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EXPERIMENTAL ANALYSIS OF AN ABSORPTION REFRIGERATION CYCLE RUN BY THERMAL ENERGY RELEASED IN AN INTERNAL COMBUSTION ENGINE OPERATING WITH ETHANOL

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Abstract. This paper presents an experimental analysis of an absorption refrigeration cycle operated using thermal energy released in a Diesel/Otto internal combustion engine. The engine was fueled with ethanol, and various power levels delivered by the system were examined. Charge and discharge cycles were evaluated, and parameters such as exhaust gases temperature, mass flow rate, and fuel consumption were assessed for different power values. It was observed that the mass flow rate increased with the power delivered by the engine, consistent with the literature. Measurements were taken for emissions of CO, CO₂, O₂, and NO_x, while emissions of H₂, H₂O, and N₂ were indirectly determined. The results indicated that the air/fuel ratio influenced the emissions. In general, it was observed a reduced amount of CO₂ and O₂ and an increase in the amount of CO in the exhaust gases. For a fixed power level, temperatures at the generator, rectifier, condenser, and evaporator inlets and outlets were measured over a specified period. The cycle powered by exhaust gases took longer to start operating compared to the cycle operating with GLP. The temperature at the condenser inlet was lower for the cycle operating with ethanol in the engine, and higher temperature gradients were observed along the condenser. Higher temperatures were found at the evaporator inlet. Finally, considering the measured temperatures, the coefficient of performance (COP) was evaluated, with a maximum COP of 0.053 being obtained.

Keywords: Absorption refrigeration cycle, COP, MCI, ethanol

1. INTRODUCTION

World energy demand is increasing due to industrial activity and advances in both developing and developed countries. Although the share of renewable energy sources in the total primary energy supply has been increasing in recent years, fossil fuels account for most of the energy production (Kılıç Depren et al. 2022).

Fossil fuels are used in industries to generate the required heat for the production process, but a significant portion of this heat is wasted as exhaust gases. According to (Singh and Pedersen 2016), 25.5% of the energy rejected in a Diesel engine is released as heat by the exhaust gases. This energy can be used in a refrigeration system operating by heat, such as an absorption refrigeration system (ARS) (Srikhirin, Aphornratana, and Chungpaibulpatana 2000).

The basic operation principles of the absorption and compression refrigeration systems are similar. The operation of the evaporator, expansion valve, and condenser are the same. However, in contrast to the compression refrigeration system where the vapor pressure is increased using a compressor, the absorption refrigeration system (ARS) operates by absorbing the low-pressure vapor into an absorber fluid, causing heat rejection and subsequent condensation of the refrigerant. After that, it is necessary to increase the pressure of the mixture in a pump (Stoecker and Jones 1982).

Considering that a significant part of the world energy produced is used in refrigeration systems, ARS that use alternative energy sources represent a viable choice, especially when it is taken into account the reuse of thermal energy released in several industrial processes and the use of alternative refrigerants to CFCs (chlorofluorocarbons) and HFCs (hydrofluorocarbons). One of the main advantages of this cycle is the possibility of using any type of heat source, including heat rejected from other applications (ASHRAE 2017).

Most recent research on ARS discusses new refrigerants used in systems with clean and renewable energy sources, such as solar energy (Ponmurugan and Ravikumar 2019; Zhang, Guo, and Lin 2021; Zhu et al. 2022) and the reuse of thermal energy lost to the environment, such as in the exhaust gases of internal combustion engine and industrial processes.

The literature describes some studies on utilizing the heat from exhaust gases to operate absorption refrigeration systems (ARS). A thermoeconomic analysis of an ARS using water and ammonia as working fluids was conducted by (Herrera, Arrieta, and Sodr e 2014). The system operated using the exhaust gases of a diesel internal combustion engine. The greater exergy destruction was found in the combustion process. In the refrigeration system, the greater exergy

destruction was found on the evaporator and absorber. A cycle with a combination of two energy sources (solar energy and energy from the exhaust gases from an ICE) was assessed by (Wang, Wu, and Wang 2015). The system operated with three different generators. The COP obtained for the combined cycle was 0.91 and for the system operating with solar energy was 0.60. The system operating only with the exhaust gases was not viable.

