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Designing, manufacturing and testing of a micro combined heat and power (micro-CHP) system

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Abstract: ***In the present paper a micro-CHP is designed, built and tested based on a 5 kW diesel engine that is chosen to recover its water jacketing and exhaust waste energy and convert it into hot water. The hot water may be used as heating source or domestic hot water. Heat recovery for the lube oil, radiation, convection, and conduction to ambient is not used since they all count for only 13% of the inlet fuel energy. The results include the main characteristics in the design section, some pictures of the main components, the temperature of exhaust, water jacketing and tap water at different points of the system. In addition the heat recovery at different engine loads is also given. The experiments and results show that the overall efficiency of the CHP system can reach 60% which means more than 30% increase of efficiency when comparing with the case when only electricity was supposed to be produced by the engine.***

Keywords: Combined heat and power, CHP, heat recovery, energy efficiency

1. INTRODUCTION

While lots of works and investigations are devoted to encourage renewable energy and its related technologies such as wind turbines, hydro-power systems, solar panels, biogas reactors, etc, it is essential to pay more attention to the fossil fuels, its related technologies and possible methods to increase the overall efficiency of energy conversion. Statistics and predictions published by Energy Information Administration (EIA) [1] has proved that until 2012 only 12% of the total world energy consumption was supplied by renewable energies, and the remaining 88% was supplied by different fossil fuels. EIA has also predicted that the share of renewable energies would become 16% until 2040. It means that at the year of 2040 still 84% of the world energy demand would be supplied by the fossil fuels. Consequently, consistent with these results the fossil fuels would be the main energy source for the human to the mid-century. As a result, although developing the renewable energies and the related technologies to raise their share in the world energy consumption is important; optimizing the existing energy processes and related technologies is essential to reduce emission production and increase the overall efficiency of energy systems. Hence, cleaner energy systems and optimized energy processes in industry are the foundation of cleaner production.

In addition to the methods introduced to enhance power generation efficiency, regular energy audit, punctual maintenance and correct operation of rotary and stationary energy converter equipments, and energy management can assist to keep the thermal efficiency of energy systems as high as possible [2, 3]. However, the fuel energy utilization can be improve further especially in power generation systems such as gas turbines and internal combustion engines [4]. Combined heat and power or CHP, is among the most popular methods that is still under investigation to increase fuel energy utilization in power generation units [5]. If the heat recovered in the CHP system could be used for cooling purposes the system is called Combined Cooling Heating and Power or CCHP which is also called trigeneration. The CCHP units are capable of producing simultaneous cooling, heating and power/electricity by using a single energy source. The cooling system is usually an absorption chiller, adsorption chiller, ejector cooling system, heat pump, compression chiller, or a combination of these systems. The CCHP and CHP cycles can be coupled with different renewable energy systems such as solar heating, photovoltaic cells, and wind turbines as well.

The main components of a CHP cycle are the prime mover, heat recovery, and control system. If the CHP is supposed to become a CCHP the cooling system will be another main component of the cycle.

The power generator unit (PGU) or prime mover of a CHP system may be chosen among different types of fuel cells [6], micro steam or micro gas turbines [7], industrial large size gas turbines [8], industrial steam turbines[9] , Stirling engines [10], internal combustion engines [11] etc.

Deciding about the PGU of a CHP cycle requires gathering and analyzing so much technical, economical, environmental and social data about the PGUs. The technical data may include the thermal efficiency, power to heat ratio, exergy efficiency, etc. The environmental characteristics to be considered in the decision making are noise generation and emission productions such as carbon monoxide, carbon dioxide, nitrogen oxides, sulfur oxide, soot, particulates etc. The economical criteria usually used are net present value, payback period, internal rate of return, present value premium, etc. The social or miscellaneous concerns also important in the decision making step. Examples of these concerns include footprint of equipment, easiness of operation and maintenance, availability of spare parts, guarantee/ warrantee services, sanctions over some technologies for some countries, etc [12-14]. Since some of the characteristics can be found only qualitatively, general statistical methods cannot be used for decision-making. Therefore by using decision making methods such as grey incident method [12], and fuzzy logic [13] right prime mover would be chosen. M. Ebrahimi et al [14] used grey incident approach and fuzzy logic simultaneously to choose the right prime mover for a residential-CCHP system in five different climates of Iran; they also made a comparison between the results of two algorithms. They concluded that internal combustions engines are the best choice for all climates of Iran.

