17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0363
ANALYSIS OF THE SPECIFIC FUEL CONSUMPTION OF A DIESEL GENERATOR SET INFLUENCED BY THE COOLING FLUID TEMPERATURE

Lucas Nagib de Freitas
Universidade Federal do Pará – UFPA, FEM, Rua Augusto Corrêa, 1 – Guamá, Belém - PA, Brasil
lucasn.defreitas@gmail.com

João Gabriel Bezerra da Silva
Universidade Federal do Pará – UFPA, FEM, Rua Augusto Corrêa, 1 – Guamá, Belém - PA, Brasil
jgbsmec@gmail.com

Hendrick Maxil Zárate Rocha
Universidade Federal do Pará – UFPA, FEM, Rua Augusto Corrêa, 1 – Guamá, Belém - PA, Brasil
henzaro@gmail.com

Antonilson Oliveira da Conceição
Universidade Federal do Pará – UFPA, FEM, Rua Augusto Corrêa, 1 – Guamá, Belém - PA, Brasil
antonilson@ufpa.br

Edson Alves Sousa
Universidade Federal do Pará – UFPA, FEM, Rua Augusto Corrêa, 1 – Guamá, Belém - PA, Brasil
edsonalves@ufpa.br

Paola Evelen Costa Baia
Universidade Federal do Pará – FEM, UFPA, PA, Brasil
paolabaia@hotmail.com

Abstract. *The purpose of this work is to investigate the influence on the thermo-energetic performance given by the increase in the operating temperature of an internal diesel combustion engine reducing the dissipation of the thermal load transferred to the cooling fluid by restricting the flow of water through the radiator. Modifications were made in the line of input of the thermal exchange system of the engine. Power, fuel consumption and temperature parameters were collected for energy analysis of the effects after the engine temperature changes. As a result, a significant reduction in the specific fuel consumption and an improvement in the overall thermal performance of the generator set were obtained.*

Keywords: *Generator set, Operating temperature, thermal efficiency.*

1. INTRODUCTION

The Brazilian energy matrix uses several sources to generate electricity, a portion of the total comes from the thermal generation from the burning of fuel consumed by diesel generator sets (MME, 2018). This way of generating energy is not very efficient due to the large thermal losses by heat transfer through the walls of internal combustion engines (ELETROBRAS, 2010 and GTON, 2016), which is most often necessary to maintain the structural integrity of the motor, which is limited by the phase change temperature of the materials which constitute its components, thus avoiding failures due to thermal stress, conserving lubrication and avoiding greater damages (HEYWOOD, 1988). Another situation is the heavy reliance on petroleum-derived fuels consumed by these machines and the negative health and environmental consequences of their emissions (MMA, 2009). Many studies and research have been conducted to tailor and optimize internal combustion engines using alternative sources to reduce the consumption of fossil fuels. In Brazil, commercial diesel has 8% biodiesel blended in its composition, being known as diesel B8 (MDA, 2017).

One of the ways to improve the efficiency of combustion engines is to minimize heat transfer losses through the cylinder walls (SOUZA, 2016), in particular for engines with temperature control by liquid cooling fluids integrated with a radiator heat exchanger system. With the objective of reducing the specific fuel consumption, this paper proposes to investigate the behavior of the thermal efficiency of an internal combustion engine, compression ignition of 3.9 liters fed with commercial diesel B8 through the minimization of the thermal exchange coming from the cooling system acting on raising the temperature of the cooling fluid by restricting the flow of the fluid through a valve installed in the inlet line of the engine radiator.

2. THEORETICAL REFERENCE

Cooling systems for internal combustion engines have the purpose of controlling the flow of heat dissipated by the walls of the engine while maintaining a temperature range when in operation. It is necessary that the engine is heated to operate in perfect conditions of lubrication, as well as there are processes that depend on the heating to achieve its better performance of operation.

The internal combustion engines are designed to remove part of the energy of a fuel released in the combustion process transformed it into shaft power. In compression-ignition engines, the fuel comes in contact with the mass of air at high energy levels, forming the air-fuel mixture in the beginning, initiating the burning process (HEYWOOD, 1988 and BRUNETTI, 2012). According to the First Law of Thermodynamics, the energy released by the fuel within the cylinder of an engine is represented by the sum of the effective rate of energy delivered to the piston, the heat dissipated by the walls and the cooling fluid (DA SILVA, 2017 and TREVAS, 2017).