A diffusion-absorption refrigeration system using the exhaust gases from a Diesel engine of a truck was studied by (Aly et al. 2017). The authors adapted the electric refrigerator to include a heat exchanger. The higher COP found was 0.1. (Hanriot et al. 2019) evaluated the operation of the generator of an ARS run by thermal energy released in an Otto engine. The COP was 0.05. An ARS was designed to operate with exhaust gases from a 4-stroke gasoline Toyota 3RZ-FE engine (Kaewpradub et al. 2018). It was found that an engine speed between 1200 and 1400 rpm is suitable for operation. The opening of the expansion valve at 72.7% of the total opening of the separator outlet yielded a maximum cooling load and COP of 266 W and 0.08, respectively.

In the present study, it was experimentally evaluated an ARS operating with exhaust gases from an engine operating in a flow test bench. The engine, originally operating in a Diesel cycle, was modified to operate in an Otto cycle as well. The performance of the system was evaluated by measurements of temperature, mass flow rate, fuel consumption, and emissions.

2. MATERIALS AND METHODS

Experimental tests were performed in an absorption refrigerator working with the reuse of the thermal energy from the exhaust gases of an engine operating in the flow test bench shown in Figure 1. The engine is coupled with a generator that converts mechanical energy into electrical energy. The engine operated in a Diesel cycle, but it was modified to also operate in an Otto cycle, allowing its operation with ethanol (de Morais et al. 2019). The engine is a series 229-4, running in a constant rotation of (1800 ± 100) rpm, with the main characteristics listed in Table 1.



Figure 1. Engine.

Table 1. Engine characteristics.

Model	Valves	Injection	Displacement	Compression ratio
MWM D229-4	4 per cylinder	Direct	3.92 dm^3	17:1

The refrigerator used in the experimental tests is depicted in Figure 2. It can be operated with a thermoresistance using alternating or direct current, as well as with liquefied petroleum gas (LPG), as indicated in Figure 3. To enable operation with exhaust gases from an internal combustion engine, the system was modified to include a heat exchanger at the generator inlet. The refrigerator has a capacity of 76.5 liters and a power output of 180 W.



Figure 2. Refrigerator.

