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EXPERIMENTAL ANALYSIS ON THE PERFORMANCE OF AN INTERNAL COMBUSTION ENGINE: THE RECOVERY OF RESIDUAL HEAT OF THE JACKET WATER AND EXHAUST GASES

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ABSTRACT. *In this article a small internal combustion engine operating in Otto cycle is analyzed. A rational use of the power supplied by the fuel has been the heat recovery of jacket water and the exhaust gases, to allow for the production of useful heat. This paper shows the experimental study of an engine associated with two heat exchangers for the production of hot water at 50 °C. Based on experimental data the production possibilities of hot water are simulated. The study considers the temperature of the exhaust gases, exit water temperature, flow of exhaust gases and refrigeration water as function of the engine rotational speed, ranging between 1,000 to 2,000 rpm. As a conclusion a Sankey Diagram was evaluated to indicate the level of performance of the system operating in cogeneration version and the levels of recovery capacity of the residual heat for hot water production.*

Keywords: *Internal Combustion Engine, Heat Recovery, Cogeneration*

1. INTRODUCTION

The successive energy crises have estimulated the study of more efficient ways for the use of the available energy in fuels. A more rational application of the energy supplied by the fuels has been the heat recovery of jacket water and exhaust gases in an internal combustion engine to produce useful heat.

In this concept, several countries have been implanted and developed compact cogenerators (Bidini *et al.*, 1998), which, in the version that uses internal combustion engines, allows for the production of hot or cold water, hot or cold air, in some cases, the production of saturated steam at low pressure, besides the generation of electricity. In his paper Amundsen (1990) reported that the smallest experimental unit which has been object of research in the United States of America has presented a capacity of 2 kW and is used in commercial/residential applications. There are units of 5 kW in Japan and in the European Union there are systems with 7 kW commercially available (Silveira, 1994).

The air standard Otto and Diesel cycles are used to describe the processes that happen in an internal combustion engine. The efficiency of both cycles rises with an increase in the compression ratio (Klein, 1991). Therefore, the higher compression ratio, the better. However it is well known that spark-ignition engines have compression ratios limited to 10:1, to prevent the pre-ignition of the air/fuel mixture.

In this paper an engine that operates according to the Otto cycle with levels of shaft power between 0.7 and 1.5 kW, which are associated to heat exchangers for the production of hot water in thermal process, is analyzed. Based on the experimental data from the engine, the energy contents of the exhaust gases and jacket water are determined as a function of the temperature levels and mass flow, and an analysis of the availability for the calculations of actual hot water production is made.

2. PROPOSED SYSTEM FOR USE OF THE AVAILABLE ENERGY

A compact cogeneration plant for use of the available residual heats in the jacket water and exhaust gases was utilized as shown in Fig. 1.

The available energy in the fuel is transformed in shaft power and used for electricity generation. The water supplied is used to the refrigeration of the engine in place of a radiator. The exhaust gases and jacket water that leaves the engine transfer heat in systems gas/water (plate heat exchanger) or water/water (shell and tube heat exchanger) generating hot water for use in thermal processes.

