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SISTEMA DE AR CONDICIONADO PARA VEÍCULO DE TRANSPORTE COLETIVO BASEADO EM SISTEMA DE REFRIGERAÇÃO POR ABSORÇÃO UTILIZANDO GASES DE ESCAPE DE COMBUSTÃO

Jorge Waschington do Carmo Junior[1*] & Antônio Gabriel Souza Almeida[1**]

RESUMO

CARMO JR, J. W.; ALMEIDA, A.G.S. Air conditioning system for mass transit vehicle based on an absorption refrigeration system using combustion exhaust gases. **Perspectivas Online: Exatas & Engenharia**, v. 10, n. 30, p. 15- 29, 2020.

Este artigo examina o calor disponível em motores a diesel de combustão interna para ativação de sistemas de ar condicionado automotivos com ciclo de refrigeração por absorção usando par amônia-água. Em primeiro lugar, foi realizado um estudo exergético dos ciclos do motor e da absorção em conjunto, para avaliar a viabilidade técnica da utilização deste sistema para veículos de climatização de transportes públicos. A modelagem e simulação foram desenvolvidas por meio de algoritmos na plataforma Engineering Equation Solver, levando em consideração balanço de massa, primeira e segunda leis da Termodinâmica, identificando rejeitos e perdas no sistema térmico. A simulação do motor de combustão interna é modelada para a flexibilidade do biodiesel, para fornecer uma análise de energia e exergia em função do tipo de combustível utilizado no motor. Foi possível analisar os efeitos que as variações nos gases de escapamento do motor podem causar no ciclo de refrigeração e determinar o estado termodinâmico no ciclo de refrigeração, o comportamento do coeficiente de desempenho, potência refrigerada e exergia distribuída em função da variação da temperatura de condensação e evaporação, e as condições dos gases no gerador.

Keywords: absorption refrigeration; automotive air conditioning; exergy; combustion engines

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AIR CONDITIONING SYSTEM FOR MASS TRANSIT VEHICLE BASED ON AN ABSORPTION REFRIGERATION SYSTEM USING COMBUSTION EXHAUST GASES

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ABSTRACT

CARMO JR, J. W.; ALMEIDA, A.G.S. Air conditioning system for mass transit vehicle based on an absorption refrigeration system using combustion exhaust gases. **Perspectivas Online: Exatas & Engenharia**, v. 10, n. 30, p. 15-29, 2020.

This paper examines the available heat of internal combustion diesel engines for activating automotive air conditioning systems with an absorption refrigeration cycle using ammonia-water pair. Firstly, an exergetic study was carried out of both the engine and absorption cycles working together, to assess the technical feasibility of using this system for air-conditioning vehicles for public transport. The modeling and simulation were developed through algorithms on the Engineering Equation Solver platform, taking into account mass balance, the first and second laws of Thermodynamics, identifying tailings and losses in the thermal system. The simulation of the internal combustion engine is modeled for the flexibility of biodiesel, to provide an energy and exergy analysis depending on the type of fuel used in the engine. It was possible to analyze the effects that variations in the engine exhaust gases can cause in the refrigeration cycle and to determine the thermodynamic state in the refrigeration cycle, the behavior of the coefficient of performance, refrigerated power and exergy distributed in function of the variation in the condensation and evaporation temperature, and the conditions of gases in the generator.

Keywords: absorption refrigeration; automotive air conditioning; exergy; combustion engines

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1. INTRODUCTION

Currently, all technological research and development should be in line with energy efficiency requirements and environmental preservation. Absorption refrigeration systems emerge in this scenario and there are several features that make them a good option, especially where there is an available thermal energy source.

In a motor vehicle driven by a reciprocating internal combustion engine, traditional vehicular air conditioning system based on a refrigeration cycle by vapor compression increases the fuel consumption by at least 15% and causes a reduction in power provided by engine (KAYNAKLI and HORUZ, 2003).

In an internal combustion engine, a maximum of 40% of the chemical energy of the fuel is converted into useful mechanical energy (KOEHLER et al, 1997), approximately 30% to 32% is released as exhaust gases at temperatures above 400°C, and approximately 30% to 28% is dissipated by the cooling system, with cooling water being routed to the radiator at around 100°C. In total, more than 50% of the energy released by the fuel is lost (HORUZ, 1999).

A refrigeration system by absorption depends on a high temperature source to provide a vaporization of the coolant and the decoupling from the absorbent solution. Studies have shown that it is possible to use heat sources with temperatures of 100°C to 200°C for use in absorption systems, with COP close to 1 (TALOM et al, 2009). Some absorption refrigeration systems, such as those using ammonia water pair, can work with evaporation temperatures below -50°C (MANZELA et al, 2010).

Part of the energy which is typically released as heat to the environment could be used for a vehicular air conditioning system by absorption.

Most public transport buses in large Brazilian cities offer little thermal comfort to users and drivers/conductors. Internal temperature conditions are usually regulated with natural ventilation through sliding side windows and tilting windows on the roof. Overcrowding and long standstills in traffic jam, combined with severe climatic conditions such as high ambient temperature and high relative humidity, culminating with high rainfall, affect the comfort of the occupants of the vehicle, as they often require the closing of natural ventilation. When an air conditioning system is used, these are based on compression refrigeration systems, which reduce the mechanical power available for transmission and increase fuel consumption, contributing to the increase in atmospheric emissions.

The objective of this work was to develop a model and simulation of a thermal system, with the aid of software Engineering Equation Solver (EES) (KLEIN, 2009), to ascertain the availability of thermal waste of an internal combustion engine to power an absorption refrigeration system through a generator, according to the coupling shown in Figure 1. A simulation was developed of a Diesel cycle internal combustion engine operating with mixtures of mineral diesel and biodiesel at any proportion. The simulation enables the analysis of the energy and exergy depending on the composition of the fuel used. It also identifies the locations of the thermal waste in the engine, the quantities and the qualities of the wasted energy. This makes it possible to check and select the exergy availability of combustion engine to feed an air conditioning system for a mass transit vehicle using an absorption refrigeration system.