Part of the heat produced by the combustion is transferred through the cylinder walls, head, piston, inlet and exhaust valves, lubricating oil and others. (HEYWOOD, 1988). The coolant circulates in the regions with the highest heat flux, exchanging heat with the engine block and head, and then discarding this energy in the radiator (FERGUSON, 2001; HEYWOOD, 1988 and SOUZA, 2016).

According to Sousa (2016), raising the temperature of the engine cooling fluid improves the thermal efficiency, so the driving force given by the temperature difference between the walls of the combustion chamber and the cooling fluid is of lower magnitude, reducing the amount of heat transferred by the walls resulting in reduced specific fuel consumption.

2.1. HEAT REJECTION IN ENGINES

2.1.1. MECHANISMS OF HEAT TRANSFER

Heywood (1988) says that the heat transfer from the combustion chamber to the cooling fluid occurs in three transfer mechanisms: conduction, convection and a small amount by irradiation and can be disregarded in the transfer models. Thus, Figure 1 schematically depicts the distribution of heat flow and temperatures in the surfaces and walls of the combustion chamber of an internal combustion engine.

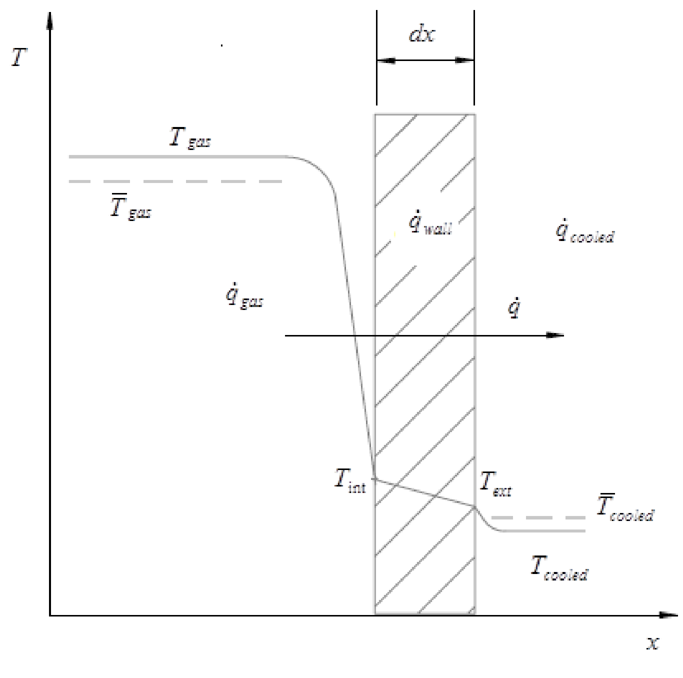

Figure 1 – Distribution of heat flux and temperature in the combustion chamber wall (HEYWOOD, 1988)

Analyzing the scheme of figure 1, the heat transferred from the combustion gases with average temperature $\overline{T}_{gas}$ for the internal surface of the combustion chamber is given by the heat transfer mechanism by convection. In this case, the term of heat transferred by radiation is insigficant, considering only the mechanism of convection $\dot{q}_{gas}$ as in Eq.1 (Heywood, 1988).

$$\dot{q}_{gas} = h_{gas}(\overline{T}_{gas} - T_{\text{int}}) \tag{1}$$

h_{gas} is the convective coefficient of the combustion gases and T_{int} is the temperature of the inner wall of the combustion chamber.

The amount of energy transferred by the walls of the combustion chamber considering a unidirectional heat flow is formulated by the law of Fourier conduction (Eq.2), being directly proportional to the temperature gradient dT/dx in the x direction perpendicular to the thermal exchange surface (HEYWOOD, 1988; INCROPERA, 2003).

$$\dot{q}_{wall} = k_{wall}\frac{dT}{dx} = k_{wall}\frac{(T_{\text{int}} - T_{ext})}{\Delta x} \tag{2}$$

k is the conductive property of the material of each wall and T_{ext} is the temperature of the outer wall.

