HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

COMBINED PRODUCTION OF ELECTRICITY AND HEAT IN A MICROCOGENERATION UNIT

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ABSTRACT

Diesel engines are widely used in industrial activities in Peru for electricity generation and heat production. The requirement of different types of energy and its separate generation represent a higher demand for fossil fuels, when the equipment used are internal combustion engines, and higher emission of high-temperature pollutant gases to the environment; all of this, with a deficient utilization of the energy supplied by the fuel. In this context, a Diesel cycle generator of 40 kW was evaluated for the production of electricity and heat. The engine was mapped with different electrical charges (5 kW, 10 kW, 15 kW, 20 kW, 25 kW and 30 kW) simulated by a copper resistance submerged in a tank with salty water. A regenerator was used for the recovery of the exhaust gases heat to allow cogeneration. The experimental device was monitored and instrumented with K type thermocouples, differential pressure sensors, power meters, flow meters, among others; all the signals were received and stored by a data acquisition system for its processing and interpretation. The electrical power, thermal power, specific fuel consumption, thermal efficiency and electric efficiency were evaluated for conventional electricity generation and for combined production of electricity and heat.

NOMENCLATURE

$Q_{exhaust}$ = Exhaust gases heat, [W]
$\dot{m}_{exhaust}$ = Exhaust mass flow, [kg/h]
$Cp_{exhaust}$ = Specific heat of the exhaust, $\left[{}^{J}\!/\!_{kg \cdot K} \right]$
$\Delta T_{exhaust}$ = Temperature difference of the exhaust, [°C]
Q_{fuel} = Fuel heat, [W]
$\dot{m}_{fuel}$ =Fuel mass flow, [kg/h]
LHV = low heating value diesel, [J/kg]
Q_{water}= Water heat, [W]
$\dot{m}_{water}$ = Water mass flow,[kg/h]
Cp_{water} = Specific heat of the water, $\left[{}^{J}\!/\!_{kg \cdot K} \right]$
ΔT_{water} = Temperature difference of the exhaust, [°C]
η_{cog} = Cogenerator thermal efficiency, []
η_{adit} = Increased efficiency by cogeneration, []
η_1 = Efficiency without cogeneration, []
P_{ele} = electrical power produced, [W]
η_2 = Efficiency with cogeneration, [W]
U = Heat exchange global coefficient
A = heat exchange surface of cogenerator, [m^2]
LMTD = log mean temperature difference for crossflow, [°C]

INTRODUCTION

The requirement of different types of energy and its separate generation represent a demand of higher quantities of fossil fuels, when the equipment used are internal combustion engines, and the emission of higher quantities of high temperature exhaust gases, all of this, with a deficient utilization of the energy provided by the fuel.

The combined generation of electricity and heat (cogeneration) is a proved technology which exists more than 100 years ago and is mainly used in big-scale electricity generation plants and for industrial applications. Though, the actual trend involves the development of microcogeneration systems, which have less than 50 kW electrical power output.

This technology involves the utilization of the same energy source for the generation of these two types of energy, diminishing, this way, the quantity of fossil fuels required for its obtainment.

Microcogeneration units are typically run for heating applications in residential or commercial buildings like conventional boilers. These systems generate electricity and heat at very high-efficiencies and help to save fuel, cut greenhouse gas emissions and reduce electricity costs. Most units operate in a grid-parallel mode, so that the building covers its electrical needs from the electrical network, and it can also sell electricity to the network.

In the last few years there has been a trend for the usage of microcogeneration units in isolated regions. Buildings with no grid connection and/or less reliable electrical energy supply are more likely to use microcogeneration systems in connection with battery systems and hot water. There is also an opportunity to use biofuels instead of diesel or other fossil fuels, which would be a more environmentally friendly alternative.

Experimental studies made show that microcogeneration is feasible in facilities as small as a house, and it is also a very effective technique for an efficient utilization of resources.

This research work pretends to establish the first steps for the implementation of trigeneration technology on a big-scale in Peru with the objective of reducing the consumption of fossil fuels, contributing with the environmental care and offering the opportunity to reduce the energy costs in Peruvian enterprises.

EXPERIMENTAL MODEL

An experimental model was designed and built for the evaluation of a Diesel cycle engine for electricity and heat production. The heat was recovered from the residual heat from the engine.

The experimental model (Figure 1) was made by three modules: the tests section, the electric load and the Data Acquisition System.