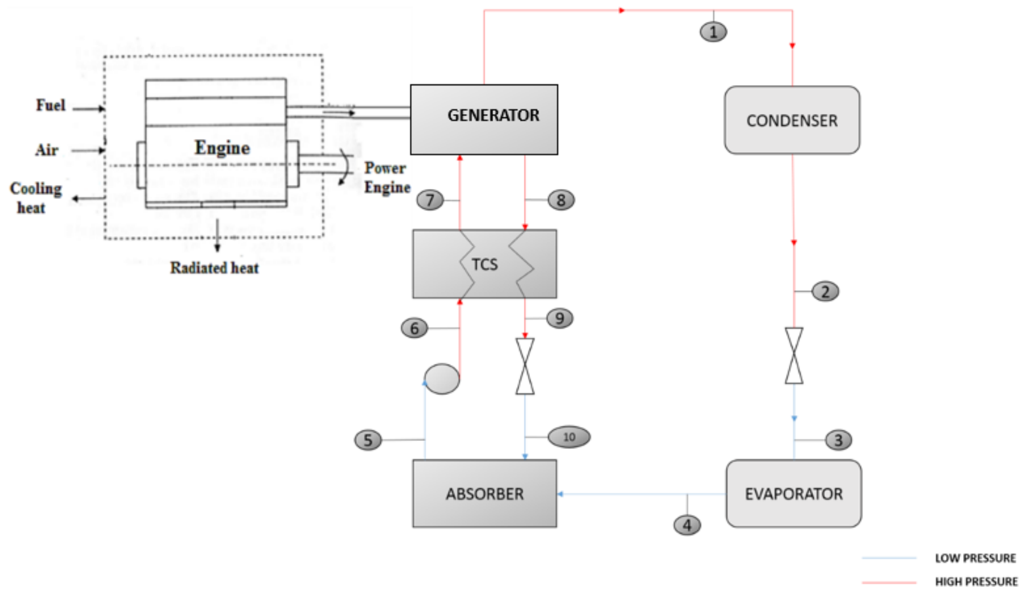

Figure 1. Coupling system.

Many papers report the use of exhaust gases of vehicular combustion engines as a thermal energy source for air conditioning systems with refrigeration cycles by absorption Talbi and Agnew (2002) present a theoretical verification based on a simulation of a refrigeration. system by absorption with fluid pairs of lithium bromide and water, using the exhaust gases from an internal combustion engine, Diesel cycle, as thermal energy input. While Manzela et al. (2010) studied the use of a refrigeration system by absorbing ammonia-water using the exhaust gases of an internal combustion engine as a power source, assessing the availability of energy and the impact of refrigeration system by absorption in the engine performance, in the exhaust emissions and economy of energy. The results showed the feasibility of using exhaust gases as an energy source for feeding the absorption system. These gases have a high energetic potential although the refrigeration system used in the tests do not take advantage of this at all. It was found that the performance and emissions of the engine were not affected due to the adjustment of the engine exhaust gases that feed the refrigeration system. In addition, Sahoo et al. (2004) concentrate on the modeling and simulation of vehicular air conditioning systems by absorption using as a heat source the thermal waste from internal combustion engines based on the Otto cycle, used in small cars running on gasoline and/or ethanol. A thermoeconomic analysis of the coupling of thermal availability of an Otto cycle internal combustion engine, powered by gasoline, with a refrigeration system by absorption using the ammonia-water pair was carried out. The absorption system was considered capable of cooling the passenger compartment of a passenger car, with a simulation of system energy balance, using first and second Thermodynamics laws, achieving efficiency and few energy losses in all components and in the overall system. An economic assessment of the investment payback period based on the economy in terms of fuel consumption achieved was also reported.

Dimensions of cars are incompatible with the size of existing refrigeration systems by absorption. Given the available technology, implementing a vehicular air conditioning system by absorption which meets the removal needs of the thermal load of passenger vehicles is unfeasible. On the other hand, vehicles with Diesel combustion engines are more robust and bigger as they are generally used for loads and mass passenger transport. The high torque provided by diesel engines, combined with their large sizes, makes the installation of a refrigeration system by absorption for air conditioning more feasible.

Rêgo et al. (2014) carried out an experimental analysis of a refrigeration system by absorption where the exhaust system of an internal combustion engine of a car was connected to the generator element of the system. The performance of the refrigeration system was evaluated based on the supplied heat. The refrigeration system performed better when the amount of heat input is controlled based on the temperature of the generator of the absorption cycle. It was concluded that by dynamically controlling the amount of heat input, the range of uses of the absorption refrigeration system powered by the heat of the exhaust gases can be expanded.

Abu-Ein et al. (2009) presents an exergetic analysis of a refrigeration system by absorbing water-ammonia 10 kW, whose energy source is solar. They obtained the coefficient of performance (COP), exergetic coefficient of performance (ECOP) and the loss of exergy (dE) in each of system components for varying operating conditions. The minimum and maximum values of COP and ECOP were found when the temperature in the generator reaches 110°C and 200°C respectively. Approximately 40% of the loss of exergy in the system was found in the generator. The maximum losses of exergy in the absorption system occurred when the temperature in the generator was 130 °C, for all evaporator temperatures.

Zhou et al. (2011) developed a computational simulation of a refrigeration system by absorption of water-lithium bromide, powered by the heat from the exhaust gases and the water from the engine cooling system. The refrigeration power provided by this system is used to cool or heat the passenger compartment, as an air conditioner, as well as to help the vehicle's own cooling system. They reported a reduction in fuel consumption, even using compact heat transfer surfaces.

Xu et al. (2013) analyzed a solution to a problem reported by other studies, namely the influence of the variation in the emission of exhaust gases from a combustion engine over absorption systems: the use of a absorption-compression hybrid refrigeration system, fed by exhaust gases and the power generated by the combustion engine.

2. MATERIALS AND METHODS

A thermodynamic model of the internal combustion engine based on the Diesel cycle was developed using a mixture of mineral diesel with bio-diesel and a chiller based in an absorption refrigeration cycle using ammonia-water pair with a rectifier in the generator output. The aim of this was to integrate the cycles to form an air conditioning system taking advantage of the thermal waste of the combustion engine. The simulation model was developed on the (EES) platform (KLEIN, 2009), taking into account the mass balance, and the first and second laws of Thermodynamics.