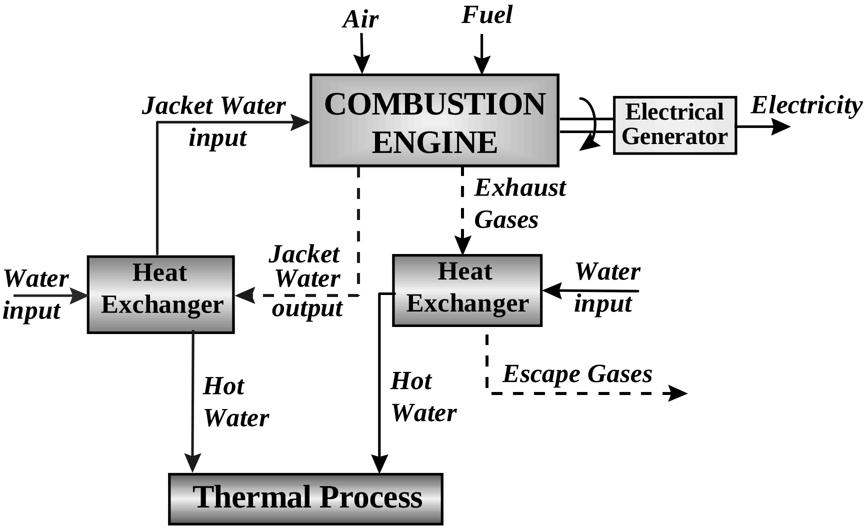


Figure 1 - Cogeneration plant diagram

The use of the residual heat from internal combustion engines is adapted for small demands as the heating of the water at 50°C and for the control of the environmental pollution, or to improve the efficiency of the power generation, although some factors as low exhaust temperature becomes one of the weak points of this cogeneration plant (Babus'Haq *et al.*, 1988).

In a combined heat and power plant the global efficiency is defined as an electrical energy produced plus the residual heat useful compared with the heat supplied by the combustion of the fuel that can be improved increasing the use of the heat.

3. EXPERIMENTAL ANALYSIS OF THE ENGINE

The engine studied is a Petter-Plint engine and has the characteristics presented in Fig. 2.

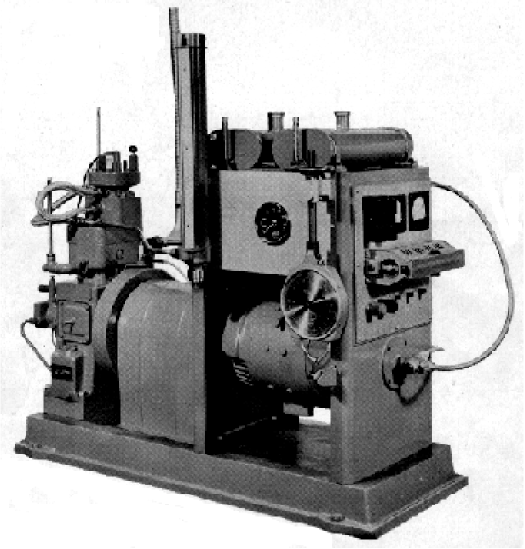


Figure 2 - Petter – Plint internal combustion engine

That engine presents the physical characteristics related in Table 1.

Table 1. Physics characteristics Petter-Plint

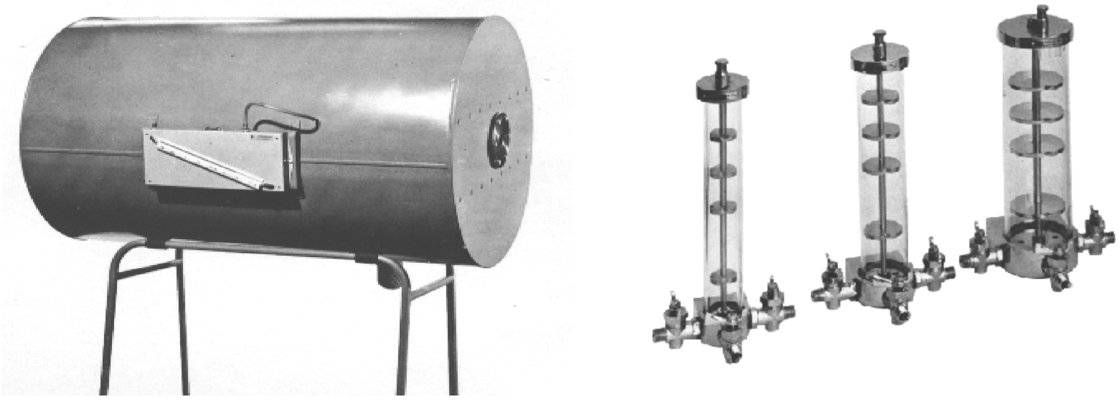
Bore	85.0 mm
Stroke	82.5 mm
Cubic Capacity	468.0 cm^3
Compression ratio	4:1 to 10:1
Governed speed range	1,000 to 2,000 rpm
Nominal power output	2.24 kW
Length	1.52 m
Width	0.61 m
Height	1.14 m

Basically, the engine is a single cylinder water-cooled unit of conventional design, spark-ignition, four-stroke engine and has a special feature that the volume of the combustion chamber may be varied by means of a counter-piston.