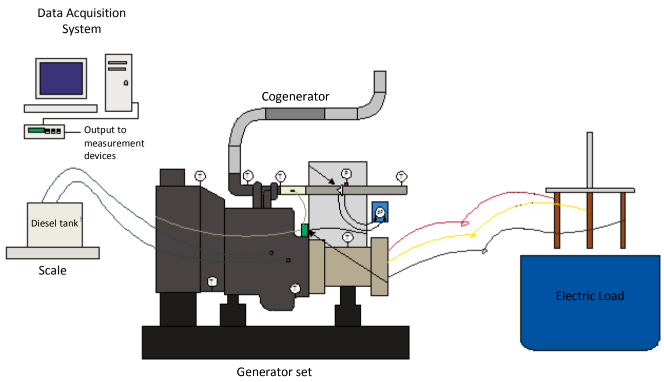

Figure 1 Experimental model

TESTS SECTION

The tests section was made by the generator set and the cogenerator.

Generator set

A generator set conformed by a 4-cylinder Diesel cycle engine coupled to an electricity generator. The technical features of the engine and the generator are shown in Tables 1 and 2, respectively.

To find the air mass flow that enters the engine, a nozzle type flow meter was used to cause a pressure drop measurable by a differential pressure transducer. A nozzle made of stainless steel was fabricated and used according to the NBR ISO 5167-1 Standard. The smaller diameter of the nozzle was 38.1 mm and the diameter ratio was 0.75 to cause the lowest pressure drop allowable and to avoid restricting the air to the engine.

The nozzle was coupled with a flange to a PVC tube with a diameter of 2”, according to the dimensions indicated in the ISO Standard mentioned before to make an appropriate measurement. A differential pressure transducer with a working range from -1 to 1 psi was used to measure this parameter.

The amount of diesel consumed by the engine was measured using a fuel tank of 20 liters of capacity and a scale. The tank was connected through 6.25 mm diameter hoses for diesel to the feeding and return system. The scale was connected to the Data Acquisition System using a PC and a RS-232 port.

The temperature was measured using K type thermocouples (Chromel-Alumel) in different points of the generator set: air in the inlet and outlet from the turbocharger, exhaust gases, water inlet and the outlet from the radiator, diesel, oil, biogas in the inlet and the generator set case.

Table 1 Technical features of the engine

Feature	Description
Brand	Cummins
Model	4BT3.9
Functioning cycle	4-strokes
Number of cylinders	4
Type	Vertical, in-line
Unitary cylinder capacity	0.975 l
Total cylinder capacity	3.9 l
Bore	102 mm
Stroke	120 mm
Compression ratio	16.5:1
Injection system	Direct
Net power output	36 kW
Engine speed	1800 rpm
Speed regulation	Electronic
Aspiration	Turbocharged
Electric start system	24 V DC
Valves per cylinder	2 (admission and exhaust)

Table 2 Technical features of the electricity generator

Feature	Description
Brand	Stamford
Model	PI114J
Type	Synchronous alternator
Electric potential difference	220/440 V
Poles	4, 12
Lines	4
Frequency	60 Hz
Power factor	0,8

Cogenerator

The cogenerator for the heat recovery from the exhaust gases was a shell-tube heat exchanger. This device was built with the objective of heating water, which is why exhaust gases circulated in the tubes and water circulated in the shell.

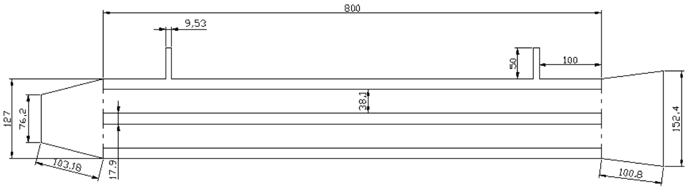

Figure 2 Side view of the structure of the cogenerator

The volumetric flow of water in the inlet to the heat exchanger was measured using a flow meter with working range from 1 to 15 GPM and an outlet from 0 to 5 VDC, with precision of ±2%.

To know the temperatures of the water and the gases in the inlet and the outlet of the heat exchanger, K type thermocouples were also used; they were also connected to the Data Acquisition System.

One of the objectives of the study was to prove that the device used for the heat exchange, i.e. the cogenerator, would not cause a pressure drop that could damage the performance of the engine. This is why, a differential pressure transducer between the inlet and the outlet of the gases in the cogenerator was installed. The device used had the same characteristics than the one used for the air flow measurement.