2.1. Energy and Exergy analysis of Diesel cycle internal combustion engine

Equation (1) shows the combustion modeling based on the stoichiometric burning of biofuel, as a mixture in any proportion of Biodiesel plus fossil diesel, where the biodiesel is generated by residual fat oil.

For the purposes of simplification, the concept of equivalent fuel, named C_xH_y for fossil diesel and $C_nH_mO_w$ for biodieselC, H and O are the carbon, hydrogen and oxygen atoms, respectively, and “x”, “y”, “n”, “m” and “w” are the number of atoms present in the general case of the balanced equation for combustion of biodiesel fuel.

$$P_d.C_xH_y + P_b.C_nH_mO_w + a.(O_2 + 3{,}76N_2) \rightarrow z.(b.CO_2 + d.O_2 + c.CO + g.H_2O + i.N_2 + e.NO + f.NO_2) \quad (1)$$

The proportion of biofuel mixture is given by Pd for fossil diesel and Pb for biodiesel, the coefficients “b”, “d”, “c”, “g”, “i”, “e” and “f” represent the fractions of the combustion products, while that “a” and “z”represent the coefficients to be determined.

The emissions of exhaust gases to be obtained with the aid of a portable gas analyzer which can evaluate the concentrations of CO, CO_2, NO, NO_2 and O_2 installing a probe in the engine exhaust and keeping a constant speed.

Some considerations were made to proceed with the energy and exergy analysis of the internal combustion engine:

- Engine operates at steady state
- Combustion products are treated as an ideal gas mixture
- To calculate the exergy the effects of motion and gravity are despised.

Equations (2) to (11) represent the algorithm used in the simulation to develop the energy analysis of the Diesel cycle internal combustion engine. Tesfa et al. (2013) determine the lower calorific value of a biofuel, just indicating the proportion of biodiesel in the mixture, and Alptekin et al. (2008) determine the density in a similar way, making possible the determination of the energy of the fuel.

To determine the radiation heat in the engine block is complex as this radiation is random and comes from any physical part of the engine, so the area used for calculating the energy dispersion around the engine was a surface of a cube using the Stefan-Boltzmann constant and the emissivity of the material used in the manufacture of the engine

Through the functions of the EES platform, it was possible to determine the density and specific heat of exhaust gases and with the aid of a coupled probe in the vehicle exhaust its volumetric flow rate and temperature was measure so as to determine its energy and exergy.

$$\mathrm{LHV_{fuel}} = -0.041 \cdot \mathrm{P}_b + 42.32 \quad (2)$$

$$d_{\mathrm{fuel}} = 0.0004 \cdot \mathrm{P}_b + 0.8424 \quad (3)$$

$$m_{\mathrm{fuel}} = d_{\mathrm{fuel}} \cdot \mathrm{V_{fuel}} \quad (4)$$

$$\boldsymbol{Flow_{fuel}} = \frac{\boldsymbol{m_{fuel}}}{\boldsymbol{t}} \quad (5)$$

$$\mathrm{En_{fuel}} = \mathrm{Flow_{fuel}}.\mathrm{LHV_{fuel}} \quad (6)$$

$$\boldsymbol{H}_{\mathrm{water}} = \dot{\boldsymbol{m}}_{\mathrm{water}}.\mathrm{cp_{water}}.\,\Delta\boldsymbol{T} \quad (7)$$

$$\boldsymbol{H}_{\mathrm{rad}} = \sigma.\mathrm{A}.\boldsymbol{\epsilon}.\left(\boldsymbol{T}^{\mathbf{4}}_{\mathrm{surface}} - \boldsymbol{T}^{\mathbf{4}}_{\mathrm{air}}\right) \quad (8)$$

$$H_{gases} = d_{gases}.Flow_{gases}.cp_{gases}.\left(T_{gases} - T_{env}\right) \quad (9)$$

$$En_{fuel} = H_{water} + H_{rad} + H_{gases} + Power_{engine} \quad (10)$$

$$R_{engine} = \left(Power_{engine}/En_{fuel}\right).100 \quad (11)$$

Analyzing the part referring to the combustion engine in Figure 1 and applying the concepts of first thermodynamics law and energy conservation, the engine power and its energy efficiency can be determined.

Equations (12) to (17) represent the algorithm used in the simulation to develop the exergetic analysis of the internal combustion engine of the Diesel cycle. Almeida et al. (2012) show how to determine the exergy of a liquid or solid fuel, where the ratio of the chemical exergy of a fuel with its lower calorific value is equal to a φ factor. Note that the value of this factor will always be greater than or equal to 1.0401.

Almeida et al. (2102) show how to obtain the total exergy of the gases, which is the sum of the thermo-mechanical and the chemical exergy. Only the useful working potential heat of these gases is of interest here.

$$\varphi = 1.0401 + 0.1728\ h/c + 0.0432\ o/c + 0.2169\ s/c\ (1 - 2.0628\ h/c) \quad (12)$$

$$En_{fuel} = H_{water} + H_{rad} + H_{gases} + Power_{engine} \quad (13)$$

$$R_{engine} = \left(Power_{engine}/En_{fuel}\right).100 \quad (14)$$

$$Ex_{rad} = H_{rad} * (1 - T_0/T) \quad (15)$$

$$Ex_{total} = Ex_{term} + Ex_{ch} = [(h - h_0) - T_0(s - s_0) + V_2/2 + gz] + Ex_{ch} \quad (16)$$

$$Ex_{ter} = c_p(T - T_0) - T_0\left(c_p \ln T/T_0 - R \ln P/P_0\right) \quad (17)$$

The irreversibility of the system, calculated as the destruction of exergy and the exergetic efficiency can be demonstrated in equations (18) and (19), respectively.

$$Ex_{dest} = Ex_{fuel} - Ex_{water} - Ex_{rad} - Ex_{total} - Power_{engine} \quad (18)$$

$$Ef_{ex} = \left(Power_{engine}/Ex\right).100 \quad (19)$$

2.2. Energy and Exergy Analysis of refrigeration cycle by absorption

Equations (20) to (66) represent the modeling of each control volume of the refrigeration cycle by absorption shown in Figure 1, based on the law of continuity and the 1st and 2nd law of thermodynamics.

