Energy Analysis of a Trigeneration System Using Waste Energy from a Diesel Engine for Cold and Heat Production

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***This* study performs an energy analysis of a trigeneration power system that uses the waste heat from the diesel engine of a generator. Waste heat is employed to increase boiler efficiency, significantly reducing natural gas consumption. Simultaneously, the exhaust gases are directed to a lithium bromide absorption chiller, where they are used in the production of chilled water.**

The results show that the heat generated in the cooling system can be used to heat water from 25°C to 60°C, resulting in a reduction of 42,000 m³ in the annual consumption of natural gas by the boiler. In addition, the heat from the engine's exhaust gases proved to be able to generate 5274 kW of cooling through a lithium bromide chiller, making it possible to supply chilled water to accumulator tanks.

When compared to the traditional 29.88% yield of the diesel engine, the proposed trigeneration system achieved an efficiency evolution of 73,34%, demonstrating a significant advance.

***Index Terms*—Trigeneration, diesel engine, waste heat, thermal utilization, energy efficiency, heat exchanger, absorption chiller, boiler, electric power, cooling, generator set.**

I. Introduction

The growing demand for energy efficiency and sustainability has driven the development of innovative cogeneration and trigeneration systems. Trigeneration emerges as a strategic approach to maximize energy efficiency by integrating the simultaneous production of electricity, useful heat, and cooling, reducing thermal losses and associated operational costs.

The integration of trigeneration systems with diesel engines has proven to be an effective approach to improving energy efficiency, as evidenced in studies on trigeneration systems with marine diesel engines [1]. These systems combine cogeneration with diesel engines and absorption cooling, utilizing the waste thermal energy from engine exhaust gases in the boiling process of the absorption cooling unit [7].

Efficient energy use is crucial for the development of any modern society, and energy demand is increasing daily. It is well known that fossil fuel reserves are limited and cannot be recycled. Moreover, the overexploitation of fossil resources leads to an increase in dangerous pollutants. British Petroleum predicted that at the current rate of conventional primary energy consumption, the main fossil sources (crude oil, natural gas, and coal) are rapidly depleting and will soon be exhausted. Therefore, to ensure sustainability, it is necessary to identify new energy sources or improved methods and technologies to increase energy efficiency [4].

Although many studies have been conducted in the direction of alternative fuels, such as hydrogen, biodiesel, and other additives like alcohols, this work focuses primarily on improving the energy efficiency of engines running on conventional fuels, which represent a significant portion of the current reality in commercial and industrial plants. In this context, waste heat recovery and thermal energy storage present a short-term strategy that can minimize environmental impacts by increasing the energy efficiency of fossil fuel utilization [5][8].

Among the various options available for waste heat recovery, micro-cogeneration and micro-trigeneration are rapidly growing and emerging as promising techniques for increasing overall energy efficiency and reducing total emissions. Cogeneration is a way of using fuel in a thermodynamically efficient manner, defined as the simultaneous production of heat and power. Small-scale cogeneration or Combined Heating and Power (CHP) systems for domestic and light applications, with less than 15 kW of electrical power, are generally called micro-combined heat and power systems [3]. In the trigeneration system, the demands for power, heating, and cooling are simultaneously met by a main engine, a heat recovery system, and thermally activated technology to provide cooling. Trigeneration is also known as Combined Cooling, Heating, and Power (CCHP).

This study focuses on evaluating the feasibility of trigeneration of energy in a pharmaceutical production plant, utilizing the waste heat generated by the MTU (Rolls Royce Kinetic PowerPack) generator set, equipped with a 20-valve diesel engine with a capacity of 3000 kVA. The goal is to efficiently harness the wasted heat from the engine to optimize the plant's thermal performance, especially in the context of vaccine production.

There are several possible strategies for cooling diesel engines. In situations where the thermal utilization of these systems is desired, the use of liquid-to-liquid heat exchangers becomes interesting, as the heated fluid can be directed to expected destinations. Thus, this study proposes the use of shell-and-tube heat exchangers, where the heat provided by the refrigerant to the water will be used in subsequent processes to improve boiler efficiency, reducing the natural gas consumption necessary for steam generation.

II. MATERIALS AND METHODS

The study proposes a trigeneration system using a 3000 kVA power motor generator set, containing a 20-valve diesel engine (20V4000G74S FO).

