EXPERIMENTAL SETUP AND ENERGY BALANCE OF A HYBRID MICRO-COGENERATION GROUP BASED ON DIESEL ENGINE AND ORGANIC RANKINE CYCLE

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ABSTRACT

The paper presents the experimental setup developed in the first stage of a 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 a 40 kW Diesel engine and an Organic Rankine Cycle (ORC). A brief description of the experimental setup according to the current stage of development has been delivered. The paper also presents the energy balance conducted in this research stage which aims to obtain the amount of waste heat available for the ORC. Preliminary experimental data and results have been presented. Results show that at full load the mechanical power that could be delivered by the ORC is in the range of 10.74 and 7.16 kW. Future improvement perspectives are also presented.

1. INTRODUCTION

The efficiency of thermal systems can be improved by waste heat recovery. One of the most promising solutions for waste heat recovery is the Organic Rankine Cycle (ORC) [1,2]. This technology can be successfully applied in case of electricity generators based on internal combustion engines (ICE) by recovering heat from exhaust and water cooling systems and converting it into work or electricity. In literature reports can be found regarding heat recovery systems based on ORC for heavy duty ICE [3,4]. Results point out fuel economy and enhanced thermal efficiency.

In this context, the present paper presents an experimental setup developed in the first stage of a National Research Grant called “”Hybrid micro-cogeneration group of high efficiency equipped with an electronically assisted ORC” (acronym GRUCOHYB). The Research 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 electricity generator based on a 40 kW overcharged Diesel engine and an ORC. At full load the electricity output is 36 kWe. The research objective is to recover heat from the exhaust and cooling systems of the Diesel engine ant transfer it to the ORC in order to produce electricity as well as to heat a thermal agent and to improve the overall efficiency of the micro-cogeneration group.

Furthermore, the paper presents the energy balance conducted for the micro-cogeneration group in order to determine the amount of waste heat available for ORC. Preliminary results are delivered based on experimental data.

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2. EXPERIMENTAL SETUP DESCRIPTION

An overview of the experimental setup according to the current stage of development is presented in Figure 1.