The following assumptions were adopted for the modeling:

- All processes are internally reversible
- The volume controls operate on a permanent basis
- The kinetic and potential energy effects are despised

- There is no heat loss in the pipes
- Load losses are considered negligible in relation to the system as a whole
- No pressure changes occur except by the restriction device and the pump
- The restriction devices are adiabatic.

CONDENSER

$$\dot{m}_1 = \dot{m}_2 \quad (20)$$

$$\dot{m}_1.X_1 = \dot{m}_2.X_2 \quad (21)$$

$$H_C = \dot{m}_1(h_1 - h_2) \quad (22)$$

$$\text{Ex}_C = -(1 - T/T_0).H_C \quad (23)$$

$$I_C = (\dot{m}_1.\text{ex}_1) - (\dot{m}_2.\text{ex}_2) + ((1 - T_0/T).H_C) \quad (24)$$

CONDENSER

$$\dot{m}_2 = \dot{m}_3 \quad (25)$$

$$\dot{m}_2.X_2 = \dot{m}_3.X_3 \quad (26)$$

$$h_2 = h_3 \quad (27)$$

$$I_{V1} = (\dot{m}_2.\text{ex}_2) - (\dot{m}_3.\text{ex}_3) \quad (28)$$

EXPANSION VALVE 1

$$\dot{m}_2 = \dot{m}_3 \quad (25)$$

$$\dot{m}_2.X_2 = \dot{m}_3.X_3 \quad (26)$$

$$h_2 = h_3 \quad (27)$$

$$I_{V1} = (\dot{m}_2.\text{ex}_2) - (\dot{m}_3.\text{ex}_3) \quad (28)$$

EVAPORATOR

$$\dot{m}_3 = \dot{m}_4 \quad (29)$$

$$\dot{m}_3.X_3 = \dot{m}_4.X_4 \quad (30)$$

$$H_E = \dot{m}_3(h_4 - h_3) \quad (31)$$

$$\text{Ex}_E = -(1 - T_0/T).H_E \quad (32)$$

ABSORBER

$$T_A = T_4 + T_5 + T_{10}/3 \quad (34)$$

$$\dot{m}_5 = \dot{m}_4 + \dot{m}_{10} \quad (35)$$

$$\dot{m}_5.X_5 = \dot{m}_4.X_4 + \dot{m}_{10}.X_{10} \quad (36)$$

$$H_A = (\dot{m}_5.h_5) - (\dot{m}_4.h_4) - (\dot{m}_{10}.h_{10}) \quad (37)$$

$$\text{Ex}_A = -(1 - T_0/T).H_A \quad (38)$$

$$I_A = (\dot{m}_4.\text{ex}_4) + (\dot{m}_{10}.\text{ex}_{10}) - (\dot{m}_5.\text{ex}_5) + ((1 - T_0/T).H_A) \quad (39)$$

PUMP

$$\dot{m}_5 = \dot{m}_6 \quad (40)$$

$$\dot{m}_5.X_5 = \dot{m}_6.X_6 \quad (41)$$

$$W_P = v_5.(P_6 - P_5/Efic).\dot{m}_5 \quad (42)$$

$$h_6 = h_5 + (W_P/\dot{m}_5) \quad (43)$$

$$\text{Ex}_P = W_P \quad (44)$$

$$I_P = (\dot{m}_5.\text{ex}_5) - (\dot{m}_6.\text{ex}_6) + (W_P) \quad (45)$$

RECTIFIER

$$\dot{m}_6 = \dot{m}_{13} \quad (46)$$

$$\dot{m}_{11} = \dot{m}_1 + \dot{m}_{12} \quad (47)$$

$$\dot{m}_6.X_6 = \dot{m}_{13}.X_{13} \quad (48)$$

$$\dot{m}_{11}.X_{11} = \dot{m}_1.\text{X}_1 + \dot{m}_{12}.X_{12} \quad (49)$$

$$(\dot{m}_{13}.h_{13}) - (\dot{m}_6.h_6) = (\dot{m}_1.h_1) + (\dot{m}_{12}.h_{12}) - (\dot{m}_{11}.h_{11}) \quad (50)$$

$$I_R = (\dot{m}_{11}.\text{ex}_{11}) + (\dot{m}_6.\text{ex}_6) - (\dot{m}_1.\text{ex}_1) - (\dot{m}_{13}.\text{ex}_{13}) - (\dot{m}_{12}.\text{ex}_{12}) \quad (51)$$

HEAT EXCHANGER

$$\dot{m}_{13} = \dot{m}_7 \quad (52)$$

$$\dot{m}_8 = \dot{m}_9 \quad (53)$$

$$\dot{m}_{13}.X_{13} = \dot{m}_7.X_7 \quad (54)$$

$$\dot{m}_8.X_8 = \dot{m}_9.X_9 \quad (55)$$

$$(\dot{m}_9.h_9) - (\dot{m}_8.h_8) = (\dot{m}_7.h_7) - (\dot{m}_{13}.h_{13}) \quad (56)$$

$$I_{\text{HE}} = (\dot{m}_8.\text{ex}_8) + (\dot{m}_{13}.\text{ex}_{13}) - (\dot{m}_7.\text{ex}_7) - (\dot{m}_9.X_9) \quad (57)$$

GENERATOR

$$\dot{m}_7 + \dot{m}_{12} = \dot{m}_{11} + \dot{m}_8 \quad (58)$$

$$\dot{m}_7.X_7 + \dot{m}_{12}.X_{12} = \dot{m}_{11}.X_{11} + \dot{m}_8.X_8 \quad (59)$$

$$H_G = (\dot{m}_1.h_1) + (\dot{m}_{13}.h_{13}) + (\dot{m}_8.h_8) - (\dot{m}_7.h_7) - (\dot{m}_6.h_6) \quad (60)$$

$$\text{Ex}_G = -(1 - T_0/T_G).H_G \quad (61)$$

$$I_G = (\dot{m}_7.\text{ex}_7) + (\dot{m}_{12}.\text{ex}_{12}) - (\dot{m}_{11}.\text{ex}_{11}) - (\dot{m}_8.\text{ex}_8) + ((1 - T_0/T).H_G) \quad (62)$$

EXPANSION VALVE 2

$$\dot{m}_9 = \dot{m}_{10} \quad (63)$$

$$\dot{m}_9.X_9 = \dot{m}_{10}.X_{10} \quad (64)$$

$$h_9 = h_{10} \quad (65)$$

$$I_{V2} = (\dot{m}_9.\text{ex}_9) - (\dot{m}_{10}.\text{ex}_{10}) \quad (66)$$

The coefficient of performance (COP) of a refrigeration system is measured in terms of the removed heat, the heat supplied and the work cycle.

