load) although the drying time was reduced, but the rate of fuel consumption and hence specific energy consumption was increased.

Table 1 shows the comparisons of energy efficiency between combined heat and power (CHP) application and electricity generation. It can be seen that the energy efficiency of CHP is from 68% to 210% higher than that of electricity generation.

Table 1 also shows the comparisons of brake specific fuel consumption (BSFC) between the two systems at different engine loads. It can be seen that considerable decrease in BSFC when the simultaneous use of heat and power was used. The reduction in brake specific fuel consumption varies from 1.008% at 25% load to 0.250 at full load. Also, brake specific fuel consumption of CHP is from 40.7% to 67.7% lower than that of electricity generation.

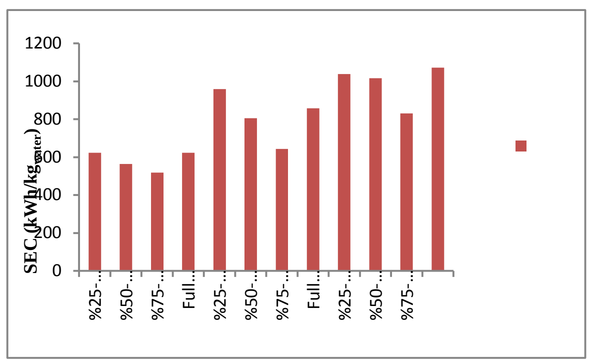


Figure 8. Specific energy consumption of drying at different thickness and engine loads.

Table 1.

Engine Load (%)	Increase of efficiency (η_{CHP} - η_{el})	Increase rate (%) (η_{CHP} - η_{el})/η_{el}	Decrease of BSFC (m^3/kW h) ($BSFC_{CHP}$ - $BSFC_{el}$)	Decrease rate (%) ($BSFC_{CHP}$ - $BSFC_{el}$)/ $BSFC_{el}$
25	14	210	1.008	67.7
50	14	126	0.498	55.8
75	16	100	0.323	50.1
Full	10	68	0.250	40.7

CONCLUSIONS

In this work, a combined heat and power system is presented and tested for drying apple slice. In this article showed the use of CHP system is very suitable for energy saving and CHP dryer is a good alternative for conventional dryers in industrial applications.

The drying kinetics and energy parameters of the system have been evaluated. The following conclusions can be drawn from experimental results:

1- Drying time decreased significantly with increasing the engine load. In addition, with increasing the thickness of sample drying time increased. The minimum and maximum of drying time was found for thickness of 3 mm (full loads) and 7 mm (25% loads) of samples, respectively.

2- 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 518-1071kWh/kg_{water}. The lowest specific energy consumption of the drying process was around 518 kWh/kg_{water} that was observed in 75% engine load and thickness of 3 mm.

3- The present study confirms the importance of heat recovery to improve the system energy consumption and efficiency. 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 68-210% in system efficiency was observed. The maximum efficiency was obtained at 75% engine load. Although, brake specific fuel consumption (BSFC) are from 40.7% to 67.7% lower than that of single generation under different engine loads.

Generally, for the abovementioned reason, this study shows that the use of exhaust waste heat of an engine-generator for drying process in the final energy consumption is very reasonable.

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