The engine was mounted on a cast iron plate that also carries the electrical dynamometer. Cooling water flowmeter and inlet and outlet thermometers are provided. In addition, the equipment may be provided for the measurements of air consumption, for indicate exhaust temperatures, measurements of fuel consumption and temperatures in another necessary points.

The air consumption meter is illustrated in Fig. 3(a). The size of the airbox is determined by the characteristics of the engine to which it is associated. A sharp edged orifice is connected and the pressure drop across the orifice, which does not exceed 7.5 cm of water is measured by an inclined manometer.

The measuring element of fuel consumption consists of a cylindrical glass tube in which a central support carries four spacers so that a measured volume of fuel is contained between successive spacers. In this study the volume of fuel is 25 cm^3.



(a) (b)

Figure 3 - Consumption meters:
(a) air consumption; (b) fuel consumption

The water flowmeter in Fig. 4, operates on the principle of the Reynold’s Column and it is particularly suitable for use with internal combustion engines. It is a simple calibrated method of measuring cooling water flow from water jackets.

Figure 4 -Water flowmeter.

3.1 Experimental measurements

The compression ratio used to obtain experimental data is 10:1, with inlet water temperature at 21 °C. Several measurements are shown in Table 2.

Table 2. Measured values of consumption and temperatures

Rotation (rpm)	Exit Water Temperature (°C)	Exhaust gases temperature (°C)	Fuel Consumption (kg/h)	Air Consumption (kg/h)	Mass Flow of jacket water (kg/h)
1,200	71	376	0.592	8.04	54.6
1,500	78	378	0.645	9.39	56.3
1,800	83	432	0.691	10.40	57.6

Note: Environmental conditions - Pressure: 611 mmHg; Temperature: 21°C; relative humidity: 60%.

In function of those mass flows values and temperatures, the involved thermal energy and generated electricity were obtained. The amounts of heat shown in Table 3 were obtained with the use of the following equations:

$$Q = m\ .\ Cp\ .\ \Delta T \qquad (1)$$

where:

Q - Heat flux [W]
m - mass flow [kg/s]
ΔT - Temperature difference [K]
Cp - specific heat at constant pressure [J/kg K]

For find the available energy in the fuel :

$$E_{comb} = m_{comb}\ .\ LHV \qquad (2)$$

where:

Ecomb - power supplied by the fuel [W]
m_{comb} - fuel consumption [kg/s]
LHV - Lower heat value [J/kg]

The following thermal parameters were used for the calculations:

- LHV of the fuel = 4.187×10^7 J/kg
- Specific heat of the water = 4.187×10^3 J/kg K
- Specific heat of the gases = 1.088×10^3 J/kg K (medium value calculated as a function of the gases composition and temperature).

Table 3. Available power in the process

Rotation (rpm)	Power supplied by the fuel (W)	Shaft Power (W)	Power available in the gases (W)	Power available in the jacket water (W)	Power in the electrical generator (W)	Losses (W)
1,200	6,884	1,326	1,695	3,175	1,260	688
1,500	7,505	1,023	2,000	3,732	972	750
1,800	8,038	726	2,354	4,154	690	804

Thus, the percentual level of available power can be calculated. Table 4 shows the maximum possibility to recovery useful heat as a function of the rotational speed. Here, the thermal efficiency is defined as shaft power divided by the power supplied by the fuel, and the others also use the same bases for calculations.

The global percentual shown in the Table 4 is found by adding the percentual available in the gases, in the water to the thermal efficiency, considering an electrical generator efficiency of 95% (ninety five percent).

Table 4. Percentual levels of use of the power supplied by the fuel

Rotation (rpm)	**Percentual available in the gases (%)**	**Percentual available in the jacket water (%)**	**Thermal performance (%)**	**Global percentual available (%)**	**Air/Fuel Ratio**
1,200	24.62	46.12	19.26	89.04	13.58
1,500	26.65	49.73	13.63	89.33	14.56
1,800	29.29	51.68	9.03	89.55	15.05

3.2 Plot of the experimental results

After the measurements the obtained values were indicated in graphs that show the behavior of the several parameters studied as a function of the engine rotational speed.

Figure 5 shows the mass flows of the exhaust gases and jacket water. Figure 6 shows temperatures of gases and jacket water and Fig. 7 shows the power available.

