Applied Mechanics and Materials Vol. 659 (2014) pp 440-445
Online available since 2014/Oct/01 at www.scientific.net
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doi:10.4028/www.scientific.net/AMM.659.440

Submitted: 30.04.2014
Revised: 23.05.2014
Accepted: 27.05.2014

Experimental Investigation of Waste Heat Available for a Hybrid Micro-Cogeneration Group Involving a Diesel Engine Electric Generator and Organic Rankine Cycle

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Keywords: Internal combustion engine, heat recovery, Organic Rakine Cycle.

Abstract. The paper presents the work developed in the first stage of Research Grant called "Hybrid micro-cogeneration group of high efficiency equipped with an electronically assisted ORC" (acronym GRUCOHYB). The Research Grant is in progress at the Thermal Research Centre, Faculty of Mechanical and Mechatronics Engineering from University Politehnica of Bucharest having as research partner the Rokura Company. The hybrid micro-cogeneration group involves the use of an electric generator based on a 40 kW overcharged Diesel engine and an Organic Rankine Cycle (ORC). The aim of the research is to recover the waste heat available in the exhaust gas and cooling water and transfer it to the ORC in order to convert it into electricity. A description of the experimental setup is given according to the current stage of development. Also the paper presents the experimental results obtained and which show the amount of waste heat available for recovery for different engine operation loads. Based on these experimental results the proper ORC configuration and working fluid can be determined. Several possible ORC configurations suitable for this application are highlighted. Future work and development perspectives are also discussed.

Introduction

The oil crisis from the 1970s together with increased environmental concerns led to several attempts of finding reliable alternatives to internal combustion engines (ICE) [1]. However, the high cost and low efficiency of other engine types prevented a radical change in vehicle propulsion. Instead, the focus was on heat recovery systems aiming to improve the engine efficiency by adding a useful effect derived from conversion of waste heat into work or electricity. In that period, research has been conducted on systems that increase the engine efficiency by means of waste heat recovery (WHR), but due to a drop in oil price their implementation has been slowed down [1].

In 1973, Morgan et al. have been one of the first to study the possibility of using an external combustion Rankine engine for an automobile application [1,2]. Also, in 1976 Patel and Doyle documented the first application of an ORC for heat recovery from a Mack Trucks Diesel engine [1-4]. In the following period many researchers focused on WHR from ICE based on Rankine engines [1]. In 1981 Heywood made a comparison between conventional and alternative engines and recognized the use of an ORC as a suitable method for improving the engine efficiency [5]. In the same year Marciniak et al. compared seven ORC working fluids [6] and in 1984 Angelino et al. described Italian research in the field [7]. Next, Badr et al. developed an evaluation of working fluid selection criteria base on thermophysical properties [8] and in 1985 Bailey made a techno-economical analysis for three power cycles suitable for WHR from an ICE [9]. In the last twenty years, the subject has been intensively studied and numerous papers, studies and books dealing with ORC configurations, working fluids, expanders, mathematical modeling and optimization have been published as presented in the work of Sprouse et al. [1] and Bertrand et al. [10].

In this context the paper presents a part of the work conducted in the Framework of a National Research Program [11]. The work refers to a hybrid micro-cogeneration group which involves the use of an electric generator based on a 40 kW overcharged Diesel engine and an ORC. In present paper the experimental results concerning the waste heat available for recovery from engine exhaust gas and cooling water for different engine operation loads are presented. The available heat will be converted into electricity using the ORC system aiming to improve the overall efficiency of the system and to reduce fuel consumption.

Experimental setup description

The experimental setup, according to the present stage of development is presented in Fig. 1 where the main components are: 1- Diesel engine; 2- electric generator; 3 – exhaust gas pipe; 4- fuel tank; 5-air flow meter; 6 - automation and data acquisition panel; 7 - electricity distribution panel and 8 - electric heaters (load simulation).