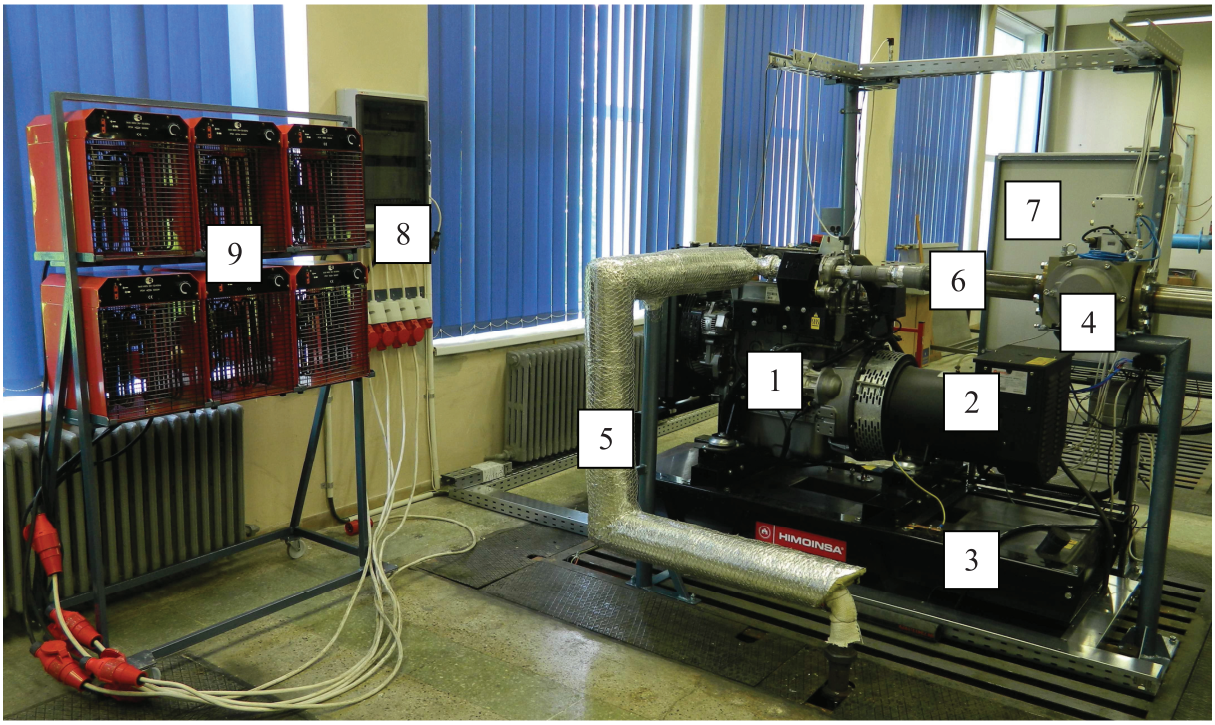

Figure 1: Overview of the experimental setup

The components visible and indexed in Figure 1 are: 1 – Diesel engine; 2 – electricity generator; 3 – fuel tank; 4 – air flow meter; 5 – exhaust pipe; 6 - air inlet pipe; 7 – automation and data acquisition panel; 8- electricity distribution system; 9 – electricity consumers. The experimental setup has many another components that will be presented in a much detailed work. The instrumentation available on the experimental setup and which allows conducting the energy balance is presented in Table 1.

Tabelul 1: Instrumentation of the experimental setup

Nr. crt.	Measured parameter
1.	Ambient pressure [bar]
2.	Ambient temperature [^oC]
3.	Combustion air volume flow rate [m^3/h]
4.	Overcharge air pressure [bar]
5.	Overcharge air temperature [^oC]
6.	Engine intake air pressure [bar]
7.	Engine intake air temperature [^oC]
8.	Cooling water inlet pressure [bar]
9.	Cooling water inlet temperature [^oC]
10.	Cooling water volume flow rate [m^3/h]
11.	Cooling water outlet pressure [bar]
12.	Cooling water outlet temperature [^oC]
13.	Turbine inlet exhaust gas pressure [bar]

14.	Turbine inlet exhaust gas temperature [°C]
15.	Turbine outlet exhaust gas pressure [bar]
16.	Turbine outlet exhaust gas temperature [°C]
17.	Fuel engine intake pressure [bar]
18.	Exhaust gas temperature [°C]
19.	Hourly fuel consumption [l/h]
20.	Active Power [kW]

3. ENERGY BALANCE

According to the current stage of development the energy balance equation for the experimental setup can be written as follows:

$$\dot{Q}_{fuel} = P + \dot{Q}_{wcs} + \dot{Q}_{eg} + \dot{Q}_{rest} \quad (1)$$

Where: $\dot{Q}_{fuel}$ is the heat flux received through fuel combustion; P is the amount of mechanical power produced; $\dot{Q}_{wcs}$ 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.

The heat flux received through fuel combustion can be computed as:

$$\dot{Q}_{fuel} = \dot{m}_{fuel} \cdot H_{ifuel} \; [kW] \quad (2)$$

Where $\dot{m}_{fuel}$ $[kg/s]$ is the fuel mass flow rate and H_{ifuel} $[kJ/kg]$ is the inferior fuel heat value.

The fuel mass flow rate can be determined:

$$\dot{m}_{fuel} = [(C_h \cdot 10^{-3})/3600] \cdot \rho_{fuel} \; [kg/s] \quad (3)$$

In eq. (3), C_h $[l/h]$ is the hourly fuel consumption which is experimentally determined and ρ_{fuel} $[kg/m^3]$ is the fuel density and its value is considered from data available in literature for a temperature of 20 °C [5]. Thus $\rho_{fuel} = 822 \; kg/m^3$. The inferior fuel heat value is also considered from data available in literature [5,6]: $H_{ifuel} = 42000 \; kJ/kg$.

