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Feasibility Evaluation of the Use Organic Rankine Cycle (ORC) Technology for Energy Production from Exhaust Gases Recovery: A Case Study of Local Industry in Colombia

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Abstract

The main objective of this research is to determine the technical and economic feasibility of using heat recovered from the gases emitted by an internal combustion engine of 1.75 MW of power, to generate energy using an Organic Rankine Cycle (ORC). The investigation verified the potential of electricity generation with engine exhaust gases of a company on the Caribbean coast of Colombia, where an additional 250 kW can be obtained with the exhaust gases by igniting two engines.

The project has a recoverable investment in 7 years with excellent economic returns, which represents a great opportunity for energy savings in the studied system that will be reflected in the competitiveness and productivity of the company.

Keywords: Organic Rankine Cycle, exhaust gases recovery, energy microgeneration

1 Introduction

The use of unconventional recovery systems from sources of energy classified as waste has still little application in Colombia, however, this technology is being encouraged at the governmental level. According to the Indicative Action Plan of Energy Efficiency (PAI PROURE 2017 - 2022) developed by the Ministry of Mines and Energy of Colombia, energy efficiency is considered a mechanism to ensure energy supply, becoming a vehicle to increase national productivity and competitiveness [1]. In accordance with these goals, the Mining and Energy Planning Unit (UPME) has developed tax benefits in Colombia for energy efficiency projects/efficient energy management, including recovery of waste heat, thus helping to reduce capital costs and accelerating the recovery of investment [2]. The latest scientific research on waste gas recovery systems of internal combustion engines using ORC is aimed at the direct use of exhaust gases in diesel engines or developing dual cascade cycles that can simultaneously recover the waste heat from the exhaust gas and engine coolant, thus obtaining higher cycle efficiencies [3]. Due to the high cost of an ORC micro unit, some studies are aimed at the use of these systems, using instead of microturbines other types of expanders such as tilting plate rotors, demonstrating excellent performance and cost reduction [4].

In Colombia, some research related to the implementation of ORC technology for heat recovery has been carried out. Among them, the study developed by the University of Antioquia in agreement with Ecopetrol (Colombian Petroleum Company) [5] stands out, without satisfactory results because higher temperatures are required to guarantee technical feasibility. The Centro de Desarrollo Tecnológico del Gas (Technological Development Center of Gas) explores the potential to generate energy from waste gases from the compressor units of the gas compressor stations belonging to two companies in the energy sector in Colombia, where a good overview can be corroborated for this type of technologies [6].

An internal combustion engine only converts a third of the chemical energy of the fuel into mechanical energy the remaining two thirds is converted into heat inside the combustion engine and then released into the atmosphere. This article seeks to show the possibilities of implementing an energy recovery technology such as the systems ORC, already applied in other countries with success, improving and optimizing the common processes at the industrial level with thermal sources of waste that can be used [7].

A fundamental part of the ORC systems are the devices that comprise it. Basically, an ORC plant has two heat exchangers (one evaporator and one condenser), one pump and one expander [8]. However, complementary units can be added to increase efficiency or simplicity. An addition that improves efficiency is the use of pre-heaters, either with another heat exchanger at the exit of the expander or take some external fluid with thermal capacity [9]. On the other hand, heat exchangers are subject to study for the improvement of heat transfer capacity per unit area or volume, and research is aimed at improving this item by simplifying the ORC units [10].
For all the above described and the importance of this topic, the present investigation was developed, whose main objective was to determine the technical and economic feasibility of using heat recovered from the gases emitted by an internal combustion engine of 1.75 MW of power, to generate energy using an Organic Rankine Cycle (ORC).

2 Methodology

The purpose of the study consisted in verifying the viability of the application of an ORC in a company that generates and sells energy. The generation of energy in this company presents a demand that does not allow the continuous operation of its internal combustion engines, these operating intervals force the engine to work below its nominal parameters, therefore the kilowatt generated is less efficient and more expensive. To continue with a reliable operation and low energy production costs, the company was asked to generate a percentage of the energy from the thermal waste of the engines, applying the ORC technology, which is advantageous given the location of the company, the type of operation of the plant, and the generation experience of the company. The capacity of generation or potential useable energy of the gases and radiators is up to an additional 0.5 MW, without fuel costs and without affecting the environment, taking advantage of the immediate proximity to the Magdalena River, the main fluvial artery of Colombia.

The company generates energy from 4 gas internal combustion engines, CUMMINS, each of 1750 KW, with a thermal efficiency at full load of 38.7%. The engines operate according to the customers' energy demand, which normally ranges from 2 to 4 MW per day, and only in certain periods of the month can it exceed 5 MW. The basic characteristics of the exhaust gases are described in Table 1.

Table 1. Thermal gas data of CUMMINS engines at 75% load.