For the side in direct contact with the cooling fluid, the convective heat exchange $\dot{q}_{cooled}$, is characterized by the movement of the fluid by removing heat from the surface which has been transferred by the wall of the combustion chamber by the driving mechanism. $\overline{T}_{cooled}$ represents the average temperature of the cooling fluid..

$$\dot{q}_{cooled} = h_{cooled}(T_{ext} - \overline{T}_{cooled}) \tag{3}$$

2.1.2. ENERGY BALANCE

Applying the principles of the First Law of Thermodynamics to an open system, the equation describing the energy balance for an internal combustion engine is formulated by Eq.4 (HEYWOOD, 1988).

$$\dot{m}_f h_f + \dot{m}_a h_a = \dot{W}_b + \dot{Q}_{cooled} + \dot{Q}_{misc} + (\dot{m}_f + \dot{m}_a)h_e \tag{4}$$

The parcel $\dot{m}_f h_f$ corresponds to the mass and sensitive energy of the circulating waste gas, ie flue gases not swept by the piston corresponding to the volume of the combustion chamber;

$\dot{m}_a h_a$ contemplates the mass of entrance in volume of control of the engine, referring to the admitted mass of the air and the fuel injected.

$\dot{W}_b$ is the work done on the piston by adding the available energy in the engine axis (axis power) plus the energy dissipated by friction, also known as friction power.

The energy lost by the heat flow in the wall of the combustion chamber $\dot{Q}_{cooled}$ in practice corresponds to the amount of energy dissipated by the lubricating oil and the cooling fluid, also involving other components of the engine.

The portion given by $(\dot{m}_f + \dot{m}_a)h_e$ encompasses the energies dissipated by the exhaust gases, leaks by the seal between the piston sealing rings and the cylinder wall, and the mass of fuel that has not burned until the opening of the exhaust valve.

2.1.3. PERFORMANCE PARAMETERS

The mathematical models for engine performance analysis shown below to evaluate the effects produced by the engine operating temperature variation under study are the same models developed by Heywood (1988) and Brunetti (2012).

The shaft power P_{axis} is the difference between the indicated effective power P_{eff} and the friction power given by Eq.5.

$$P_{axis} = P_{eff} - P_{fric} \tag{5}$$

The calculation of P_{eff} is obtained by Eq.6, relates the indicated effective mean $IMEP$, the displacement V_{cyl}, the rotation N in rpm and the number of turns of the crankshaft n_r required to complete a complete engine cycle. For 4 stroke engines $n_r = 2$ and 2 stroke engines $n_r = 1$.

$$P_{eff} = \frac{IMEP \times V_{cyl} \times N}{n_r} \tag{6}$$

The $IMEP$ is calculated by the integral of the pressure curve as a function of the cylinder volume for each position of the crankshaft and corresponds to the work performed on the equivalent piston P_{eff}.

The electric power P_{elec} given by Eq. 7, is the parameter commonly used for performance analysis of generator sets and is directly related to the power produced in the motor shaft and the efficiency of the electric generator η_{elec}.

$$P_{elec} = \eta_{elec} \times P_{axis} \tag{7}$$

The specific consumption is an effective parameter to evaluate how well the fuel delivered to the engine is being used, its value is given in consumption per unit of power in the form of Eq.8.

$$SFC = \frac{\dot{m}_{fuel}}{P_{elec}} \tag{8}$$

Eq.9 uses the electrical power produced by the motor shaft to determine the thermal efficiency η_T based on the upper calorific value PCS of the fuel.

$$\eta_T = \frac{P_{elec}}{P_{fuel}} = \frac{P_{elec}}{\dot{m}_{fuel} \times PCS} \tag{9}$$

3. EXPERIMENTAL PROCEDURE

The constructive characteristics and technical specifications of the generator set used in the development of this work are present in table 1.

Model of Generator set	C40D64
Eletric Power	39 kW
Engine	Diesel Cycle – 4 Stroke
Number of cylinders / Displacement	4 / 3.9L
Compression Ratio	17,5:1
Working speed	1800 rpm

Table 1 - Characteristics of the generator set.

The engine operated with commercial B8 diesel oil in a range of 1800 rpm of rotation, three working rates were evaluated at 40, 60 and 80% of the maximum power of the generator set. For performance analysis, we determined the parameters of consumption, power and temperatures at specific points of the generator set.

Fuel consumption was determined with a volumetric flowmeter model LSF41 supplied by the Oval, with an accuracy of ± 1% of the reading. In order to calculate the fuel consumption, the fuel temperature was measured by a type K thermocouple installed in the feed line near the inlet of the flow sensor, as well as temperature values of the combustion gases and water temperatures were recorded with the objective of determining the permanent regime by the stability of the temperature records for data collection.