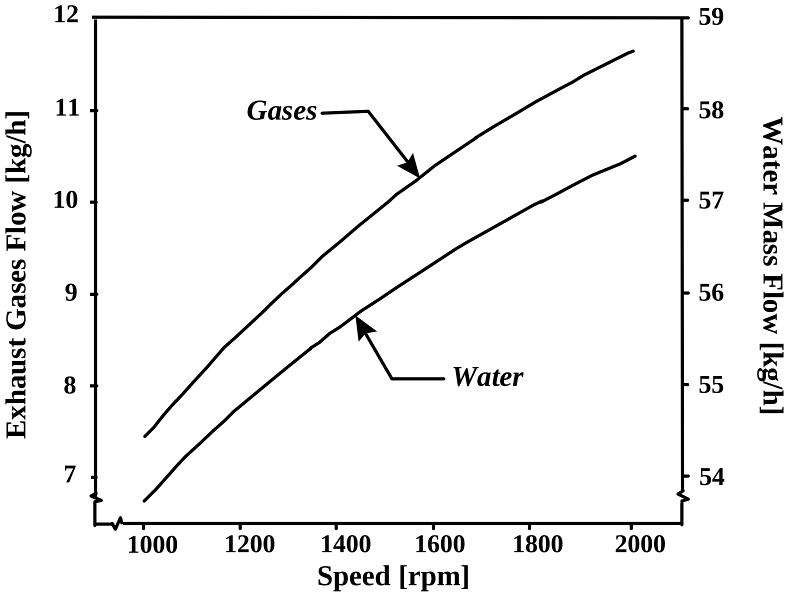


Figure 5 - Mass flows available as function of the rotational speed.

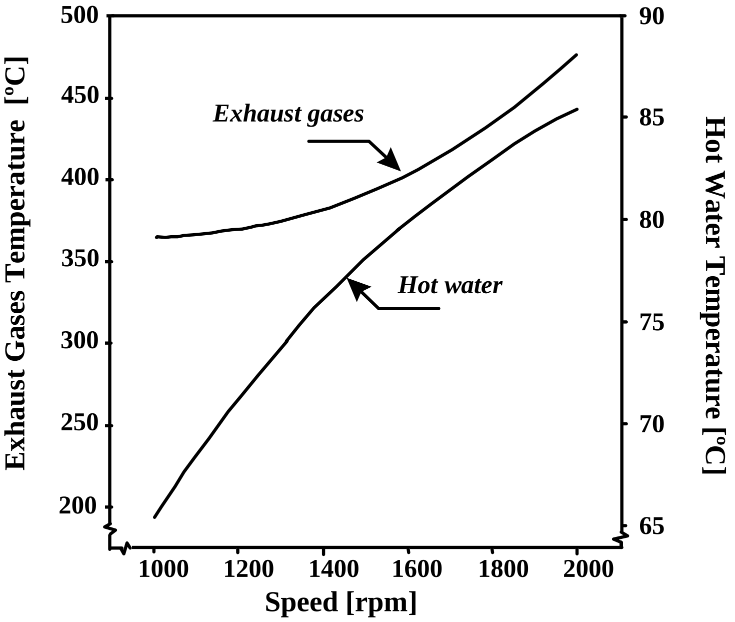


Figure 6 - Temperature levels as a function of the rotational speed.

In high rotations there are higher temperatures for the exhaust gases and jacket water.

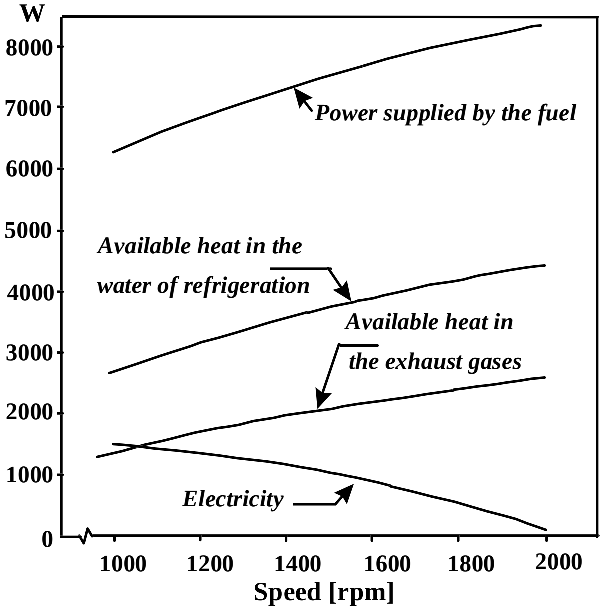


Figure 7 – The values of the available energy

Its can be observed that electricity is the only energy form that decreases with the increase of the rotation.