The power produced $P[kW]$ can be determined as follows:

$$P = P_{el} / \eta_{conv} \; [kW] \quad (4)$$

Where P_{el} $[kW]$ is the amount of electric power obtained and it is directly determined on the experimental setup; η_{conv} is a conversion factor of mechanical power into electrical power considered for the present calculation to be η_{conv}=0.98 [7].

Next, the heat flux rejected through the water cooling system can be computed as follows:

$$\dot{Q}_{wcs} = \dot{m}_w \cdot c_w \cdot (t_e - t_i)\,[kW] \tag{5}$$

In eq. (5) $\dot{m}_w\,[kg/s]$ is the water mass flow rate; $c_w\,[kJ/(kgK)]$ the water heat capacity; t_e *[°C]* and t_i *[°C]* are water temperatures at engine outlet and inlet, respectively.

Water mass flow rate can be determined using experimental data as follows:

$$\dot{m}_w = [(\dot{V}_w \cdot 10^{-3})/3600] \cdot \rho_w\,[kg/s] \tag{6}$$

Where, $\dot{V}_w\,[l/h]$ is the water volume flow rate measured on the experimental setup and $\rho_w = 1000\ kg/m^3$ is water density. For water heat capacity the following value has been considered $c_w = 4.186\ kJ/(kgK)$ [7]. Water temperatures at the inlet (t_i) and outlet (t_e) of the engine are directly measured.

The heat flux $\dot{Q}_{eg}[kW]$ rejected through exhaust gases is computed as:

$$\dot{Q}_{eg} = \dot{Q}_{eg}^{total} - \dot{Q}_{air}\,[kW] \tag{7}$$

Where, $\dot{Q}_{eg}^{total}\,[kW]$ is the total heat flux available in exhaust gases and $\dot{Q}_{air}\,[kW]$ is the heat flux due to the fresh load.

The total heat flux available in exhaust gases can be determined as:

$$\dot{Q}_{eg}^{total} = \dot{m}_{ge} \cdot c_{pge} \cdot T_{ge}\,[kW] \tag{8}$$

In eq. (8) $\dot{m}_{ge}\,[kg/s]$ is the exhaust gasses mass flow rate; $c_{pge}\,[kJ/(kgK)]$ is the heat capacity at constant pressure of exhaust gases and $T_{ge}\,[K]$ is the temperature of exhaust gases. Heat capacity of exhaust gases is considered from available data in literature according to experimental data [5].

The exhaust mass flow rate is:

$$\dot{m}_{ge} = \dot{m}_{fuel} + \dot{m}_{air}\,[kg/s] \tag{9}$$

The fuel mass flow rate $\dot{m}_{fuel}$ is computed according to eq. (3) and the air mass flow rate $\dot{m}_{air}$ is determined as:

$$\dot{m}_{air} = (\dot{V}_{air}/3600) \cdot \rho_{air}[kg/s] \tag{11}$$

Where, $\dot{V}_{air}[m^3/h]$ is the air volume flow rate and it is experimentally determined; $\rho_{air}\,[kg/m^3]$ is air density computed for ambient parameters.

Thus, the heat flux due to the fresh load can be determined:

$$\dot{Q}_{air} = \dot{m}_{air} \cdot c_{pair} \cdot T_{air}[kW] \tag{12}$$

Where, $c_{pair}\,[kJ/(kgK)]$ is the heat capacity at constant pressure and its value is considered from data available in literature $c_{pair} = 1.013\ kJ/(kgK)$ [7] and T_{air} is the measured ambient air temperature.

Based on eqns. (1)-(12) the heat flux that cannot be directly determined $\dot{Q}_{rest}$ is:

$$\dot{Q}_{rest} = \dot{Q}_{fuel} - P_{el} - \dot{Q}_{wcs} - \dot{Q}_{eg}[kW] \tag{13}$$

As it can be noticed in eqns. (1)-(12) some data like H_{ifuel}, ρ_{fuel} and c_{ge} are adopted from literature because in the current stage of development the experimental setup does not allow their determination. In future research stages H_{ifuel} will be determined based on fuel elemental analysis and c_{pge} based on exhaust gases composition derived by using a gas analyzer.