The electrical magnitudes were measured using a SAGA 4500 energy analyzer manufactured by Landis + Gyr and 1% accuracy of the reading, recording values of power, voltage, current and frequency in the three phases of the generator.

The temperature was controlled by a drawer-type valve installed in the flow line of the cooling fluid. The fluid displacement was in the direction of engine output and radiator inlet dissipating any thermal load absorbed as the fluid flowed through the thermal block galleries of the engine block. The increase in temperature was due to the restriction of the water flow, that is, the reduction of the flow reduced the passage of the thermal load from the engine to the radiator, raising the water temperatures in the cooling galleries. To ensure the liquid phase of the water in the piping, a thermocouple and a manometer were installed in the drawer-type valve installation position by monitoring the temperature and pressure, leaving them, away from the liquid-vapor saturation boundary. Figure 2 shows schematically the installation of the tools in the water circulation line.

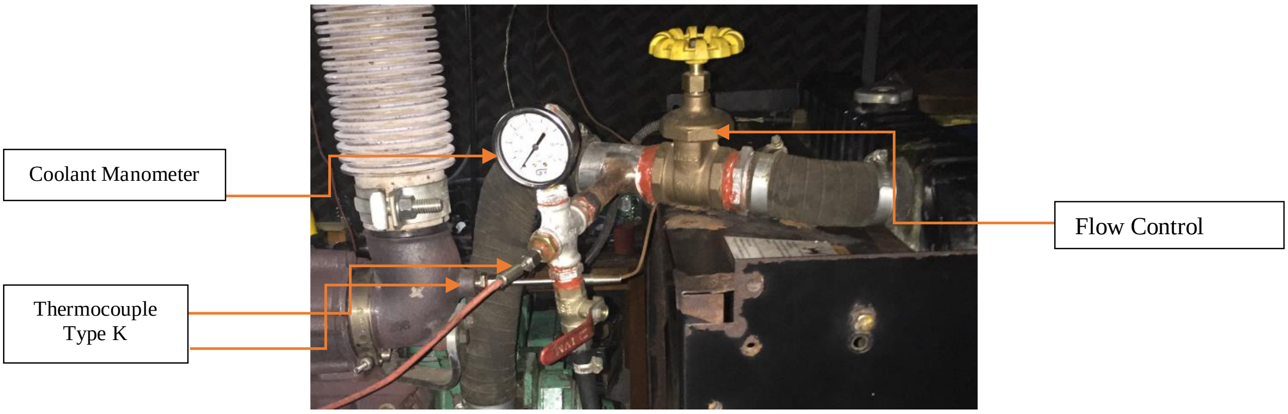

Figure 2: Water temperature control system.

In order to avoid overheating and to compromise the operation of the engine, the temperature variation of the water in the position of the drawer-type was given in the approximate range of 15 ° C, ie under original operating conditions, this temperature is approximately 82 ° C and, the maximum allowed value was restricted to 97 ° C.

4. RESULTS AND DISCUSSION

The results obtained show parameters of specific fuel consumption and the reduction in percentage comparing the base of reference obtained with the engine operating in state of normal operation of temperature.

The trend of reducing the specific fuel consumption obtained with increasing coolant temperature is observed by analyzing the curves represented in the graph of figure 3. It should be noted that these curves are a representative way to analyze the influence of the temperature of the engine in the specific fuel consumption in this specific case and does not represent the actual profile because it is only two temperature points and fuel consumption.