Figure 1 graphically describes the trigeneration scheme studied. The design is based on the energy recovery of the waste heat from the diesel engine combustion process. The main thermal waste sources of heat come from the exhaust gas system and the heat radiated by the engine's internal combustion chambers (cooling system)

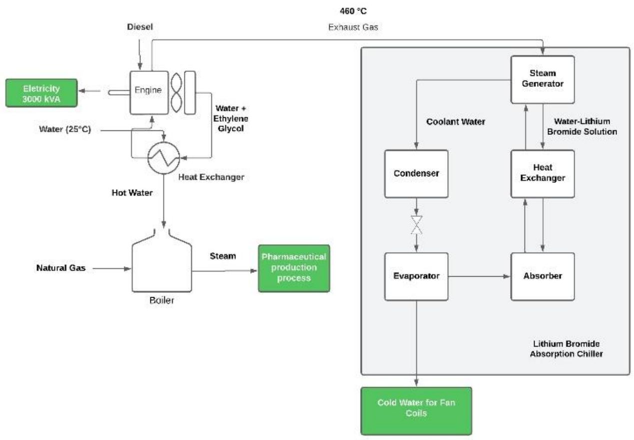

Fig. 1. Trigeneration Flow Chart

There are several possibilities for applying heat exchangers for the engine cooling process. As the objective is to take advantage of the thermal potential of this process, the use of a hull-tube heat exchanger is proposed, where the thermal exchange of the refrigerant (water + ethylene glycol) and water will occur. The system is pressurized by pumps for both fluids, which through convective heat transfer have the thermal rejection of the refrigerant to the water. The water that has received thermal energy is then pressurized to the accumulator tank of the natural gas boiler.

Under normal operating conditions, the boilers' accumulator tanks would receive water at room temperature, which through the NG combustion energy would give heat to the water until it reached the steam state. The use of the waste heat from the generator sets allows the reduction of natural gas needed to drive the boiler and generate steam, since the thermodynamic state of the heated water results in lower energy expenditure for the change of water state. The thermodynamic modeling developed will allow to evaluate how much thermal energy can be given to the water, that is, what will be the temperature of the water outlet from the heat exchanger with the refrigerant.

At the same time, it is possible to take advantage of the thermal remnant of the exhaust gases to generate chilled water. In the drug production plant in question, there are several environments that need temperature and humidity control. The factory contains a chilled water plant (CAG) and a chilled water accumulator tank that, in theory, is the result of the study of the technical and economic feasibility for the use of power generator sets in the electrical supply of chillers and cooling towers for periods of high cost of electricity from the concessionaire.

The trigeneration proposal, in this case, infers the possibility of applying a lithium bromide absorption chiller to produce chilled water, with subsequent routing by pipes to the accumulator tank, where at times of peak cost of electricity, it would supply the fan coils and ensure the cooling of the production environments.

The heat from the exhaust gases will be employed in driving the absorption chiller steam generator.

A. System Components

Engine Generator Set

Technical Description: 3000 kVA motor generator set, operating at full load conditions. The engine uses diesel as fuel with a full load consumption flow rate of 708 l/h and generates exhaust gases at a rate of 36,800 m³/h at a temperature of 460°C (table 1).

Function in System: Exhaust gases are the primary source of heat to activate the lithium bromide absorption chiller.

The following are the data obtained from the datasheet of the engine studied:

TABLE 1 - DIESEL ENGINE DATA

Fuel Consumption (Admissible tolerance +/- 5%)	**g/kWh**	**L/h**
at 100% ESP	200	708
at 75% rated output power	238	653
at 50% rated output power	197	432
at 25% rated output power	177	166
at 0% rated output power	0	0

Other Characteristics	**Value**	**Unit**
Fuel maximum inlet temperature	-	°C
Fuel maximum flow	708	L/h

Exhaust

Characteristics	**Value**	**Unit**
Exhaust gas flow	36800	m³/hr
Exhaust gas temperature	460	°C
Heat rejection to exhaust	2280	kW
Exhaust back pressure (Design value)	30	mbar
Maximum exhaust back pressure	85	mbar

Cooling Circuit

Characteristics	Value	Unit
Coolant Flow Rate	95	m³/h
Coolant Temperature From Engine	90	°C
Coolant Temperature Aftercooler	60	°C

Natural Gas Boiler

The boiler studied has the following technical specifications:

TABLE 2 - BOILER DATA

Capacity (kg/h)	1.000
Vapor Pressure (kgf/cm^2)	10
Temperature of Vapor (ºC)	170
Temperature of Feed Water (ºC)	28
Thermal Efficiency (%)	93%
Steam Generation per hour (m³/h)	6.000
Fuel consumption at maximum load (m³/h)	85,9

Lithium Bromide Absorption Chiller

Technical Description: Model CHP150HH equipment, lithium bromide absorption chiller designed to operate with an exhaust gas flow of 9.148 kg/s at 460°C, generating 5,274 kW of cooling capacity.