4. EXPERIMENTAL RESULTS

According to the energy balance described in the previous paragraph preliminary experimental investigations have been carried out for loads ranging from 100 % to 24 %. The experimental results are presented in Table 2.

Tabelul 2: Preliminary experimental results

Functional regime	Load [%]	$\dot{Q}_{fuel}$ [kW]	P [kW]	$\dot{Q}_{wcs}$ [kW]	$\dot{Q}_{eg}$ [kW]	$\dot{Q}_{rest}$ [kW]	$\dot{Q}_{air}$ [kW]
1.	100.00%	93.54	35.85	27.36	28.69	1.64	15.53
2.	92.47%	85.73	33.15	20.58	25.80	6.20	15.32
3.	81.73%	75.93	29.30	13.48	22.23	10.92	15.25
4.	72.37%	67.35	25.94	12.62	19.13	9.66	15.24
5.	58.54%	56.26	20.99	15.36	15.16	4.75	15.24
6.	48.29%	48.15	17.31	15.63	12.39	2.81	15.23
7.	24.22%	41.24	8.68	14.57	7.57	10.42	15.23

The total amount of waste heat available for the ORC can be computes as:

$$\dot{Q}^{ORC}_{available} = \dot{Q}_{wcs} + \dot{Q}_{eg} + \dot{Q}_{air}[kW] \tag{14}$$

Based on the experimental data presented in Table 2 the amount of waste heat available for ORC is presented in Table 3.

Former reports [3,8] of waste heat recovery in case of ICE using an ORC point out theoretical efficiencies between 15 and 20%, while realistic ones are between 7 and 10%. The amount of theoretical mechanical power $P^{ORC,t}_{output}[kW]$ and the realistic one $P^{ORC}_{output}[kW]$ provided by the ORC can be computed as:

$$P^{ORC,t}_{output} = \dot{Q}^{ORC}_{available} \cdot \eta^{t}_{ORC};\ P^{ORC}_{output} = \dot{Q}^{ORC}_{available} \cdot \eta_{ORC}[kW] \tag{15}$$

Where, η^{t}_{ORC} and η_{ORC} are theoretical and realistic efficiencies of the ORC system respectively. If we assume for the present calculation a theoretical efficiency of $\eta^{t}_{ORC} = 0.15$

and a realistic one of $\eta_{ORC} = 0.1$ [3], than the corresponding mechanical power outputs are also presented in Table 3.

Tabelul 3: Waste heat available for ORC

Functional regime	Load [%]	$\dot{Q}_{available}^{ORC}$ [kW]	$P_{output}^{ORC,t}$ [kW]	P_{output}^{ORC} [kW]
1.	100.00%	71.58	10.74	7.16
2.	92.47%	61.7	9.26	6.17
3.	81.73%	50.96	7.64	5.10
4.	72.37%	46.99	7.05	4.70
5.	58.54%	45.76	6.86	4.58
6.	48.29%	43.25	6.49	4.33
7.	24.22%	37.37	5.61	3.74

5. CONCLUSIONS

The paper presents the first stage of an original research involving a hybrid micro-cogeneration group which is based on a Diesel engine and an Organic Rankine Cycle (ORC). A brief description of the experimental setup according to the current stage of development has been done. The energy balance conducted in this research stage has been presented aiming to determine the amount of waste heat available for the ORC. Preliminary experimental results show that the ORC could deliver at 100% load a mechanical power between 10.74 and 7.16 kW.

Future developments will include: elemental analysis of the fuel in order to obtain the inferior heat value, exhaust gas analysis which will lead to the heat capacity at constant pressure and also the amount of CO that gives the heat lost through incomplete combustion. Also future simulation will be conducted on the heat recovery system that will deliver data necessary for choosing the appropriate equipments for the ORC system.

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