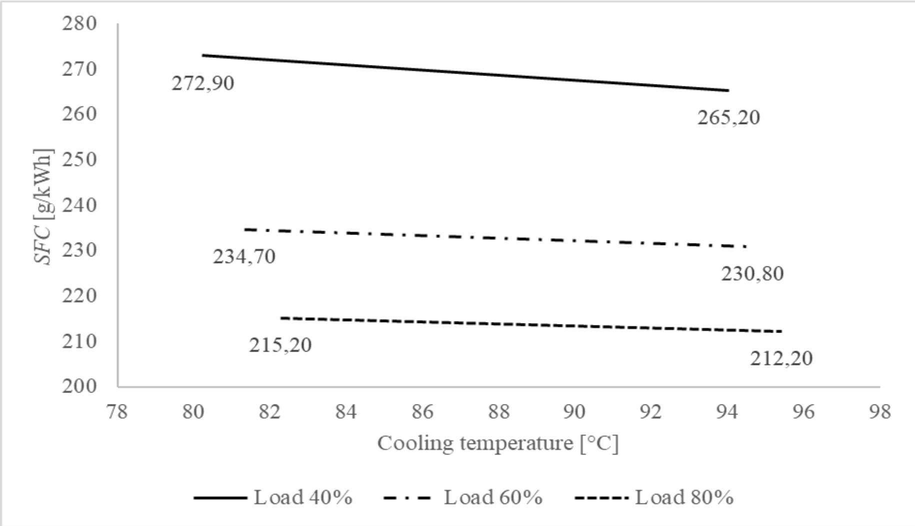

Figure 3 – Representation of SFC as a function of temperature for this study.

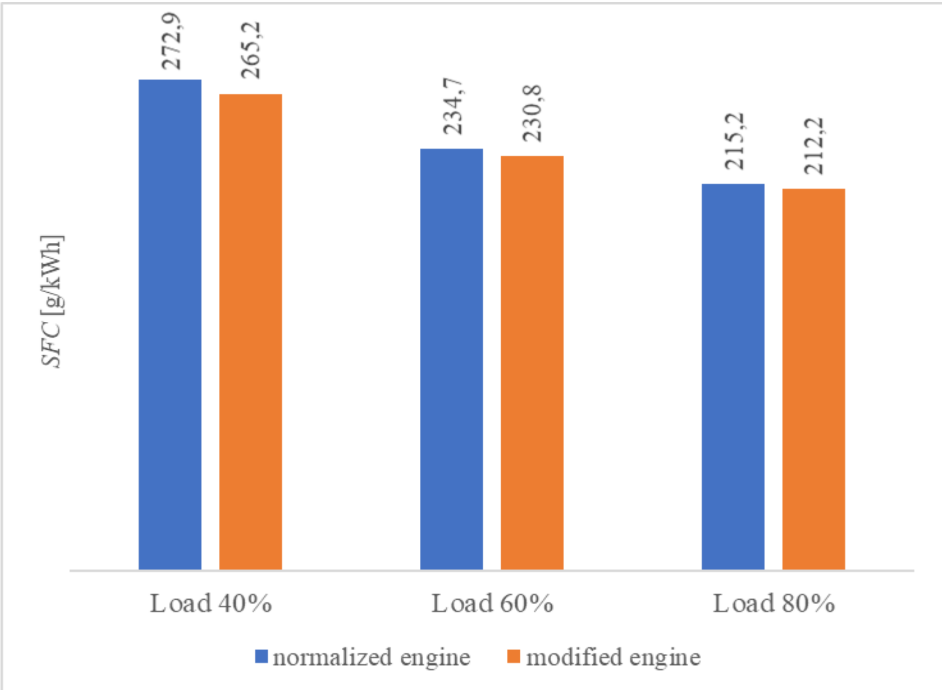

Figure 4 – SFC chart for different loads.

The figure 4 compares the results of SFC with the normalized motor compared to the results obtained by raising the temperature of the cooling fluid. This modification had a direct impact on the SFC, as observed in the graph of figure 3, especially with the engine operating at 40% of the load, obtaining an efficiency gain of 2.8%, observing the results of figure 5 for the same operating regime.

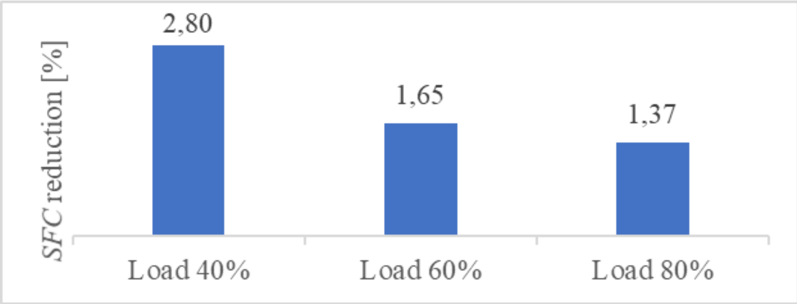

Figure 5 – Reduction of SFC according to load.

Analyzing the results of figure 5, the percentage amount of the reduction in SFC did not perpetuate for work regimes above 40% of the load. An explanation for this behavior lies in the variation of the thermal exchange gradient in the combustion chamber wall when the temperature of the cooling fluid remains almost constant regardless of the working regime, thus, the thermal exchange gradient tends to increase with the required load on the engine.