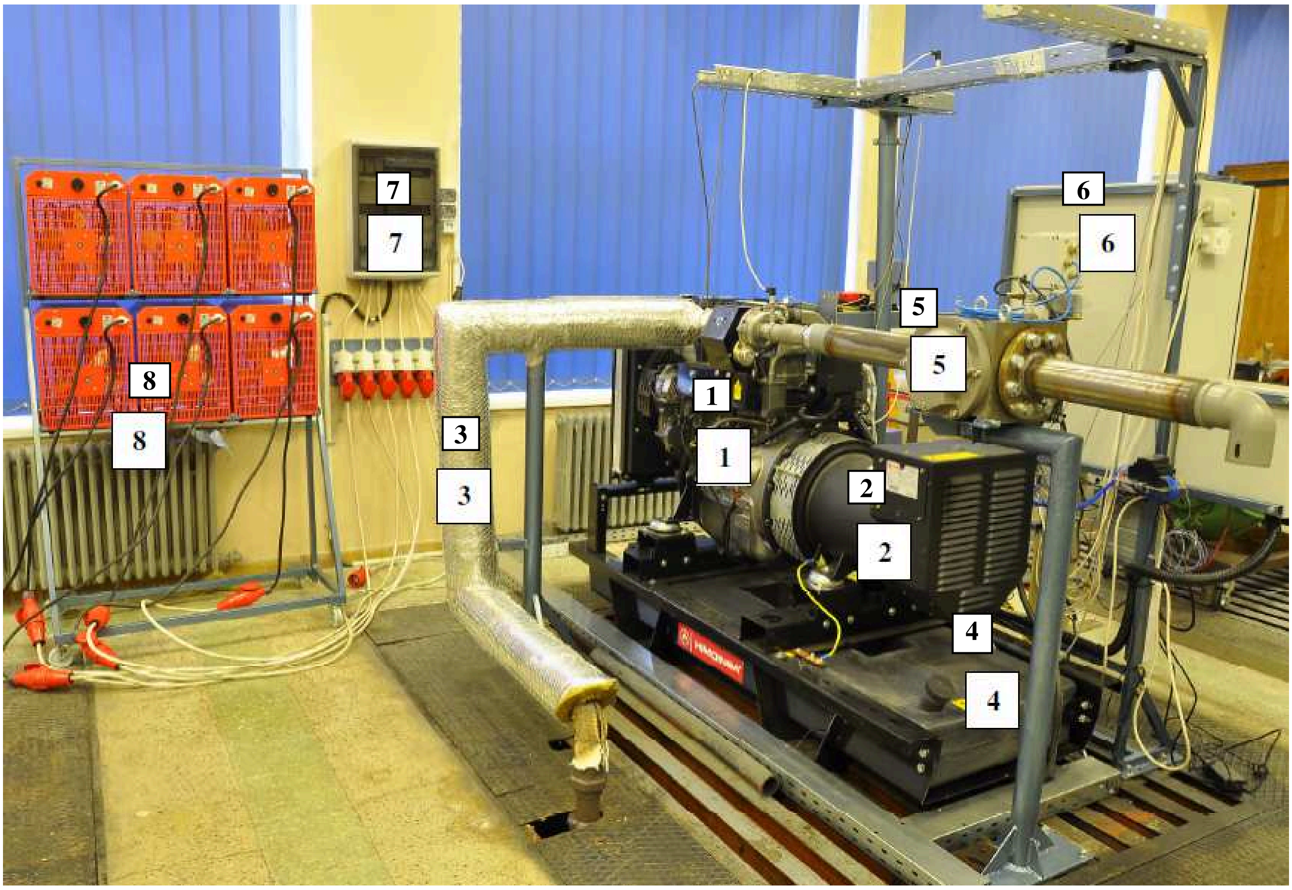


Fig. 1. Experimental setup

The instrumentation available on the experimental setup is presented in Table 1 and it allows conducting the energy balance and experimental evaluation of waste heat available for ORC.

Besides the parameters presented in Table 1, other parameters are available on the experimental setup and will be used in future work [11].

Table 1. Instrumentation of the experimental setup

Nr crt.	Parameter	MU
1	Ambient pressure	$p_{atm}[bar]$
2	Ambient temperature	$t_{atm}[^oC]$
3	Air relative humidity	$\varphi\ [\%]$
4	Intake air volume flow rate	$\dot{V}_{air}[m^3/h]$
5	Cooling water volume flow rate	$\dot{V}_w[L/h]$
6	Cooling water engine inlet temperature	$t_{wi}[^oC]$
7	Cooling water outlet temperature	$t_{wo}[^oC]$
8	Fuel hourly consumption	$C_h[L/h]$
9	Electric power production	$P_{el}[kWe]$
10	Temperature of exhaust gases	$t_{eg}[^oC]$

Experimental evaluation of waste heat

The experimental evaluation of the waste heat for the ORC has been carried out for three different operation loads of the electric generator, i.e. 100%, 75% and 50%, respectively. The load has been simulated by activating in corresponding steps the heat blowers (position 8 in Fig. 1). For each operation regime the parameters necessary for conducting the energy balance have been recorded and they are presented in Table 2.

Table 2. Experimental data

Load [%]	$p_{atm}[bar]$	$t_{atm}[^oC]$	$\varphi\ [\%]$	$\dot{V}_{air}[m^3/h]$	$\dot{V}_w[L/h]$
100	1.0157	28.52	16.67	156.00	1124.00
75	1.0153	30.14	15.96	149.82	759.70
50	1.0153	29.34	16.34	144.80	496.00
	$t_{wi}[^oC]$	$t_{wo}[^oC]$	$C_h[l/h]$	$P_{el}[kWe]$	$t_{eg}[^oC]$
100	54.47	74.88	9.5	33.66	477.1
75	53.41	74.11	7.45	26.92	403.12
50	47.19	73.40	5.75	20.3	327.4

Using the experimental data the parameters presented in Table 3 have been computed [11].