In Fig. 8 the diagram of energy flux or Sankey diagram is shown, considering 1,200 rpm and effectiveness of heat transfer water/water (shell and tube heat exchanger) as 80% and of gas/water (plate heat exchanger) as 60% .

The schematic arrangement for the cogeneration plant with internal combustion engine in the form which was proposed can be named as a thermodynamic method, and the amount of energy as a potential thermodynamic heating (Stachel et al., 1995).

It can be seen that 18% of power supplied by the fuel is electricity and 52% (37% + 15%) is hot water at 50 °C.

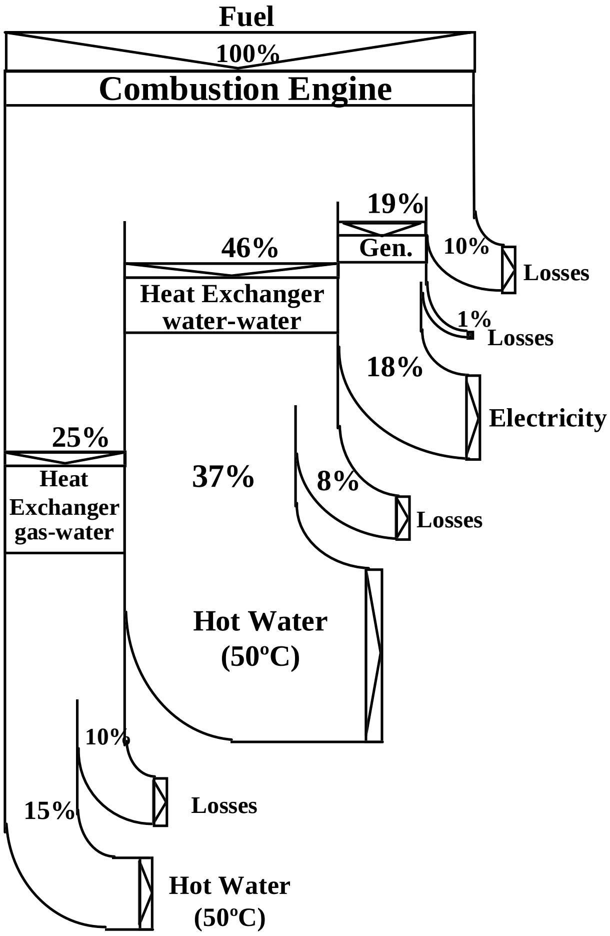


Figure 8 - Sankey´s Diagram
Note: Gen.: Generator

4. CONCLUSIONS

The cogeneration plant proposed utilizing internal combustion engine enables 52% of the heat available in the jacket water and exhaust gases, with losses of 10% and 8%, respectively, which is approximately equivalent to 71% of the energy supplied by the fuel. Those values are indication that a reasonable efficiency under the viewpoint of the cogeneration was founded. It should be taken into account that the electricity generated in the system in study (18%) is small when compared with the usual (around 35%).

If combustion is inefficient it increases the temperatures of the exhaust gases, causing a considerable loss of energy in those gases demanding a high mass flows of jacket water and, as a consequency more heat transfer. The engine presents very high values of residual heat, that is certainly due to problems with combustion and in the system of refrigeration.

The diagram of Sankey shows that the use of the residual heat of the engine in study is advantageous. It is necessary an analysis of the demands of electricity and the involved costs which can suggest improvements in the combustion process decreasing the amount of heat available in the exhaust gases and water and improvements in the refrigeration system.

For this process with an engine operating as specified and measured, the cogeneration plant is highly advisable. For a next paper an experimental data will be obtained with GLP, allowing a comparison with the results presented in this paper. Experimental and comparative measures will also be made with relation to the level of pollutant emission for the system operating with gas oil and GLP.

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