In the present paper a micro-CHP system is designed, manufactured and tested. Except for the engine the rest of components were built by the team and assembled to produce 5 kW of electricity and recover at least 5 kW of heat at the full load operation. It means that in this case the cycle efficiency would be doubled. The waste heat of exhaust gases and water jacketing are recovered as hot water that can be used for heating purpose or hot tap. The results show significant fuel saving.

2. Modeling and design:

The heart of the micro-CHP which is supposed to be built is a diesel engine with the following characteristics given in Table 1.

Table 1. The diesel engine characteristics

Parameter	Magnitude
Nominal electricity, E (kW)	5
Fuel consumption, F (kg/s)	0.0004
Electrical efficiency, η_e (%)	27
Exhaust temperature, T_{ex} (℃)	540
Exhaust flow rate, $\dot{m}_{ex}$ ($\mathbf{kg.s^{-1}}$)	0.0111
Water jacketing, $\dot{m}_{wj}$ ($\mathbf{kg.s^{-1}}$)	0.17
Water jacketing inlet temperature, $T_{wj,in}$ (℃)	95
Water jacketing outlet temperature, $T_{wj,out}$ (℃)	103

The fuel energy would be consumed by engine for producing electricity and heat losses. The heat losses appear in the exhaust gases, water jacketing, oil, and other losses such as friction and radiation. The energy balance for the engine can be modeled as below:

$$F = E + \dot{Q}_{ex} + \dot{Q}_{wj} + \dot{Q}_{oil} + \dot{Q}_r = \eta_e F + \dot{Q}_{ex} + \dot{Q}_{wj} + \dot{Q}_{oil} + \dot{Q}_r = \frac{E}{\eta_e} \quad (1)$$

$$\dot{Q} = \dot{m} c_p \Delta T \quad (2)$$

In which $\dot{Q}_{ex}$ is the exhaust energy, $\dot{Q}_{wj}$ is the water jacketing, $\dot{Q}_{oil}$ is the oil energy, and $\dot{Q}_r$ is the other losses such as friction and radiation.

A heat recovery system has been designed to recover the heat losses from the exhaust and water jacketing. A the heat recovery system for the exhaust gas is a shell and tube heat exchanger and a plate heat exchanger is used to recover the heat from the water jacketing. The schematic of the micro-CHP cycle is presented in Fig.1.

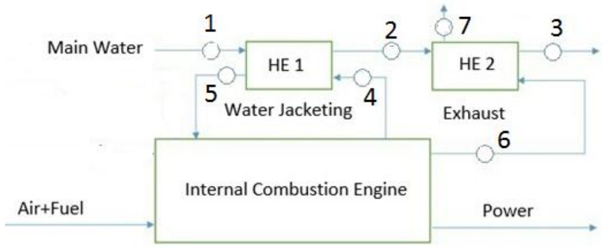

Figure 1. the schematic diagram of the micro-CHP and shell and tube (HE1) and plate (HE2) heat exchangers

As it can be seen from the Fig.1, the main water first enters the plate heat exchanger at point 1 and receives heat from water jacketing. This exchanger is supposed to decrease the water jacketing temperature from 103 ℃ to 95 ℃. Then the preheated water enters the shell and tube exchanger at point 2 to be heated by the exhaust gases. To avoid condensation and corrosion in the gas side of shell and tube exchanger its temperature should stay above the dew point.

Considering the discussions presented, the temperature and mass flow rate at each point of the cycle can be predicted by using the first law of thermodynamics. After determining the thermodynamics of the cycle, the heat recovery systems should be designed and their heating surface should be calculated.