The exergetic efficiency provides the performance of refrigeration system by absorption based on the second law of thermodynamics in terms of exergy transferred from the evaporator and generator.

3. RESULTS AND DISCUSSION

3.1 Analysis of thermal system coupling

Figure 2 and 5 shows the graphic interface of the thermodynamic model, the Diesel cycle combustion engine and the absorption refrigeration cycle, developed with the aid of EES. The simulation was powered with data collected from a public transport vehicle in operation, presenting the operational conditions of these vehicles.

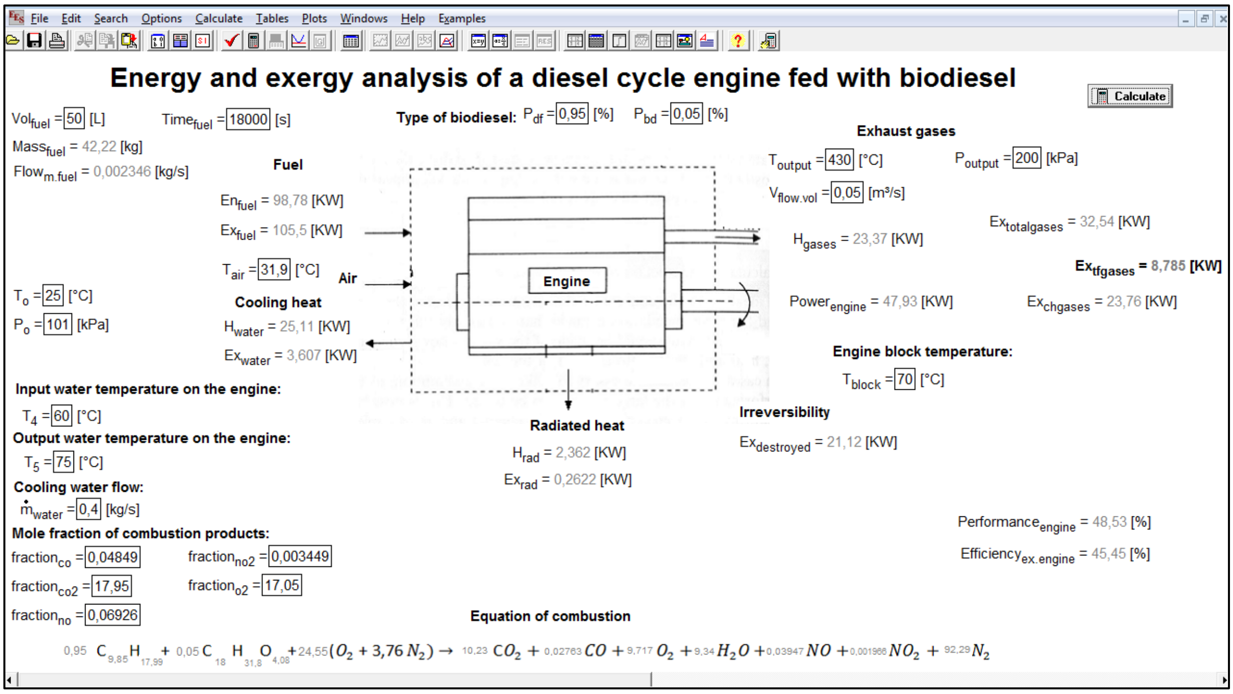

Figure 2. Graphic interface of the EES – Combustion engine

From Figure 2 and Table 1, the data regarding the water-cooling system, the irradiated heat of the engine block and the exhaust gas exergy rates can be seen. The highest available exergy rate was found in the exhaust gases with 89.37%. This is divided into two parts: chemical exergy (65.25%) and thermophysics (24.12%). As there will be no new chemical reaction with the exhaust gases to be used as a source of heat in the refrigeration system, only the thermal part of the gases, the thermophysical exergy, which still becomes a greater percentage than the exergy from the cooling system and the irradiated heat of the engine block. Therefore, it would be interesting to increase the useful thermal potential of the exhaust gases and try to obtain a reduction in the percentage of chemical exergy which in this case will be released into the environment.

Figures 3 and 4 present an analysis of the biofuel composition variation with the exergy available from the exhaust gases. It can be observed that the increase in biodiesel in the composition of the fuel provides a slight variation in the thermophysical exergy, and consequently a slight variation in the chemical exergy of gases exhaust. According to Lapuerta et al. (2008), with biodiesel there is an increase of up to 14% in specific consumption compared to that for diesel fuel leading to higher rates of gas emissions with high temperatures. The presence of oxygen associated chemically to the biodiesel molecule has the effect of reducing the concentration of pollutants in the exhaust gases due to the better burning of the fuel in the engine. These emissions with pure biodiesel and their blends with diesel oil have been reported in studies conducted by the American Environmental Protection Agency (2002). According to this organization, the emissions of carbon monoxide (CO) show an exponential reduction with an increasing percentage of biodiesel. On the other hand, most of the studies analyzed show a rapid increase in NOx emissions with the use of biodiesel, although this is dependent on the operating conditions and engine type. This therefore demonstrates that it is not possible to increase the thermal availability without increasing the chemical availability of exhaust gases.