Exhaust Air Flow	**Values**
Exhaust gas flow mass, kg/s (lb/hr)	2.60 (20502)
Exhaust gas flow volume, m3/s (cfm)	5.72 (12114)
Exhaust after turbine, °C (°F)	504 (939)

Source: Engine technical datasheet

An engine emits gases at a rate of 2.6 kg / s at 75% partial load and at a temperature of 504 ° C. This thermal current has a power calculated from equation (1), assuming ideal gas behavior, whose approximation is valid with a wide margin of error, neglecting the amount of kinetic energy of gases due to its insignificant value.

$$\dot{E}_{gases} = \dot{m}h \; [kW] \tag{1}$$

$$\dot{E}_{gases} = \left(2{,}6\frac{kg}{s}\right)\left(795\frac{kJ}{kg}\right) = 2067kW$$

Here $\dot{E}_{gases}$ is the thermal power of the gases, $\dot{m}$ is the mass flow of the exhaust gases and h is the enthalpy of those gases according to ISO properties.

This indicates that the exhaust gases have a potential of up to 2 MW for a load of 75%, which amounts to 2.3 MW when the engine works at 100% capacity.

The exergy available in the gases is calculated from equation (2).

$$X_{flujo\ gases} = \dot{m}\left[(h - h_0) - T_0(s - s_0) + \frac{V^2}{2}\right] \tag{2}$$

$$X_{flujo\ gases} = \left(2{,}9\frac{kg}{s}\right)\left[\left((795 - 300)\frac{kJ}{kg}\right) - 300K\frac{(2{,}68-1{,}7)kJ}{kg.K} + \frac{79^2}{2x1000}\frac{m^2}{s^2}\right] = 531\ kW$$

Where $X_{flujo\ gases}$ is the exergy of the exhaust gases, $\dot{m}$ is the mass flow of the exhaust gases, h and h_0 are the enthalpies at the exhaust temperature and ambient temperature respectively, T_0 is the ambient temperature (27 °C), s and s_0 are the entropies at the temperature of the gases and ambient temperature respectively and V, represents the speed of the gases. The result is approximately ½ MW of exegetical power, which reflects the high potential to produce work from the mass of gases expelled. The amount can increase up to 589 kW at full load. This quantity represents 31% of the energy that the engine currently generates.

In response to the variable demand of the company, and obeying the cost / benefit requirements, alternatives for the ORC unit were explored in the current market.
The selected ORC unit must meet the following criteria: 1) Studies and success cases executed in the world, 2) Adaptability to the technical conditions of the Colombian company, 3. Low acquisition, operation and maintenance costs and 4. Apprehension of technology in our environment
In this study, the following companies were contacted that commercialize technology that uses waste gases for power generation: the Italian Turboden, the American company Ormat, and the Chinese company Kaishan Technologies. The first two mentioned companies use microturbines as an expander device and organic fluids ranging from refrigerants to hydrocarbons and alcohols. On the other hand, Kaishan Technologies uses expander screws that are devices of lower cost and maintainability and less technical complexity than microturbines; The R-245fa refrigerant is used as working fluid. disadvantage of the turbines.

3 Results

The selected company was Kaishan Technologies. Kaishan's technology is low cost, because in comparison to its similar Ormat and Turboden that use turbines as expanders, the Kaishan plants use screw expanders. China, the country of origin of the company, has a high number of investigations and publications concerning ORC applications with internal combustion engines. Likewise, the company is the leader in pneumatic technologies in China and ORC applied successfully.

The adaptability of a system composed of a screw expander to the operating conditions of the engines of the company under study, variable energy demand thus less amount of combustion gases emitted and therefore less energy by heat transfer in the evaporator, which can increase the amount of moisture in the working fluid. The increase in the humidity of the working fluid would limit the use of turbines as an expander device but would have no influence on the operation of expander screws, a device used by the manufacturer Kaishan Technologies.

The technology with screw expander is patented by Kaishan Technologies engineers, its commercial development is only offered by this company worldwide. For the purposes of apprehension and assimilation of technology in our local environment, the use of the screw expander offers the advantage of having become widespread in recent years in Colombia. For the development of the project, a Kaishan 250 kW nominal capacity unit that would operate for an engine under the scheme shown in Figure 1 is proposed, generating 188 kW. Table 2 shows the technical characteristics that the manufacturer of the ORC plant proposes for the use of the exhaust gases of the company's engines.