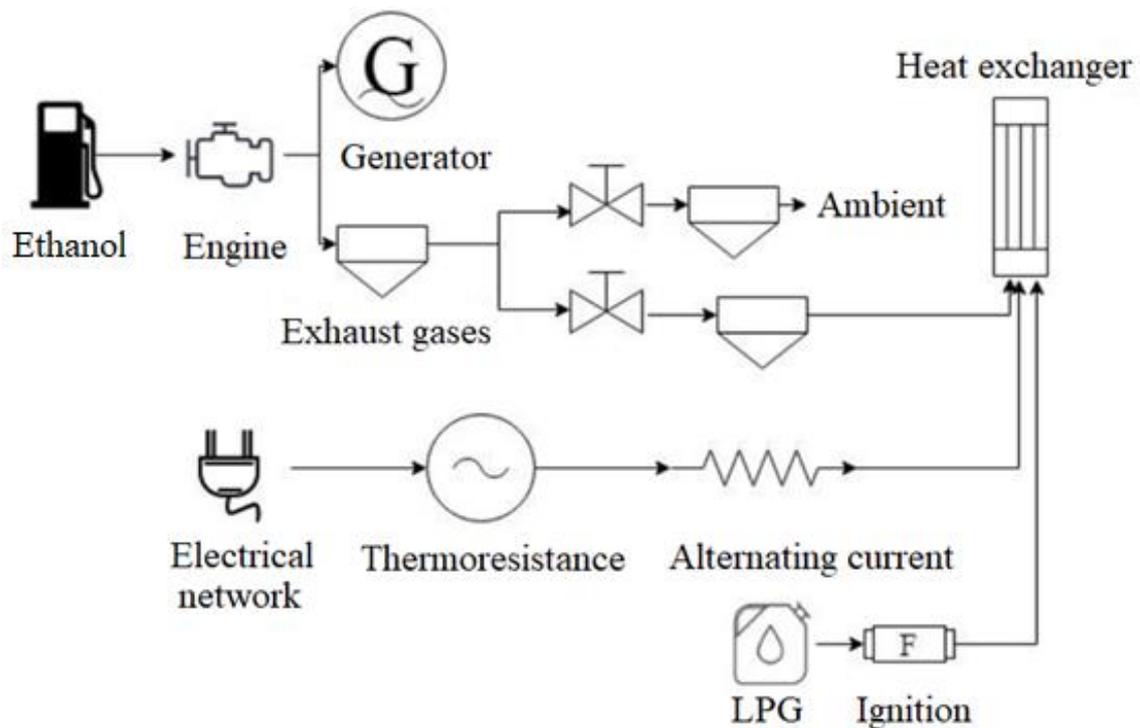


Figure 3. Schematics of the heat sources.

Experimental tests were performed to evaluate temperature, atmospheric pressure, mass flow rate, and species concentration of the exhaust gases, as well as engine power.

K-type thermocouples and DS18B20 sensors were used for the measurement of temperature. The range of the thermocouples was -270 to 1200°C , sensitivity of $41 \mu\text{V}/^{\circ}\text{C}$, and resolution of 1.4°C . The digital sensors have an accuracy of 0.5°C and a range of -55 to 125°C . The pressure sensor is an MPX-4250 AP, with a range of 20 to 250 kPa and an accuracy of 1.5%. The mass flow rate was determined using an MAF (mass air flow), a sensor generally used for the measurement in ICE. The composition of the exhaust gases was measured with the California Analytical Models equipment, which detects the amount of CH_4 and THC, the concentration of CO , CO_2 and O_2 through the techniques of

flame ionization (CO), absorption of infrared (CO_2) and paramagnetic (O_2). The technique of chemical luminescence is used to evaluate the concentration of NO and NOx. Data from the sensors were obtained in LabVIEW using a data acquisition board NI USB6363. The sample timestep was of 1 minute, due to the low variation of the temperature.

As performed by (de Moraes et al. 2019), the tests lasted for 4 h, taking into account the time required for the system to achieve steady-state conditions. The tests followed the ISO standard (ISO 2002), which sets a standard procedure for the determination of the performance of internal combustion engines. 17 temperature sensors were distributed along the inlet and outlet of the generator, condenser, evaporator, absorber, reservoir, hydrogen, and heat source, and to measure ambient temperature and the rectifier. A complete description of the methodology can be found in (Vasconcellos 2019).

The experimental tests were performed according to ISO 15550:2016 (ISO 2005), varying the power every 3 minutes. From 0 to 20 kW, the power was increased in 5 kW. Above 20 kW, the power was increased in 2.5 kW. For the fixed power test, the engine was turned on without any power. When the thermostatic valve was on, a power of 27.5 kW was applied. Finally, for the variable power test (referred to as discharge power), a 17.5 kW power was applied. After 1h, a discharge of 2.5 kW was performed every 30 minutes until reaching the power of 12.5 kW. After that, the power was maintained for 20 minutes, and the exhaust valve was closed for 10 more minutes.

3. RESULTS AND DISCUSSION

Experimental tests were conducted under three different conditions: standard, fixed power, and discharge power conditions. The results of exhaustion temperature and mass flow rate, as well as the fuel consumption, are presented in Figure 4.