ELECTRIC LOAD

An electric resistance was used to simulate the electric load of the generator set (Figure 3). It was made by three copper bars correspondent to the three phases of the generator and a tank full of salty water (0.5%). To vary the energy consumption of the engine, the bars were submerged into the salty water using a manual elevator, varying the submersion depth. The generator and the electric resistance were connected through protected electric wire.

Figure 3 Electric load

All the signals emitted by the measurement instruments, except the scale, were acquired by the Data Acquisition System, which sent them to a personal computer (PC) through an RS-232 port, for its later processing and analysis.

The software used for the data acquisition was HP BenchLink Data Logger, which has a Windows type interface easy to configure and manage.

For the acquisition of signals from the electronic scale, LabVIEW® was used. This software had also a Windows type interface, which allowed it easy management. The data was also obtained through an RS-232 connection between the scale and a laptop.

EXPERIMENTAL PROCEDURE

The development of the study included tests of the Diesel cycle engine with and without the components for trigeneration (regenerator and chillers) to evaluate the performance of the system. The tests were made with a fixed speed of 1800 RPM, because the generator set was designed to work only at that speed.

Tests were made in diesel mode for 5 kW, 10 kW, 15 kW, 20 kW, 25 kW and 30 kW of the maximum load. The objective was to determine the characteristic curves of the engine in terms of performance, which were taken as a base for the comparison between conventional generation and cogeneration.

For the cogeneration tests, mass flow and temperature measurements were made. The water mass flow was regulated verifying the parameter in the Data Acquisition System. Once the engine's permanent regime of operation was reached in standby, the electric resistance was connected to the generator and submerged in the salty water according to the desired electric load.

Table 1 Studied uncertainties

Parameter	Uncertainty
T	± 0.2 °C
$\dot{m}_{fuel}$	± 1 %
$\dot{m}_{air}$	± 5 %
$\dot{m}_{exhaust}$	± 5 %
$\dot{m}_{water}$	± 2 %
ΔP	± 0.075%
ΔT	± 0,28 °C
Q_{fuel}	± 1 %
P_{ele}	± 5 %
Q_{water}	$\pm\sqrt{\left(\frac{\delta\dot{m}}{m}\right)^2+\left(\frac{\delta\Delta T}{\Delta T}\right)^2}$
$Q_{exhaust}$	$\pm\sqrt{\left(\frac{\delta\dot{m}}{m}\right)^2+\left(\frac{\delta\Delta T}{\Delta T}\right)^2}$
η_{cog}	$\pm\sqrt{\left(\frac{\delta Q_{water}}{Q_{exhaust}}\right)^2+\left(\frac{Q_{water}}{Q_{exhaust}^2}\delta Q_{exhaust}\right)^2}$

η_1	$\pm\sqrt{\left(\frac{\delta P_{ele}}{Q_{fuel}}\right)^2+\left(\frac{P_{ele}\cdot\delta Q_{fuel}}{Q_{fuel}^{\ 2}}\right)^2}$
η_2	$\pm\sqrt{\left(\frac{\delta P_{ele}}{Q_{fuel}}\right)^2+\left(\frac{\delta Q_{water}}{Q_{fuel}}\right)^2+\left(\frac{\left(P_{ele}+P_{water}\right)\cdot\delta Q_{fuel}}{Q_{fuel}^{\ 2}}\right)^2}$
U	$\pm\ \pm\sqrt{\left(\frac{\delta Q_{water}}{Q_{water}}\right)^2+\left(\frac{\delta LMTD}{LMTD}\right)^2}$

DATA REDUCTION

Exhaust gases heat

$$Q_{exhaust}=\dot{m}_{exhaust}\cdot Cp_{exhaust}\cdot\Delta T_{exhaust} \qquad (01)$$

Water heat

$$Q_{water}=\dot{m}_{water}\cdot Cp_{water}\cdot\Delta T_{water} \qquad (02)$$

Fuel heat

$$Q_{fuel}=\dot{m}_{fuel}\cdot LHV \qquad (03)$$

Cogenerator thermal efficiency

$$\eta_{cog}=\frac{Q_{water}}{Q_{exhaust}} \qquad (04)$$

Efficiency without cogeneration

$$\eta_1=\frac{P_{ele}}{Q_{fuel}} \qquad (05)$$

Efficiency with cogeneration

$$\eta_2=\frac{P_{ele}+Q_{water}}{Q_{fuel}} \qquad (06)$$

Heat exchange global coefficient

$$U=\frac{Q_{water}}{A\cdot LMTD} \qquad (07)$$

RESULTS

Figure 4 shows the variation of temperature in different positions. The studied water flow was 0.09 kg/s. It can be observed that for higher electric loads, the temperature difference of the exhaust gases between the inlet and the outlet increase and the difference between the temperature of the water in the inlet and in the outlet was also higher, showing, mainly, a higher heat transfer from the gases to the water.