To achieve the highest possible heat transfer the hot and cold streams in both the HE1 and HE2 are supposed to be counter flow. In this case the logarithmic mean temperature difference (LMTD) of the hot and cold streams can be calculated as below:

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{ln(\frac{\Delta T_1}{\Delta T_2})}$$
$$\Delta T_1 = T_{hot,out} - T_{cold,in} \quad (3)$$
$$\Delta T_2 = T_{hot,in} - T_{cold,out}$$

To determine the heat surface area of each heat exchanger the following equation should be used:

$$Q = UA\Delta T_{LMTD} \quad (4)$$

In which U is the total heat transfer coefficient and A is heat surface area of the exchanger. Q can be the part of heat which is supposed to be transferred from the water jacketing or exhaust gases to the main water.

The heat transfer coefficient for a clean plate or tube having cold and hot stream on each side (or inside and outside of tube) can be determined as below:

$$\frac{1}{UA} = \frac{1}{A_{hot} h_{hot}} + \frac{1}{A_{cold} h_{cold}} + R_w$$

$$R_w = \begin{cases} \frac{t}{A k_w} \; for plate \\ \frac{ln(d_o / d_o)}{2 \pi L k_w} \end{cases} \quad (5)$$

In which *t* and L are the plate thickness and tube length , k_w is the conduction heat transfer coefficient of tube or plate. In addition h_{hot} and h_{cold} are the convection heat transfer coefficient for the hot and cold streams. In the shell and tube heat exchanger exhaust gases flow in the shell side and water is in the tube side. Furthermore A_{hot} and A_{cold} are the area which that hot and cold streams is in contact with.

3. RESULTS:

The micro-CHP system is now designed, built and tested. In the following some sample results for the design, structure and test are supposed to be presented.

3.1. DESIGN RESULTS:

The cycle presented in Fig. 1 is modeled thermodynamically, the energy balance for each component is calculated, the temperature and mass flow rate at each point is determined. The results of energy balance are given in table 2.

Table 2. The energy balance of engine

Parameter	kW	%
Fuel energy rate, F	18.4	100
Electricity, E	5	27
Exhaust energy rate	5.38	29
Water jacketing energy rate	5.75	31
Oil and other energy rate losses	2.6	13

As it can be seen only 27% of the fuel energy is converted to electricity, and the rest of 73% is wasted through exhaust, water jacketing, lube oil, friction, radiation and etc. Since the share of oil and other energy losses is small, heat recovery for this part is not designed. However the waste heat through exhaust and water jacketing are significant with high quality. Therefore heat recovery systems are designed for the exhaust and water jacketing.

The temperature at each state point of the Fig. 1 is also given in table 3.

As reported in table 3.

Table 3. The temperature and mass flow rate at each point of the cycle

Point	$\boldsymbol{T}$(℃)	$\dot{\boldsymbol{m}}(\boldsymbol{kg}.\boldsymbol{s}^{-1})$
1	20	0.0666
2	40.6	0.0666
3	60	0.0666
4	103	0.17
5	95	0.17
6	540	0.0111
7	70	0.0111

According to the results the water jacketing increases the main water temperature from 20 ℃ to 40.6 ℃ and then the exhaust increases it temperature to 60 ℃. It is convenient since each of water jacketing and exhausts count for same share of fuel energy that is about 30%.

The heat recovery systems for the jacketing and exhaust are also designed and the results are reported in table 4.