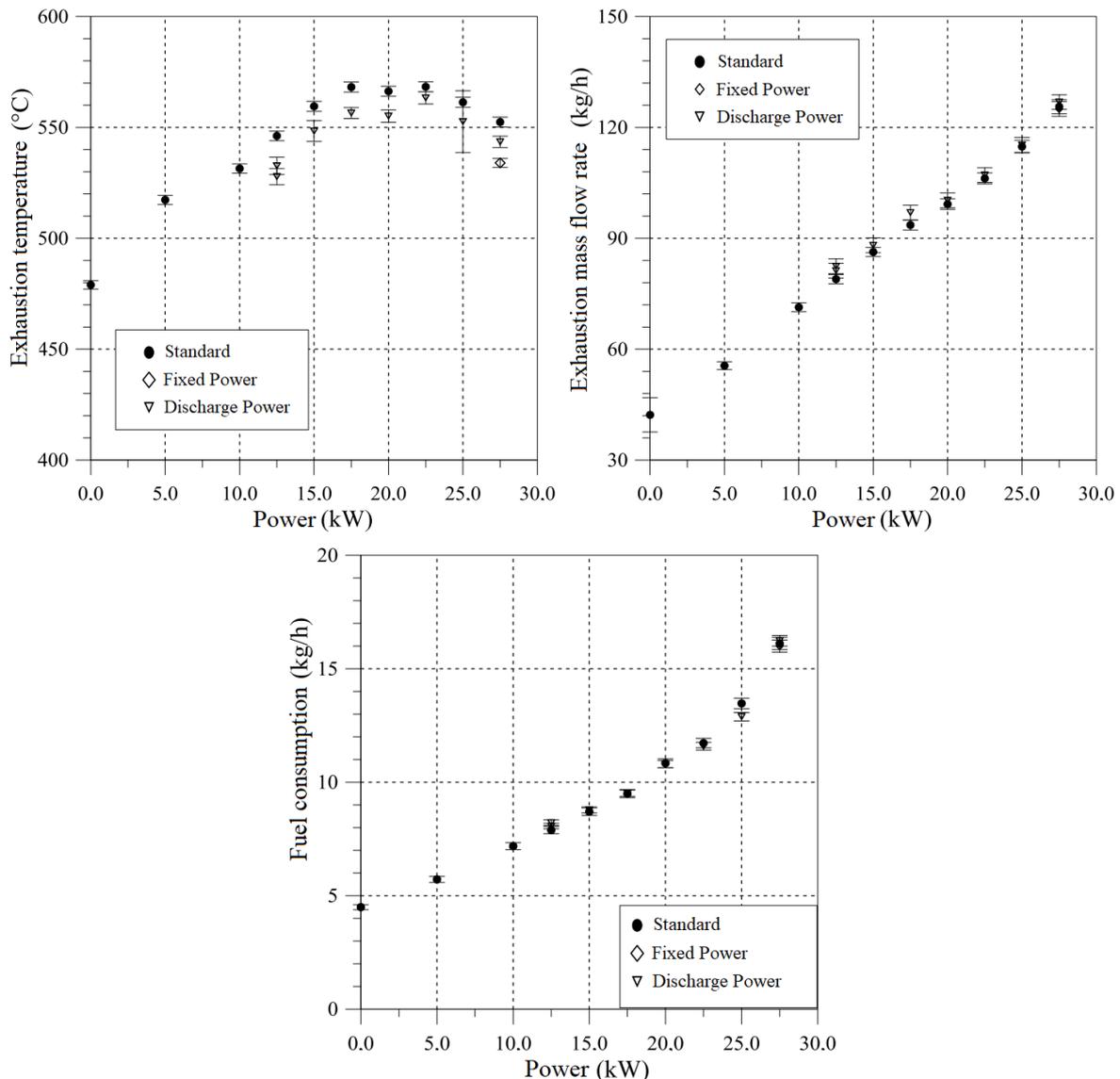


Figure 4. Temperature, mass flow rate, and fuel consumption.

The exhaustion mass flow rate and the fuel consumption increased with power, as seen in the literature (JUSTINO 2018; Moreira 2018). The spark ignition engine operates with stoichiometric combustion to maintain a fixed speed of 1800 rpm. The intake air admission was adjusted based on the engine speed, and the fuel injection was controlled according to the valve opening. For the same power, the temperature reached by the spark ignition engine was higher than that obtained by the compression ignition engine (Vasconcellos 2019), with lower mass flow rates. It was observed an increase in engine fuel consumption when the exhaust gases were used in the refrigerator.

Figure 5 presents the results of the measurements of CO₂, CO, O₂, and NO_x emissions for the engine operating with ethanol and providing heat for the refrigerator. When compared to the emissions obtained without the refrigerator (Moreira 2018), it was observed an increase in the emissions of CO. It indicates a lower quality of fuel combustion, which can be attributed to the increased work required for exhaust, resulting in higher head losses. This behavior explains the lower exhaust achieved. When comparing the standard, fixed power, and discharge power tests, it can be noticed that the CO₂ emissions were not significantly varied. For lower power values, the differences among the tests are negligible. For intermediate power values, the emissions of O₂ were reduced during the standard test. An increase in power increased the emissions of CO and decreased the emissions of CO₂, O₂, and NO_x.