Figure 5 shows the variation of the exhaust gases, the admission air and the fuel mass flow. It can be seen that the fuel mass is low compared to the exhaust gases mass flow, due, mainly, to the difference in density

Figure 6 shows the pressure drop in the exhaust heat gases and in the water flow. For all the experiments made, the pressure drop in the gases showed a constant value (smaller than 500 Pa). The pressure in the inlet of the cogenerator was very close to the atmospheric pressure, which was why the maximum pressure drop was lower than 0.6%. In the case of the water, the pressure drop kept approximately constant (1800 Pa), related to the water inlet pressure, it had a maximum value of 1.3%.

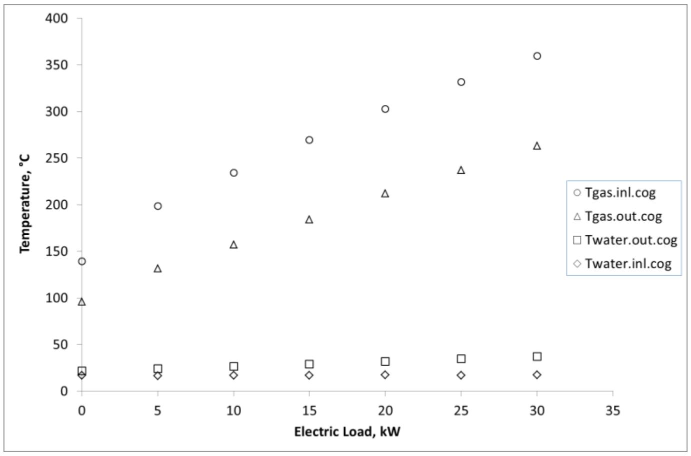

Figure 4 Variation of temperature of the exhaust gases with different electric loads

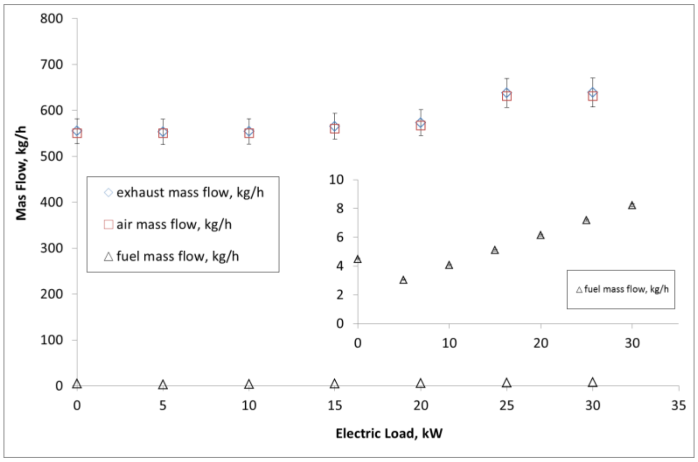

Figure 5 Mass flow of exhaust gas, air and fuel

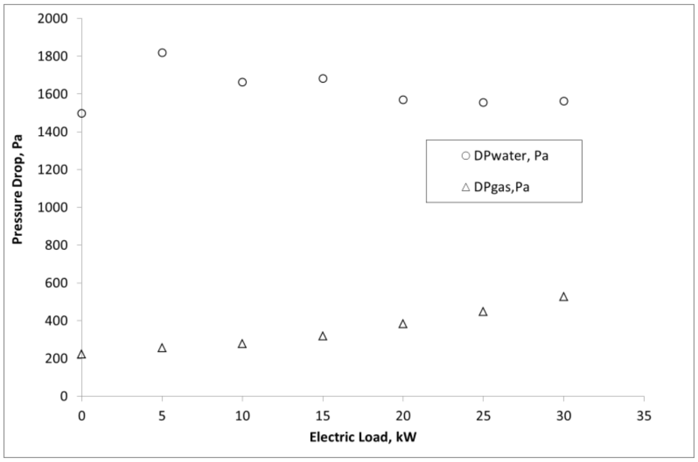

Figure 6 Pressure drop of the exhaust gases and the water.