To compensate for the increased load on the engine, the injection system provides more fuel, raising the cylinder's internal temperatures, an effect produced by the greater amount of released heat connected to the greater amount of fuel burned. In this sense, by analyzing the Fourier equation of the heat conduction (Eq. 2) described in section 2.1.1, the heat flux through the combustion chamber wall increases in direct proportions to the increase of the temperature gradient (dT/dx) when the temperatures of the internal surfaces of the walls of the combustion chamber, represented by T_{int}, increases.

One way to verify if the SFC would maintain the engine operating at higher speeds would be to restrict the heat flux in proportions equivalent to the thermal exchange gradient for each load, but such modifications would result in high temperature levels, compromising the integrity structural of the motor, even a collapse in operation.

5. CONCLUSION

In this work we investigated the influence of engine operating temperature to predict the specific fuel consumption behavior. The operating temperature has been altered by restricting the flow of the cooling fluid by means of a drawer type valve installed in the position of the hose which interconnects the thermal exchange galleries of the engine to the radiator. The investigation concluded that the increase in temperature resulted in a better thermal efficiency of the generator set given the reduction of SFC, especially when the engine operated at 40% load. For higher load regimes, the SFC reductions were lower, but satisfactory due to the thermal efficiency gain when compared to the results obtained with the motor operating at normalized temperature.

The flow of heat through the walls of the combustion chamber varies for each engine operating regime. As fuel consumption increases, the thermal load also increases by raising the heat transfer gradient through the inner walls of the combustion chamber, behavior was attributed to the lower SFC values with the increase of load on the motor shaft.

6. REFERENCES

BRUNETTI, F. *Motores de combustão interna*. São Paulo: Blucher, v1. 2012.

FERGUSON, C. R.; KIRKPATRICK, A. T. *Internal combustion engines : applied thermodynamics*. 2nd. New York: John Wiley & Sons, 2001. xiii, 369 p.

HEYWOOD, John B. *Internal Combustion Engine Fundamentals*. USA: McGraw-Hill, Inc., 1988.

MMA, Ministério do Meio Ambiente, MS, Ministério da Saúde, Ministério das Cidades. *Compromisso pela Qualidade do Ar e Saúde Ambiental*. Brasília, 2009.

MME, Ministério de Minas e Energia. <http://www.mme.gov.br>. Acesso em 2015.

MDA, Ministério do Desenvolvimento Agrário. *Progressão do biodiesel: mistura B8 é lei para 2017*. < http://www.mda.gov.br/sitemda/noticias/progress%C3%A3o-do-biodiesel-mistura-b8-%C3%A9-lei-para-2017>.

SOUSA, Moisés Abreu de. *Desenvolvimento de uma Metodologia para Minimizar o Consumo Específico de Motores Diesel Operando Com Combustível Local.* Universidade Federal do Pará, 2016.

ELETROBRÁS. *Sistemas Isolados* – Eletrobrás (2010). Disponível em: < https://www.eletrobras.com/elb/main.asp?Team=%7BF6839649-9BFF-4C62-A77C-21863DBA3F48%7D >.

GTON, Grupo Técnico Operacional da Região Norte. *Plano Anual de Operação dos Sistemas Isolados para 2017*. Eletrobrás, 2016. Disponível em: < http://www2.aneel.gov.br/aplicacoes/audiencia/arquivo/2016/083/documento/plano_anual_de_operacao_2017.pdf >.

ICROPERA, Frank P.; DEWITT, David P. *Fundamentos de transferência de Calor e de Massa*. 5 ed. Rio de Janeiro: LTC Editora, 2003.

DA SILVA, Thiago Rodrigo Vieira. *Estudo de estratégias de controle dos processos internos de um motor de combustão interna de injeção direta de etanol turbo-alimentado para maximização da eficiência global*. Dissertação de Mestrado, Programa de Pós-Graduação em Engenharia Mecânica, Universidade Federal de Minas Gerais. 2017.

TREVAS, Igor Cordeiro. *Análise de desempenho em um motor flex operando em ciclo miller a partir da variação da posição angular do comando de válvulas de aspiração e do seu curso de abertura*. Dissertação de Mestrado, Programa de Pós-Graduação em Engenharia Mecânica, Universidade Federal de Minas Gerais. 2017.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.