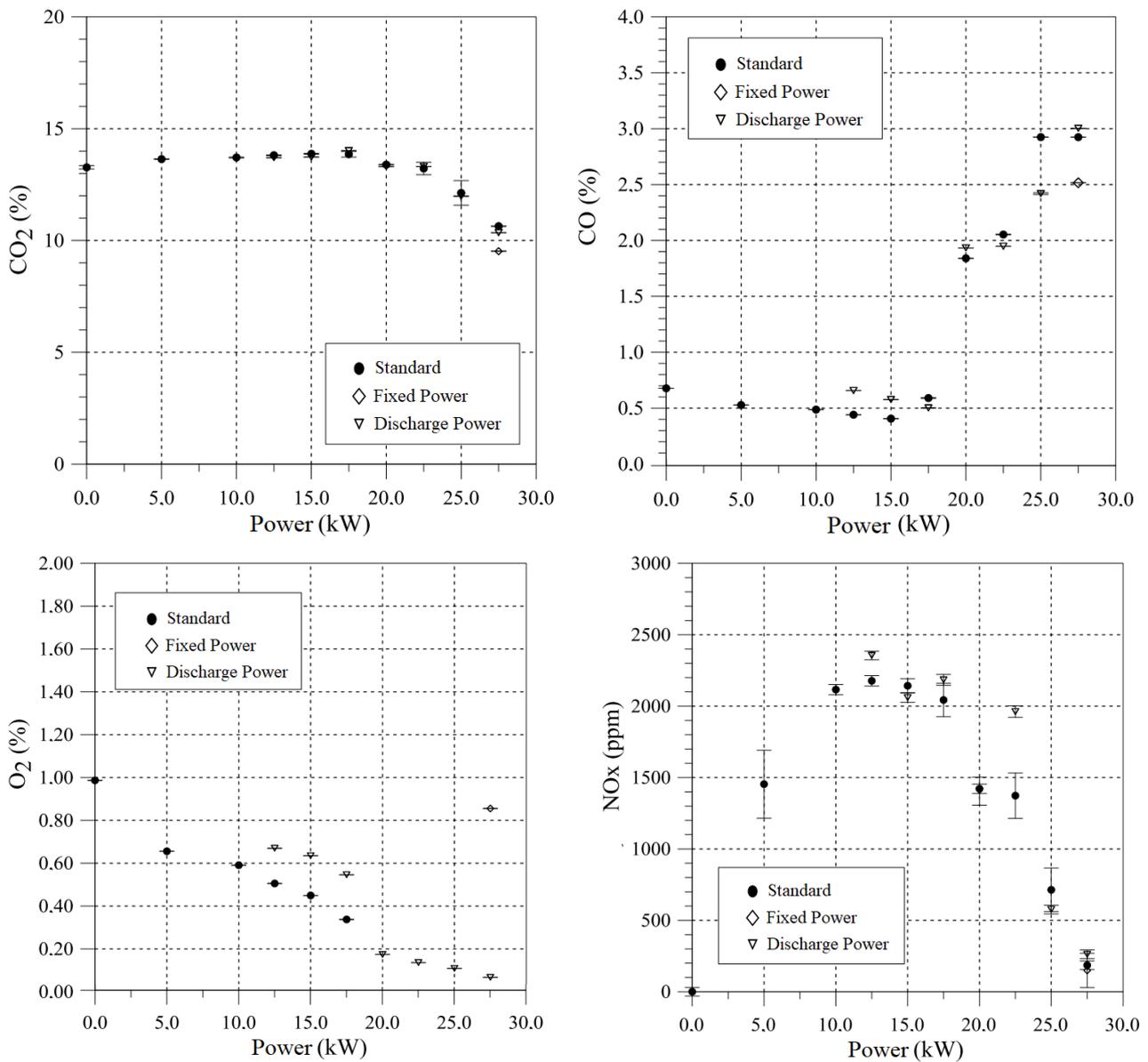


Figure 5. Emissions of CO₂, CO, O₂, and NO_x.

The emissions of H₂, H₂O, and N₂ were indirectly determined, and are shown in Figure 6. The emissions of H₂O were higher for higher power values, which can be explained by the higher availability of hydrocarbon due to the weak

air injection, which results in higher emissions of H_2O . The emissions of H_2 increased with power, and the emissions of N_2 were reduced, which is consistent with the reduction of the emissions of NO_x .