Function in the System: Generates cold water that will be distributed to fan coils for cooling indoor environments.

C System data

Fuel flow with engine at full load

$m_{comb} = 708\ L/h$

Engine cooling system coolant pump flow rate:

$m_{re} = 95\ m^3/h$

Coolant temperature coming out of the engine:

$T_{ri} = 95\ °C$

Refrigerant temperature after heat exchanger:

$T_{rf} = 60\ °C$

Flow rate of exhaust gases:

$m_{ex} = 36.800\ m^3/h$

Chiller Cooling Capacity:

$Q_{cool} = 5274\ kW$

The total energy change in a system encompasses the components of potential, kinetic, and internal energy change. In the context of thermodynamics, where systems are generally considered stationary, potential and kinetic energy variations are typically overlooked. In systems where transformations occur through heat and work, the variation of internal energy (ΔU) is governed by the following equation.

$$\Delta U = \dot{Q} - \dot{W} \quad (1)$$

Where Q is the heat transfer rate to the system and W is the work rate done by the system, both in Watts. For control volumes, open systems in which the transfer of mass and energy occurs, the first law of thermodynamics is represented by the following equation:

$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1 + \frac{(V_2^2 - V_1^2)}{2} + g(z_2 - z_1)\right) \quad (2)$$

The first step will be the application of the energy balance equations to the control volumes of the proposed flowchart. The idea at this stage is to obtain data on the production of hot water from the heat exchanger of the engine cooling system, and to perform an analysis of the sensitivity of the temperature of the water that goes to the boiler as a function of the consumption of natural gas for steam generation for the processes.

The yield of the proposed trigeneration system, can be obtained by calculating the ratio between the energy of the products (electricity, hot water and cold water) and the energy of the fuel, can be described as:

$$FUE = \frac{\dot{W}_{cicle} + \dot{Q}_{hw} + \dot{Q}_{cw}}{\dot{Q}_{in}} \quad (3)$$

III. RESULTS AND DISCUSSION

The performance of the proposed trigeneration system is then based on the thermal utilization capacity of the 2 main sources of waste heat from the diesel engine. Applying the first law of thermodynamics, it is possible to verify the capacity of the system to heat water for availability to the boiler.

The results of the energy balance of the heat exchanger with the cooling system show that using a centrifugal pump with 2 kgf/cm² of pressure and 33 m³/h of flow, the water outlet temperature of the exchanger is 60 °C.

The specified boiler has an operating condition in normal inlet water situations at a temperature of 28 °C. By making water available at 60°C, it is possible to assess the impact on increasing boiler efficiency due to reduced fuel consumption to change the state from water to steam at 10 kgf/cm³.

To determine fuel economy, the energy required to heat the water from 25°C to 60°C and the energy required to vaporize the water from these temperatures were calculated.

For heating the water from 25°C to 100°C, the specific heat capacity of water (4.18 kJ/kg°C) was considered, resulting in a total of 313,500 kJ. After the water reached 100°C, the energy required for vaporization was calculated using the latent heat of vaporization (2260 kJ/kg), yielding a total of 2,260,000 kJ. Therefore, the total energy required to heat and vaporize the water, starting from 25°C, was 2,573,500 kJ.

Additionally, the calculation was repeated for the scenario where the initial water temperature was 60°C. In this case, the energy required to heat the water from 60°C to 100°C was 167,200 kJ. Thus, the total energy required to heat and vaporize the water, starting from 60°C, was 2,427,200 kJ. Consequently, the reduction in energy required when the water initially starts at 60°C, compared to 25°C, was 146,300 kJ.

Considering that the consumption of natural gas is directly proportional to the energy required to heat and vaporize the water, the percentage reduction in fuel consumption can be calculated from the difference in heat supplied to vaporize the water at the temperature of 25°C and 60°C.

Therefore, by raising the temperature of the inlet water from 25°C to 60°C, the natural gas consumption of the boiler is reduced by approximately 5.68%. This corresponds to a saving of about 4.89 m³/h of natural gas, resulting in a new consumption of approximately 81.11 m³/h.

The results obtained show a valid reduction in natural gas consumption by increasing the temperature of the boiler inlet water. This reduction reflects a decrease in the thermal load that the boiler needs to provide, directly proportional to the amount of thermal energy required to heat the water.

If evaluated in the medium and long term, an interesting annual natural gas saving will be verified, with approximately 42,000 m³ of natural gas saved.