Table 3. Parameters computed based on experimental data

Load [%]	$c_{pair}[kJ/(kgK)]$	$\rho_{air}[kg/m^3]$	$\dot{m}_{air}[kg/s]$	$\rho_w[kg/m^3]$	$\dot{m}_w[kg/s]$	$c_w[kJ/(kgK)]$
100	1.029	1.151	0.0499	1000	0.31	4.186
75	1.028	1.145	0.0477	1000	0.21	4.186
50	1.028	1.148	0.0462	1000	0.14	4.186
	$\eta_{conv}[-]$	$\rho_{fuel}[kg/m^3]$	$\dot{m}_{fuel}[kg/s]$	$LHV[kJ/kg]$	$\dot{m}_{eg}[kg/s]$	$c_{peg}[kJ/(kgK)]$
100	0.98	822	0.0022	42000	0.0520	1.14
75	0.98	822	0.0017	42000	0.0494	1.09
50	0.98	822	0.0013	42000	0.0475	1.03

In Table 3 the following are presented: $c_{pair}[kJ/(kgK)]$ engine intake air specific heat capacity at constant pressure, $\rho_{air}[kg/m^3]$ density of engine intake air, $\dot{m}_{air}[kg/s]$ intake air mass flow rate, $\rho_w[kg/m^3]$ cooling water density, $\dot{m}_w[kg/s]$ cooling water mass flow rate, $c_w[kJ/(kgK)]$ cooling water specific heat capacity, $\rho_{fuel}[kg/m^3]$ fuel density, $\dot{m}_{fuel}[kg/s]$ fuel mass flow rate and $\dot{m}_{eg}[kg/s]$ exhaust gas mass flow rate. At this stage of development the fuel lower heat value ($LHV[kJ/kg]$), exhaust gas specific heat capacity at constant pressure ($c_{peg}[kJ/(kgK)]$) and the conversion factor of mechanical power into electric power ($\eta_{conv}[-]$) have been adopted from literature [12]. In this respect, future work will be conducted in order to determine LHV and c_{peg} based on fuel and exhaust gas composition.

The energy balance equation can be written:

$$\dot{Q}_{fuel} = P + \dot{Q}_w + \dot{Q}_{eg} + \dot{Q}_{rest} \tag{1}$$

Where: $\dot{Q}_{fuel}$ is the heat flux received through fuel combustion; P is the amount of mechanical power produced; $\dot{Q}_w$ is the heat flux rejected through the water cooling system; $\dot{Q}_{eg}$ is the heat rejected through the exhaust gases and $\dot{Q}_{rest}$ is the heat flux rejected through radiation and incomplete combustion that cannot be directly determined in this stage. Each term presented in eq. (1) has been computed [11] based on experimental data and the results are presented in Table 4.

Table 4. Energy balance

Load [%]	$\dot{Q}_{fuel}[kW]$	$P\,[kW]$	$\dot{Q}_w[kW]$	$\dot{Q}_{eg}[kW]$	$\dot{Q}_{rest}[kW]$
100	91.11	34.35	26.68	29.03	1.05
75	71.45	27.47	18.29	21.52	4.17
50	55.14	20.71	15.12	15.02	4.30

The amount of heat available for recovery with the ORC system can be computed as:

$$\dot{Q}^{ORC}_{available} = \dot{Q}^{\lim}_{eg} + \dot{Q}_w \tag{2}$$

where $\dot{Q}^{\lim}_{eg}$ is the amount of heat that can be recovered from exhaust gas, setting the minimum temperature to which the exhaust gas can be cooled to $t^{\min}_{eg} = 140\ ^oC$ [11]. Using this minimum threshold avoid the formation of acid during gas flow due to the sulphur content of the exhaust gas. $\dot{Q}^{\lim}_{eg}$ can be computed as presented below:

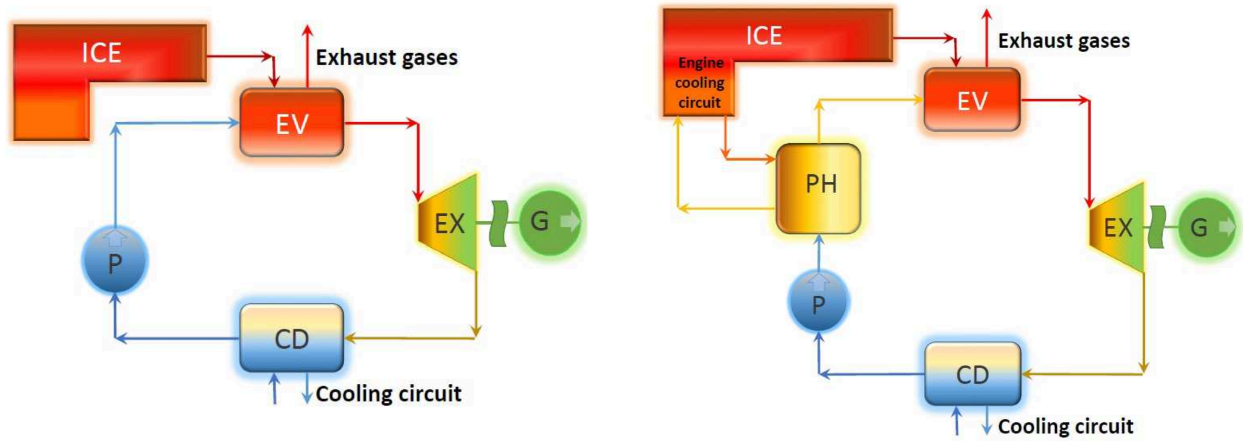
$$\dot{Q}^{\lim}_{eg} = \dot{m}_{eg} \cdot c^{med}_{peg} \cdot \left(t_{eg} - t^{\min}_{eg}\right) \tag{3}$$

where c^{med}_{eg} is the medium value of the specific heat capacity at constant pressure of exhaust gases for the $t_{eg} \div t^{\min}_{eg}$ temperature range. If the exhaust gas composition expressed in mass faction is $CO_2 = 0.15$, $H_2O = 0.05$, $O_2 = 0.05$ and $N_2 = 0.75$, then the value $c^{med}_{peg} = 1.14\ kJ/(kgK)$ [11,12] can be used to calculate $\dot{Q}^{\lim}_{eg}$. The results obtained for the amount of waste heat available for recovery are presented in Table 5.

Table 5. Amounts of waste heat available for recovery with the ORC system

Load [%]	$c_{peg}^{med}\,[kJ/(kgK)]$	$\dot{Q}_{eg}^{\lim}\,[kW]$	$\dot{Q}_{w}\,[kW]$	$\dot{Q}_{available}^{ORC}\,[kW]$
100	1.14	20.00	26.68	46.68
75	1.14	14.80	18.29	33.09
50	1.14	10.15	15.12	25.26

If the data presented in Table 5 is analyzed, one can notice that the waste heat by the engine, which is available for recovery with the ORC, increases with the increase of the operation load. Also, the amount of waste heat available from cooling water is larger than the one from exhaust gas. Even so, the waste heat available in the exhaust gases is more thermodynamically suited for conversion in useful work/electricity due to its higher temperature. Starting from these considerations, two configurations for the ORC system are identified as suitable for this application and they are presented in Fig. 2.



(a) **(b)**

Fig. 2. ORC configurations suitable for ICE waste heat recovery: a) WHR only from exhaust gases; b) WHR from exhaust gases and from engine cooling circuit

In Fig. 2 a) and b) the following notations have been used: ICE – internal combustion engine, EV – evaporator, EX – expander, G – electricity generator, CD – condenser, P – pump and PH – preheater. As it can be noticed in case of configuration a) only the heat from exhaust gas is recovered and transferred to the ORC while the heat from the engine water cooling system could be used for water heating that could serve an household application. In case of configuration b) the heat from water cooling system is used to preheat the ORC working fluid before entering the evaporator, thus increasing the overall amount of heat transferred to the ORC and converted in useful work/electricity.

Conclusions

The paper presents the work developed in the first stage of Research Grant involving a micro-cogeneration group based on a diesel engine electric generator and ORC. The aim is to recover the waste heat from engine exhaust gas and water cooling system and transfer it to the ORC for conversion into useful work/electricity. The amount of waste heat has been determined considering different operation loads of the electric generator (i.e., 100%, 75% and 50%). Results show that the amount of waste heat increases with the increase of the operation load. Also the heat available in the water cooling system is larger than the one available in the exhaust gas if the minimum temperature to which the exhaust gas can be cooled is 140 °C. Even so, the heat available in the exhaust gas is more thermodynamically suited for conversion into useful work/electricity due to its high temperature. Finally, two ORC configurations have been identified as suitable for this application. Future work involves developing the experimental setup and conducting research with the ORC module. An efficiency improvement and lower fuel consumption of the overall system is expected.

Acknowledgements

The work presented in this paper has been conducted in the Romanian National Research Framework PNII, Grant no. 75/2012 called "Hybrid micro-cogeneration group of high efficiency equipped with an electronically assisted ORC-GRUCOHYB".

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