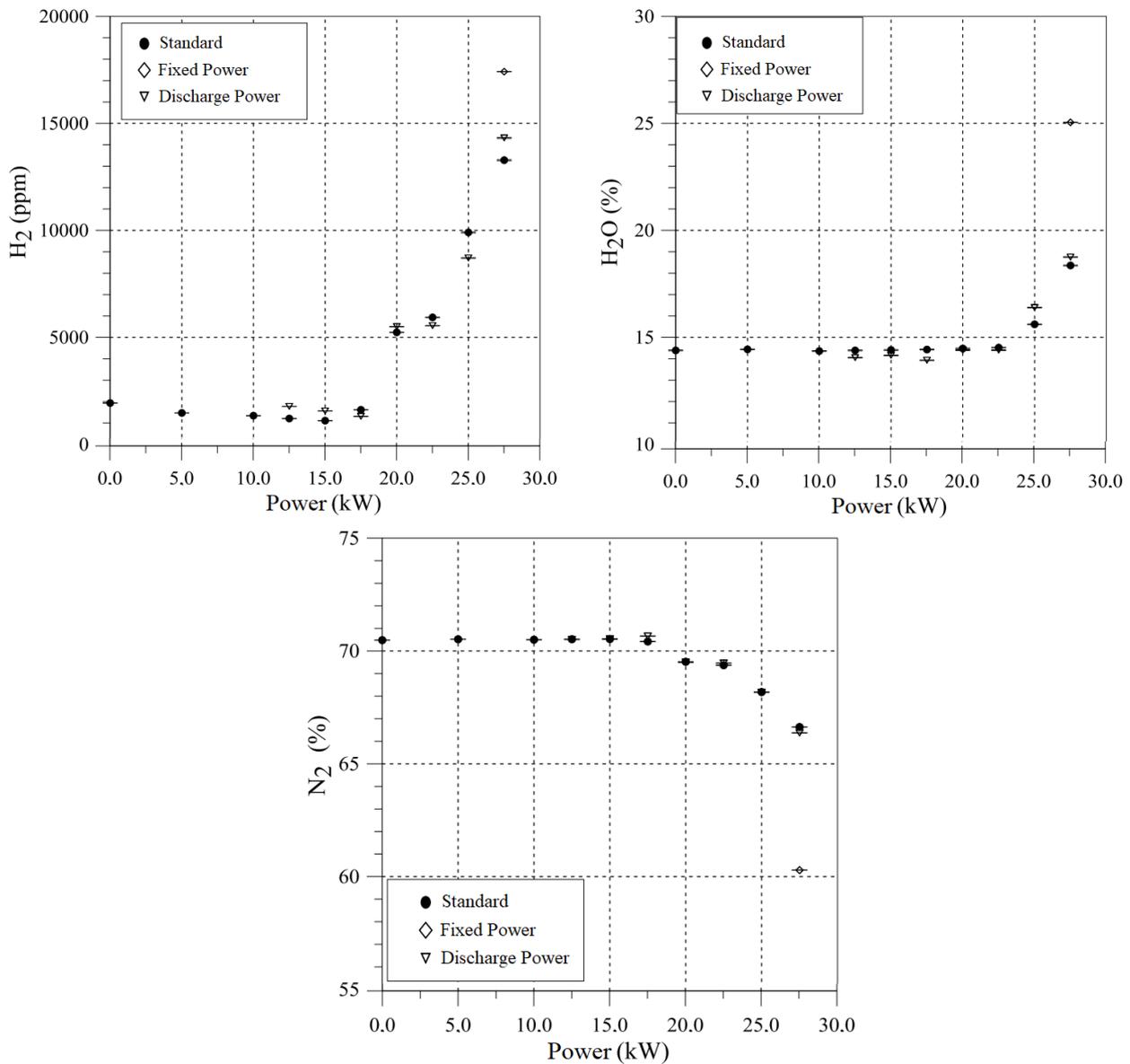


Figure 6. Emissions of N_2 , H_2 , and H_2O .