Parameter	Value
Initial water temperature (scenario 1)	25°C
Temperatura inicial da água (cenário 2)	60°C
Final water temperature	100°C
Energy required to heat water from 25°C to 100°C	313,500 kJ
Energy required to vaporize water (latent)	2,260,000 kJ
Total energy to heat and vaporize (initial 25°C)	2,573,500 kJ
Energy required to heat water from 60°C to 100°C	167,200 kJ
Total energy to heat and vaporize (initial 60°C)	2,427,200 kJ
Total energy reduction by raising the temperature from 25°C to 60°C	146,300 kJ
Percentage reduction in natural gas consumption	5.68%
Natural gas savings	4.89 m³/h
Natural gas consumption after reduction	81.11 m³/h
Natural gas anual economy	42,000 m³

The performance of the system reflects a considerable increase compared to the performance of the diesel engine under normal operating conditions, it is necessary to:

For the diesel engine without the application of the trigeneration system, only the production of electricity is considered:

- Electrical power generated: 2400 kW
- Fuel consumption: 708 L/h (equivalent to approx. 680 kg/h)
- Diesel calorific value: 42.5 MJ/kg

$$\eta_{motor} = 0{,}2988$$

Applying equation 3 to verify the yield of the trigeneration system:

Electrical power: 2400 kW
Heat provided to the cooling system: 1210 kW
Heat provided to absorption chiller: 2280 kW

$$FUE = 0{,}7334$$

The implementation of the trigeneration system results in a significant increase in energy yield, from 29.88% to 73.34%. This increase demonstrates the effectiveness of trigeneration in improving the overall efficiency of the system, making better use of the energy available in the fuel and reducing losses.

III. CONCLUSIONS

Enabling thermal reuse systems involves, in addition to technical feasibility, economic and financial issues that must be included in the analysis of the application. This study proposed to technically evaluate the feasibility of thermal use of the waste heat of a diesel engine generator set. The results indicate that using the heat of the cooling system in a thermal exchange with water at room temperature conditions at 25°C, it is possible to raise it to 60°C. This temperature gain has been shown to have a positive impact on the boiler's natural gas consumption, reducing an annual consumption of 42,000 m³ of combustible gas. It was also observed that the heat of the exhaust gases from the combustion of the engine has the capacity to generate 5274 kW of cold through a commercial lithium bromide chiller, which can later be sent in the form of chilled water to the accumulator tanks. The performance of a diesel engine under common operating conditions is 29.88%, the results point to an evolution in the performance of the system if the proposed trigeneration scheme is applied. These results show the energy potential of polygeneration matrices, since situations/conditions like this study exist in several commercial and industrial plants in the country, and as a proposal to produce future works is the exergoeconomic analysis of the system, to make the CAPEX of implementation of this matrix financially viable.

IV. ACKNOWLEDGMENT

The authors would like to thank the contribution of IPBEN members in the development of this document.

V. REFERENCES

Periodicals:

[1] Gospić, I.; Glavan, I.; Poljak, I.; Mrzljak, V. Energy, Economic and Environmental Effects of the Marine Diesel Engine Trigeneration Energy Systems. J. Mar. Sci. Eng. 2021, 9, 773. https://doi.org/10.3390/jmse9070773
[2] K. F. Fong, C.K Lee, Performance analysis of internal-combustion-engine primed trigeneration systems for use in high-rise office buildings in Hong Kong Energy Procedia 61, 2014, pp. 2319 – 2322.
[3] Kamal Kishore Khatri, Dilip Sharma, S.L. Soni, Deepak Tanwar, Experimental investigation of CI engine operated Micro-Trigeneration system, Applied Thermal Engineering, Volume 30, Issues 11–12, 2010, Pages 1505-1509, ISSN 1359-4311,
[4] Moussawi, H.A.; Fardouna, F. Hasna Louahliab, Selection based on differences between cogeneration and trigeneration in. various prime mover technologies. Renew. Sustain. Energy Rev. 2017, 74, 491–511.
[5] N.H.Shekh, B.Saiful, Waste heat recovery from a diesel engine using shell and tube heat exchanger, Applied Thermal Engineering 61,2013,pp. 355-363.
[6] N.H.Shekh, B.Saiful, Waste heat recovery from the exhaust of a diesel generator using Rankine Cycle, Energy Conversion and Management 75, 2013,pp.141–151.

[7] Ouyang, T.; Tan, X.; Tuo, X.; Qin, P.; Mo, C. Performance analysis and multi-objective optimization of a novel CCHP system integrated energy storage in large seagoing vessel. *Renewable Energy*, 2024, 224, 120185.

[8] Li, C.; Wang, Z.; Liu, H.; Guo, F.; Xiu, X.; Qin, J.; Wei, L. 4E analysis of a novel proton exchange membrane fuel cell/engine based cogeneration system with methanol fuel for ship application. *Energy* 2023, 282, 128741.

VI. BIOGRAPHIES

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