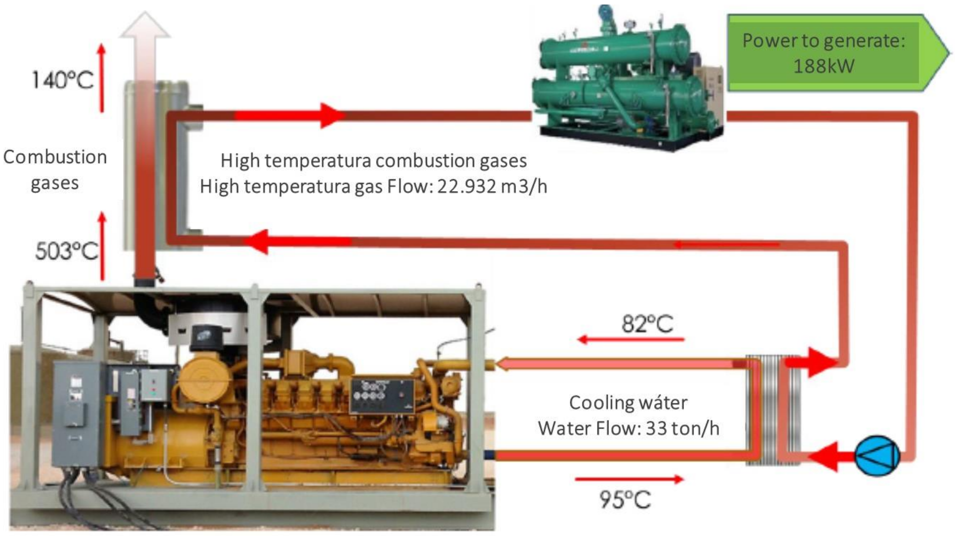
Table 2. Characteristics of the ORC KE250 unit set.

Characteristic/Device	**Description**
Nominal capacity	250 kW
Working fluid	R245fa refrigerant, friendly to the environment
Thermal efficiency	10.74%
Net power generated	188kW
Hot gas outlet temperature	140 ° C
Dimensions approx. (m):	12x12x high.
Useful life	11 years

Source: Engine technical datasheet

The proposed unit also uses the heat emitted by the engine radiator to preheat the cycle fluid, decreasing the radiator temperature, improving the performance of the engine.

Figure 1. ORC plant of Kaishan Technologies using gases emitted by a combustion engine.



Source: Kaishan Technologies

The project contemplates an initial investment of USD 657,000, which when financed with a bank loan at an interest rate of 12% EA, would have a fixed monthly installment of $ 8,864 for 10 years. The manufacturer Kaishan stipulates a plant life of 11 years and an average annual maintenance cost of 2% of the value of the plant. Considering the following definitions:

- O & M expenses: These are expenses derived from the operation of the equipment. Maintenance expenses for study purposes increased to 4% and basic operations were stipulated at 0.7% for a total O & M of 4.7%, which is a conservative value for the study.
- Value of the kWh: the current value at which the company markets the KWh is USD 0.095, which will be the price at which the KWh generated at an ORC will be sold.
- Income: It is the value perceived by the company annually for the sale of energy, calculated as:

  (90% of installed power) x (24 Hours of daily operation) x (350 days of the year) x (Value of kWh)

  This formula considers that the equipment will be used only at 90% of its total capacity that is 250 kW, and that it will operate 350 days a year, which leaves 15 days free for maintenance, training, testing and other stops. It is not considered an energy backup for this period, since for current conditions the company has excess installed capacity. The Table 3 presents the evaluation of the project over time:

Table 3: Financial balance of the ORC project

Initial considerations	**Values**
Initial investment	USD 656,667
Annual effective interest rate	12%
Income tax in free zone	15%
Monthly fee payable at 10 years	USD 8,864
Initial evaluation of the 1st year	
Income (annual)	USD 180,180
Expenses (O & M, annual)	USD 21,934
Ebitda	USD 158,247
Depreciation	USD 65,667
Taxes	USD 13,887
Cash flow	USD 144,360
Financial Indicators	
VPN (12%)	USD 197,666
Project IRR	18.60%
Period of recovery of the investment	7 years
Cost of kilowatt generated in ORC	USD 0.08674

4 Conclusions

- Organic Rankine ORC cycle technology allows generating energy from waste sources such as exhaust gases. Its variants in structure and design could contribute to increase clean kilowatts of energy for any company in the local sector.
- From this study it was possible to verify that the implementation of the project in the company is technologically and financially viable. The existence of a high potential for generating energy from waste gases, at a cost of 0.068 USD / kW with an internal rate of return of 18.6%, which in the context of energy projects, show the project as very attractive.
- A collateral benefit of the implementation of the project is the increase of the efficiency of engines with the use of engines in continuous mode at full load, independently of the demand, reducing maintenance and operation costs.
- The implementation of the proposed ORC plant was analyzed from the point of view of apprehension of the technology by the company's personnel. It was concluded that its technological simplicity, having an expander screw, allows its easy insertion.
- If the gases of the three engines are used at full load, the generation capacity could be doubled from the proposed ORC unit, in this way the costs are reduced, recovering the investment in less time (approximately three years) and increasing profits. The environmental and technological innovation advantages open a door to materialization in modern energy management for Colombia, where the maximization of the use of energy resources is a priority.

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