Table 1. Analysis of exergetic availability

Source Available	Symbol	Exergy Available [kW]	[%]
Water cooling	Ex_{water}	3.607	9.91
Engine block	Ex_{rad}	0.2622	0.72
Exhaust gases	$Extf_{gases}$	8.785	24.12
	$Exch_{gases}$	23.76	65.25
Total		36.41	100.00

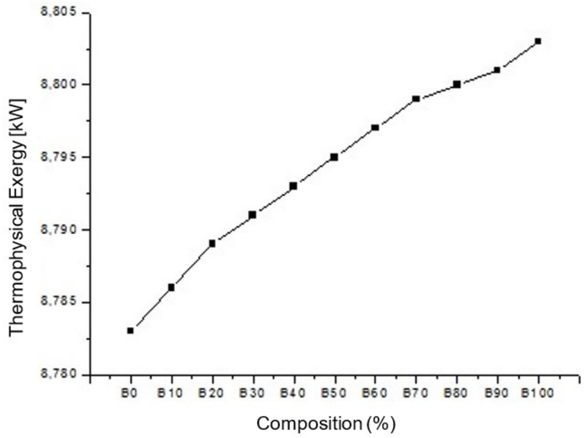

Figure 3. Composition x Thermophysical Exergy

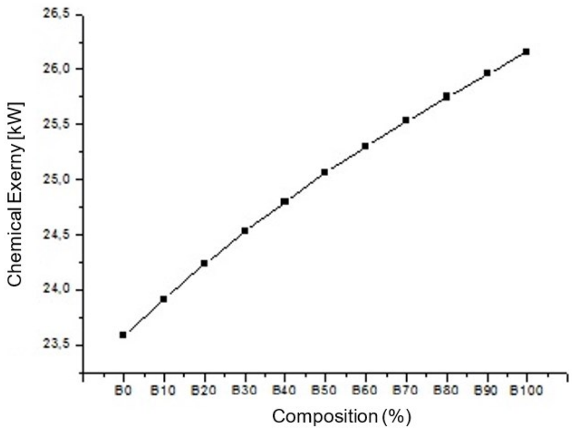

Figure 4. Composition x Chemical Exerny of gases

From this analysis it can be seen that the increase in biodiesel in the fuel composition is advantageous for the absorption refrigeration cycle because it provides a greater useful potential of energy through the exhaust gases. However, from the analysis in Table 2 the increase in biodiesel in the fuel composition causes a considerable reduction in its energy and useful potential. In turn this reduces the power and performance of the engine, and consequently discharges a larger portion of energy to the environment through the exhaust gases. According to Çetinkaya et al. (2005), the reduction in power with the use of biodiesel is explained by the lower calorific value of the biofuel.

It is necessary to select a fixed value for the biofuel composition that is most convenient, in the other words, favoring both the absorption cycle and the combustion engine. The biofuel used in this simulation was biodiesel (B5), 5% biodiesel which is the type most commercially used in Brazil. Through the simulation, this combination provided 8.875kW of thermal source for the refrigeration cycle by absorption.

Figure 5 shows the refrigeration system by absorption, modeled in the system, powered the generator by the thermophysical exergy of the diesel engine exhaust gases. This part of the simulation shows the thermodynamic state of each point, the behavior of COP, refrigeration power and exergy destroyed as a function of temperature and heat variation from the engine gases.

Table 2. Analysis of the increase biodiesel in composition

Composition	En_{fuel} [kW]	$Power_{engine}$ [kW]	Ef_{engine} [%]	$Ex_{totalgases}$ [kW]
B0	99.03	48.19	48.66	32.37
B5	98.78	47.93	48.53	32.54
B50	96.47	45.58	47.24	33.85
B100	93.68	42.76	45.64	34.96

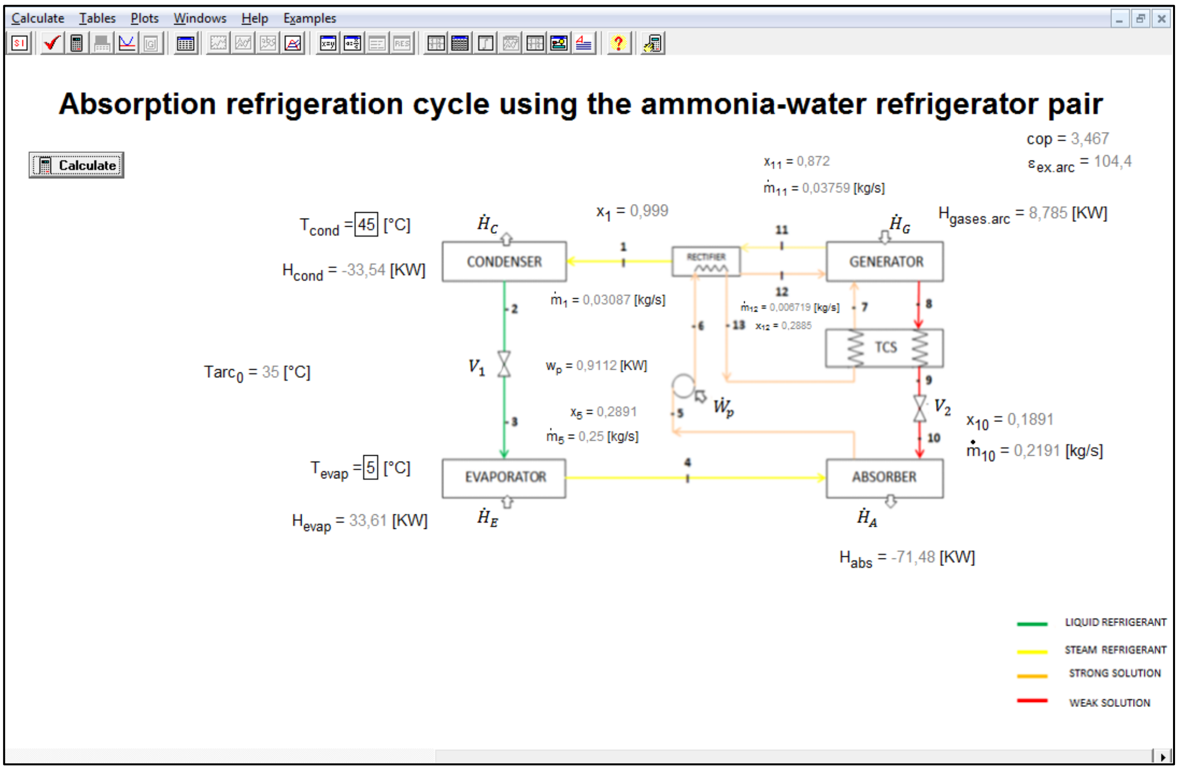

Figure 5. Graphic interface of the EES – Absorption cycle

3.2 Analysis of the influence of exhaust gases in the irreversibility of combustion engine

Figure 6 shows an analysis of the Diesel cycle combustion engine irreversibility in relation to the exhaust gases temperature. This result was obtained for fixed values of biofuel composition and exhaust gases flow for biodiesel (B5) and a flow of 0.056 (m^3/s), respectively. The increase in the temperature of exhaust gases leads to a significant increase in engine irreversibility, causing an undesirable effect.