Table 4. the main characteristics of the designed heat recovery systems

	The main characteristics of the plate heat exchanger (HE1)	Magnitude
Plate heat exchanger	Total heat transfer coefficient, U ($\mathrm{kW.m^{-2}.K^{-1}}$)	3.30
	Heat surface area, A($\mathrm{m^{-2}}$)	0.026
	LMTD (℃)	60.21
	Effective area of each plate, A($\mathrm{m^{-2}}$)	0.0041
	Projected area of each plate, A($\mathrm{m^{-2}}$)	0.0035
	Total number of plates	9
Shell and tube heat exchanger	Total heat transfer coefficient, U ($\mathrm{kW.m^{-2}.K^{-1}}$)	0.122
	Heat surface area, A($\mathrm{m^{-2}}$)	0.175
	LMTD (℃)	200
	Tube inside diameter(mm)	8
	Tube outside diameter(mm)	10
	Shell/tube material	Stainless steel
	Number of tubes	19
	Shell inside diameter (mm)	70
	Tube length (m)	0.2
	Clearance between tubes(mm)	5
	Baffle to baffle distance (m)	0.1

3.2. CONSTRUCTION RESULTS:

The data presented in the previous section was used to build the heat recovery systems. For example Fig. 2 shows the shell and tube heat exchanger built for the exhaust heat recovery.

Figure 2. The shell and tube (up) and plate (down) heat exchangers

In addition filters are constructed for the engine inlet air and exhaust before entering the shell and tube heat exchanger.

Figure 3. The filters used for the exhaust (up) and engine air inlet (down)

In addition to these components other components such as silencer, fittings, monitoring system, etc. were built and the components assembled as shown in Fig. 4.

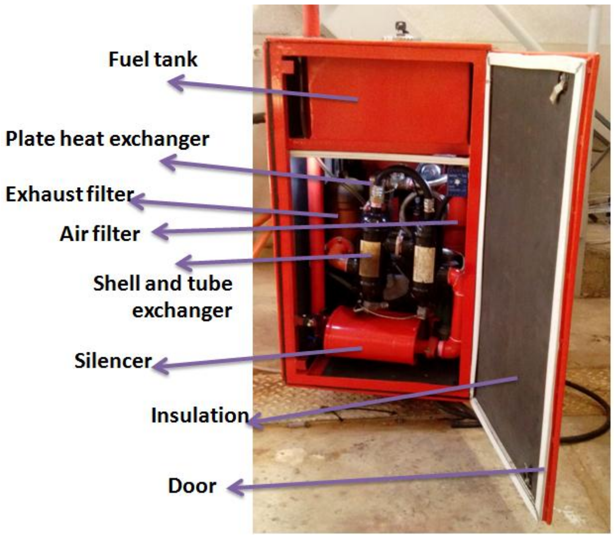

Figure 4. The micro-CHP package $1 \times 1 \times 0.5m$ $(L \times H \times W)$

3.3. TEST RESULTS:

The constructed micro-CHP is equipped with a monitoring system to monitor different important parameters of the cycle, including voltage, ampere, temperature at different points and water flow.

Fig.5 shows the electricity and heat production by the micro-CHP cycle at different loads. As it can be seen in all load conditions heat production is higher than the electricity generation, especially when the engine is operating below 50% of its full load or overloaded.

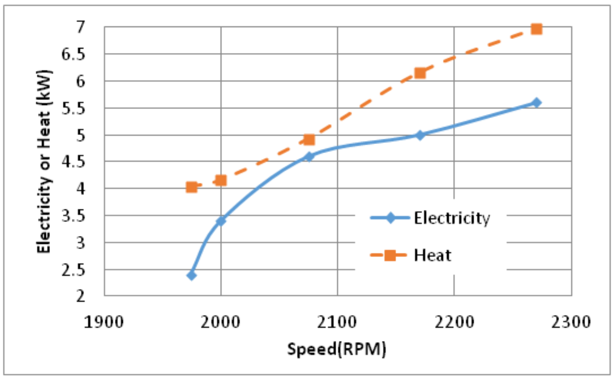

Figure 6. Heat and electricity produced by the micro-CHP

4. CONCLUSIONS:

A micro-CHP is designed, constructed, and tested to produce combined heat and power. The results showed that the micro-CHP is able to recover the heat from the exhaust and water jacketing and the overall efficiency is above 60% which means at least 30% increase in efficiency. This system can save significant amount of fuel and reduce emission production.

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