Figure 7 presents the temperature at the inlet and outlet of the generator and condenser for a variable power test. The variation of power was applied according to the following procedure. The first power of 27.5 kW was applied during 1h. After that, every 30 minutes, the power was reduced. It can be seen that after approximately 50 minutes the refrigerator cycle started to operate, being interrupted when the power reached 17.5 kW. When the power was 12.5 kW, the valve was closed, and the cycle started to operate rapidly, indicating that the refrigeration system under consideration could operate with higher power values when fed with higher flow rates.

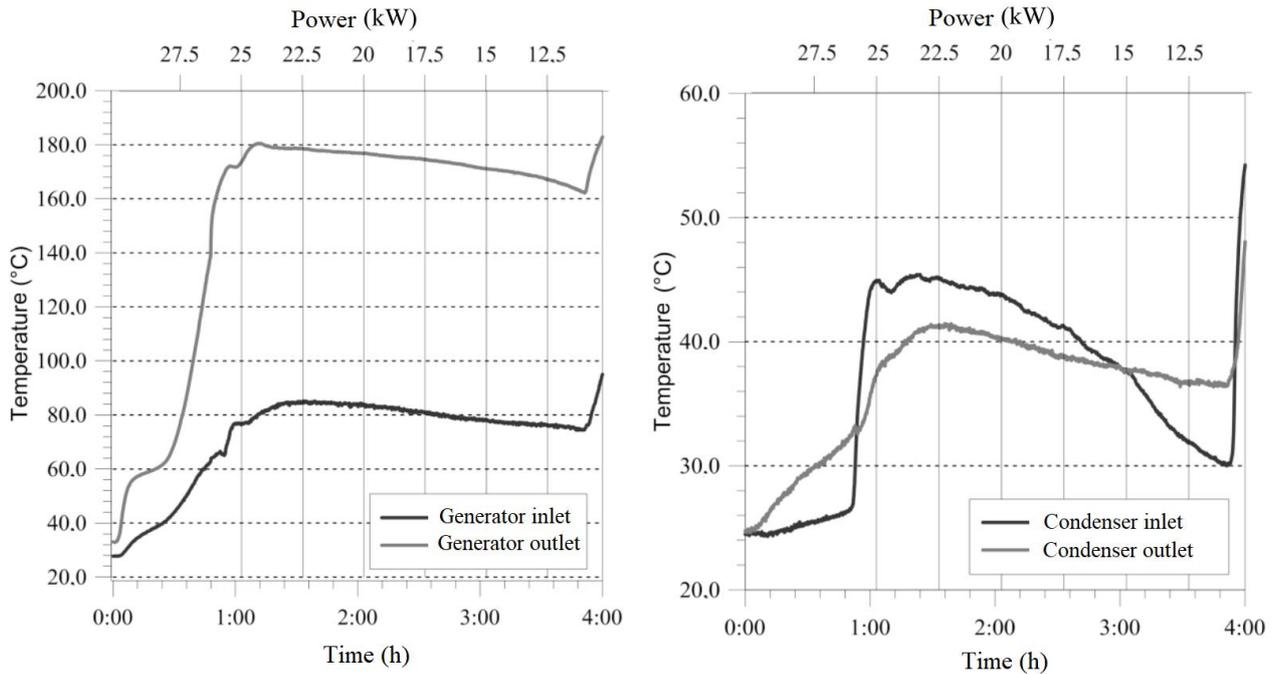


Figure 7. Temperatures in the generator and condenser.

4. CONCLUSIONS

This study presented an experimental analysis of an absorption refrigeration cycle operating with thermal energy from an internal combustion engine operating with ethanol. A heat exchanger was adapted to the generator inlet. Experimental tests were performed in standard conditions, according to ISO standards. Tests with continuous and discharged power were also performed.

When the internal combustion engine was evaluated, it was observed an increase in the exhaust temperature and fuel consumption when compared to the system operating without the refrigeration cycle. No significant variations in the exhaust temperature, mass flow rate, and fuel consumption were observed when comparing the different test conditions. It was observed that the exhaust temperature and fuel consumption increased with the power load. Additionally, an increase in power load led to higher emissions of CO, H₂, and H₂O, while causing a decrease in emissions of CO₂, O₂, NO_x, and N₂.

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