Figure 7 presents an analysis of the Diesel cycle combustion engine irreversibility in relation to exhaust gases flow. This result was obtained for static values of the biofuel composition and the temperature of exhaust gases, the biodiesel (B5) and a temperature of 325 (° C), respectively. The increase in the exhaust gases flow causes a significant reduction in engine irreversibility, providing a desirable result when working at full load.

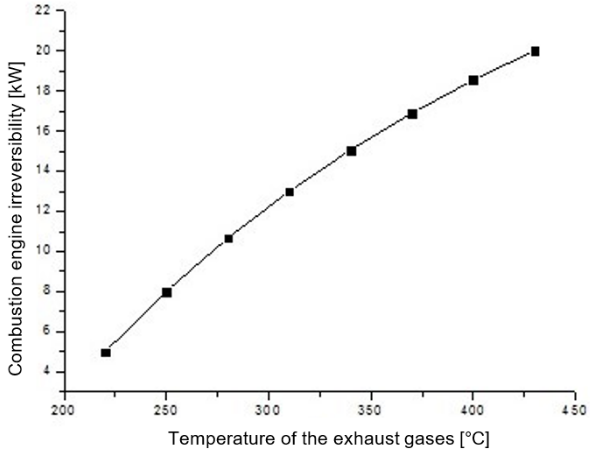

Figure 6. Exhaust gases temperature x combustion engine irreversibility

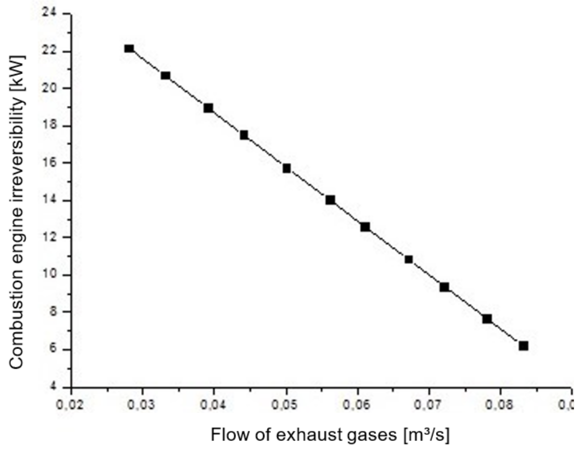

Figure 7. Flow of exahaust gases x combustion engine irreversibility

3.3 Analysis of influence of exhaust gases in irreversibility of absorption cycle

In order to define a temperature in the generator as "optimal", a comprehensive assessment is necessary, taking into account several variables and parameters of projects, as discussed in Fernández-Seara and Vázquez (2001). Table 3 shows an analysis of the irreversibility of all components of absorption cycle and in relation to the exhaust gas conditions of combustion engine, which work as a thermal source for the refrigeration system at the generator input. The results show significant irreversibility in both the generator and TCS heat exchanger.

Table 3. Irreversibility of components

Components	**Irreversibility [KW]**	**[%]**
Generator	16.410	48.15
Heat Exchanger	4.864	14.27
Rectifier	3.889	11.41
Evaporator	3.809	11.18
Absorber	2.795	8.20
Valve 1	1.444	4.24
Pump	0.441	1.30
Valve 2	0.353	1.00
Condenser	0.079	0.23
Total	**34.084**	**100.00**

Figures 8 and 9 shows an analysis of the irreversibility of the most relevant components concerning the variation in temperature and flow of feed gases, respectively. The same conditions as fixed values presented for analysis of Figures 6 and 7 are adopted.

The graph of Figure 8 shows a similar behavior to that in Figure 9, where both the rise in temperature and gas flow cause an increase in the rate of irreversibility of the generator and a reduction in the rate of heat exchanger irreversibility (TCS).

According to Aman et al. (2014), the irreversibilities occurring in the generator are mainly due to heat transfer associated with a large temperature difference in the absorber and mass transfer with a high gradient of concentration and losses in blends in the generator. In addition, as the ammonia leaving the generator is overheated, a higher temperature is required under the same pressure, which leads to greater thermodynamic losses in the generator.

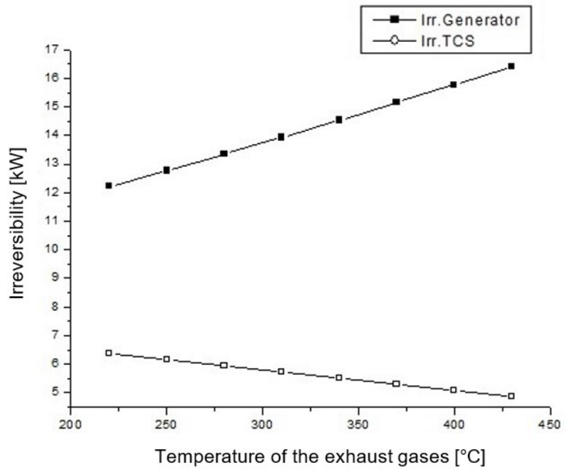

Figure 8. Exhaust gases temperature x Irreversibility

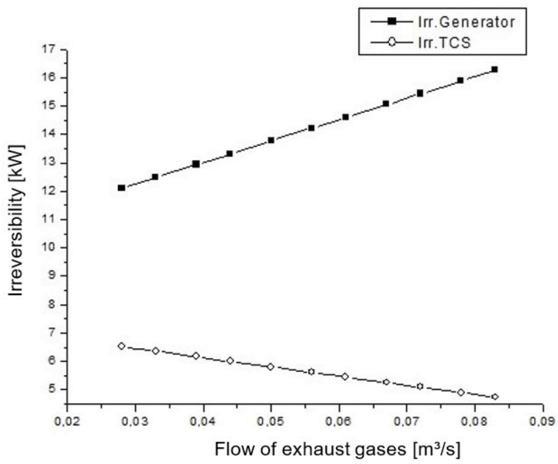

Figure 9. Flow of exahaust ga ses x irreversibility

4. CONCLUSIONS

This study presented the energy and exergy analysis of a refrigeration system by absorption using the exhaust gases of a combustion engine as source of energy so as to propose an air conditioning system for a public transport vehicle.