Figure 7 shows the variation of heat offered by the exhaust gases and the heat absorbed by the water. Between 30% and 40% of the heat offered by the exhaust gases was absorbed by the water, which is also shown in Figure 8, where efficiency varies according to the electric load.

Figure 8 has also the percentage of heat recovery regarding energy offered by the fuel. Around 9% of the energy was recovered like hot water.

We can also see that the total efficiency increases up to 44.5% (for the maximum load).

Finally, in Figure 9, the variation of the heat exchange global coefficient (U) is shown for different electric loads. Since it is a shell and tube heat exchanger, U does not show high values, mainly because the LMTD values are not very high.

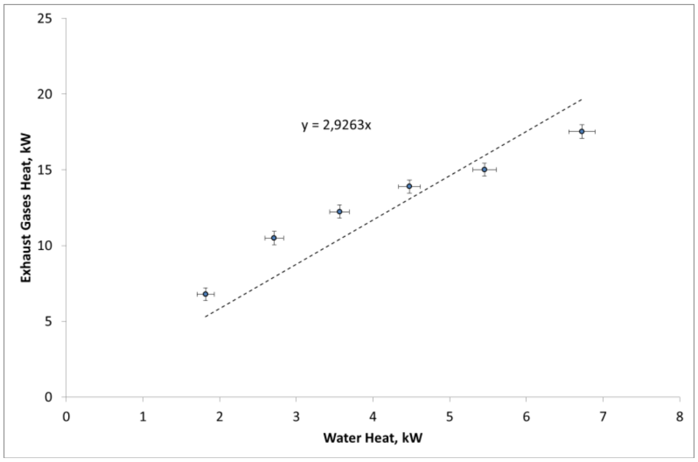

Figure 7 Variation of the heat ceded by the exhaust gases and the heat absorbed by the water.

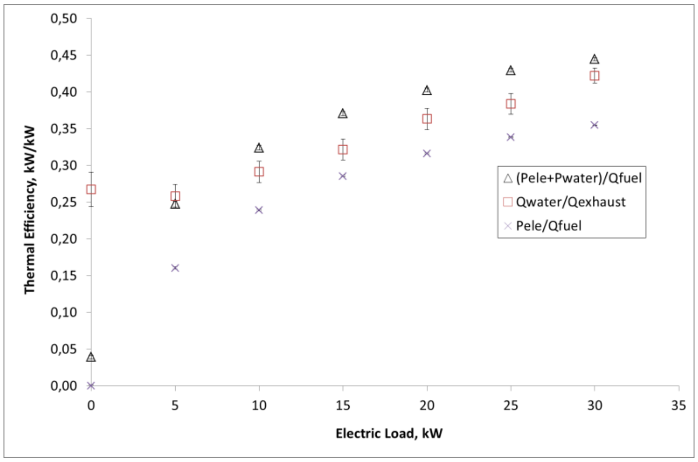

Figure 8 Energy recovery.

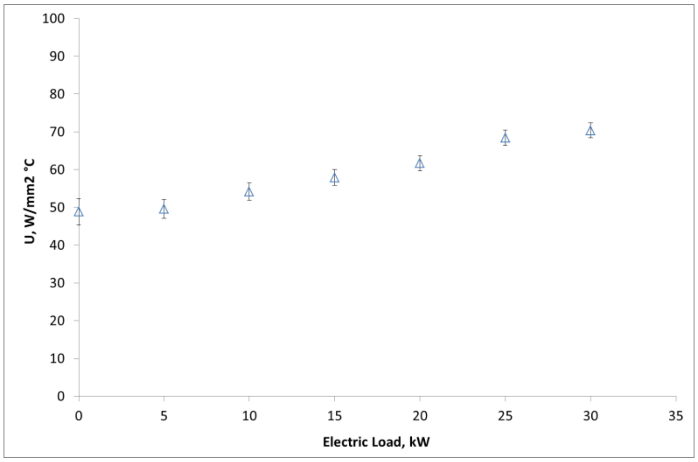

Figure 9 Variation of the heat exchange global coefficient according to the electric load

CONCLUSION

The heat exchanger used showed an acceptable performance, in thermal aspects as in permissible pressure drop.

Values of heat recovery in this microcogenerator that could allow the application of this technology in small plants of electricity generation were attained.

Microcogeneration shows itself as an opportunity for an appropriate management of energy resources, which could benefit the operations of enterprises located far from the city with energy supply problems.

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