Through a simulation developed on the EES platform, it was possible to make an analysis of waste heat of a diesel cycle combustion engine fed with any proportion of biofuel. It was observed that the flexibility of the biofuel used does not imply a drastic change in the values of the energy and exergy system, allowing the use of energy lost to exhaust to feed a refrigeration cycle.

This study showed main critical points of a thermal system using the thermophysical exergy from a diesel combustion engine exhaust gases as a thermal energy source to power a refrigeration cycle by absorption, like the integration of exhaust gases with the generator.

Our analysis demonstrated that this integration is viable and the main efforts to improve refrigeration systems by absorption should focus on developing efficient components, namely the generator, which was responsible for the greatest losses of exergy in the whole system.

As suggestions for further work, we would like to study of the best and most appropriate simplifications and design parameters based on measurements on a real refrigeration cycle by absorption, to feed and check the results in the simulation, in addition to measurements in a Diesel cycle engine in an urban public transport vehicle to verify the results of the thermal system developed in the simulation.

5. REFERENCES

ABU-EIN, S. Q. et al, Performance analysis of solar powered absorption refrigeration system. **Heat and mass transfer**, v. 46, n. 2, p. 137, 2009.

ALMEIDA, A. G. S. et al, Exergetic analysis of an air conditioning system by absorption for transport vehicles, **12o IMECE - International Mechanical Engineering Congress & Exposition**, Houston, Texas, USA, 2012.

ALPTEKIN, E.; CANAKCI, M. Determination of the density and the viscosities of biodiesel–diesel fuel blends. **Renewable energy**, v. 33, n. 12, p. 2623-2630, 2008. DOI: 10.1016/j.renene.2008.02.020

AMAN, J.; TING, DS-K.; HENSHAW, P. Residential solar air conditioning: Energy and exergy analyses of an ammonia–water absorption cooling system. **Applied Thermal Engineering**, v. 62, n. 2, p. 424-432, 2014. DOI: 10.1016/j.applthermaleng.2013.10.006

CETINKAYA, M. et al. Engine and winter road test performances of used cooking oil originated biodiesel. **Energy Conversion and Management**, v. 46, n. 7-8, p. 1279-1291, 2005. DOI: 10.1016/j.enconman.2004.06.022

EPA - United States of America Environmental Protection Agency: A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, EPA 420-P-02-001; **U.S. Environmental Protection Agency**, Washington DC, 2002.

FERNÁNDEZ-SEARA, J.; VÁZQUEZ, M. Study and control of the optimal generation temperature in NH_3–H_2O absorption refrigeration systems. **Applied Thermal Engineering**, v. 21, n. 3, p. 343-357, 2001. DOI: 10.1016/S1359-4311(00)00047-8

HORUZ, I. Vapor absorption refrigeration in road transport vehicles. **Journal of Energy Engineering**, v. 125, n. 2, p. 48-58, 1999.

KAYNAKLI, Ö.; HORUZ, I. An experimental analysis of automotive air conditioning system. **International communications in heat and mass transfer**, v. 30, n. 2, p. 273-284, 2003. DOI: 10.1061/(ASCE)0733-9402(1999)125:2(48)

KLEIN, S. A. **Engineering Equation Solver– EES**, Professional V8.279, 2009.

KOEHLER, J. et al. Absorption refrigeration system for mobile applications utilizing exhaust gases. **Heat and Mass Transfer**, v. 32, n. 5, p. 333-340, 1997. DOI: 10.1007/s002310050130

LAPUERTA, M.; ARMAS, O.; RODRIGUEZ-FERNANDEZ, J. Effect of biodiesel fuels on diesel engine emissions. **Progress in energy and combustion science**, v. 34, n. 2, p. 198-223, 2008. DOI: 10.1016/j.pecs.2007.07.001

MANZELA, A. A. et al. Using engine exhaust gas as energy source for an absorption refrigeration system. **Applied energy**, v. 87, n. 4, p. 1141-1148, 2010. DOI: 10.1016/j.apenergy.2009.07.018

RÊGO, A. T. et al. Automotive exhaust gas flow control for an ammonia–water absorption refrigeration system. **Applied thermal engineering**, v. 64, n. 1-2, p. 101-107, 2014. DOI: 10.1016/j.applthermaleng.2013.12.018

SAHOO, P. K.; MISRA, R. D.; GUPTA, A. Exergoeconomic optimisation of an aqua-ammonia absorption refrigeration system. **International Journal of Exergy**, v. 1, n. 1, p. 82-93, 2004. DOI: 10.1504/IJEX.2004.004735

TALBI, M.; AGNEW, B. Energy recovery from diesel engine exhaust gases for performance enhancement and air conditioning. **Applied thermal engineering**, v. 22, n. 6, p. 693-702, 2002. DOI: 10.1016/S1359-4311(01)00120-X

TALOM, H. L.; BEYENE, A. Heat recovery from automotive engine. **Applied Thermal Engineering,** v. 29, n. 2-3, p. 439-444, 2009. DOI: 10.1016/j.applthermaleng.2008.03.021

TESFA, B. et al. LHV predication models and LHV effect on the performance of CI engine running with biodiesel blends. **Energy conversion and management**, v. 71, p. 217-226, 2013. DOI: 10.1016/j.enconman.2013.04.005

XU, S.; LI, J.; LIU, F. An investigation on the absorption–compression hybrid refrigeration cycle driven by gases and power from vehicle engines. **International journal of energy research**, v. 37, n. 12, p. 1428-1439, 2013. DOI: 10.1002/er.2943

ZHOU, D. Y.; SHI, C. P.; YUAN, W. H. Research on LiBr Absorption Refrigeration System Using Automotive Exhausted Heat. In: **Advanced Materials Research. Trans Tech Publications Ltd**, 2011. p. 2297-2301.