Exergy analysis of a six-stroke internal combustion engine with water injection for exhaust heat recovery

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Abstract. In recent years the scientific and public awareness of the environment and energy issues brought great interest for research of advanced technologies, particularly in the efficiency of internal combustion engines. Thus, many researchers study ways to achieve better efficiencies in a more sustainable manner through various technologies, among which is the recovery of heat. A six-stroke engine is considered as one of these technologies, it uses heat from the exhaust gases and proposes the addition of an extra cycle power carried by water injection. This work consists in undertaking an exergy analysis of a six stroke engine with water injection for comparisons to be made with conventional four strokes engine. Increases were observed in the exergetic efficiency of up to 14 % for different amounts of water injected at different injection temperatures for the six stroke engine. It was also noted a decrease of about 20% in lost exergy by the engine, a fact that proves the best use of exergy released by the fuel. The six stroke engine thermodynamic analysis shows that this technology has significant potential to achieve a better use of fuel and therefore achieve better efficiencies.

Keywords: heat recovery, exergy analysis, six-stroke engine, waste heat.

1. INTRODUCTION

An internal combustion engine may be defined as an engine that burns fuel, and produces work (Martins, 2006). The rapid compression of the gas within the cylinder produces high temperatures, turbulence and heat transfer from the piston to the cylinder walls. By doing so, the hot gases produced from the combustion process can be easily channeled through the manifold and exhaust valve. The large amount of energy from the exhaust gas flow has the potential to be used for waste heat energy recovery to increase the work's yield of the engine (Stobart, 2007).

The six-stroke engine is a technology that aims the recovering of waste heat of the exhaust gases in such a manner to increase the process efficiency. The six-stroke engine by steam injection in question was invented in 2005 by Bruce Crower and it has the first four times identical to a typical combustion four-stroke engine. The two additional cycles evolve factors such as the capture and partial compression of the fourth stage exhaust gases, followed by water injection and expansion of the mixture between water vapor and exhaust gases then complete exhaustion occurs.

This work has intention to estimate the efficiency of six-stroke engine by steam injection through an exergetic analysis once this kind of analysis measures how much work is exploited over the possible potential use.

2. EFFICIENY'S ENGINE ANALYSIS

The main methods to evaluate efficiency in engines are through the first law of thermodynamics analysis (energy efficiency) and from the analysis of the second law (Exergy Efficiency) (Saidur et al., 2012). Figure 1 shows the distribution of differences from analyzes of two major efficiencies in engines.
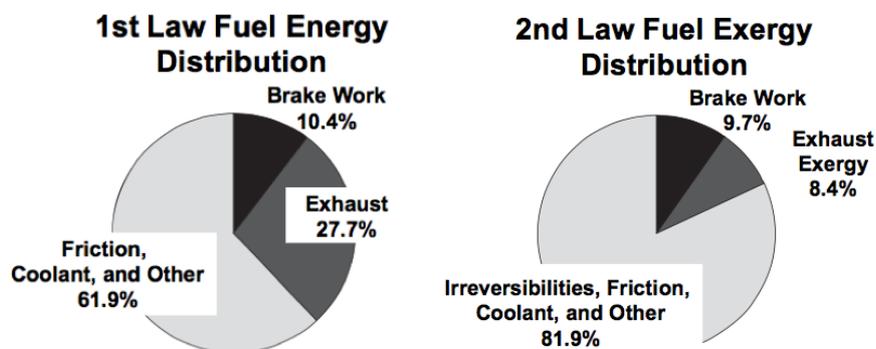

Figure 1. Analysis of the distribution of energy and exergy in an internal combustion engine (Conklin and Szybist, 2010).

It is observed in Figure (1) some differences in the values obtained for each analysis. However, the best way to observe the points in the process that can be improved is by Exergy analysis because through exergy is possible to compare fairly the different forms of energy (heat and work).

Lozano et al. (1986) defined exergy as the noble part of energy, meaning the ability to produce work. Also according to Moran and Shapiro (2009), exergy is the maximum theoretical work to be obtained from a global system comprising a system and the environment as this comes into equilibrium with the environment.

3. METHODS

The current work has the intention to conduct an analysis to quantify the exergy of an internal combustion engine which has a six-stroke cycle, it was necessary to conduct a case study based on the work of Conklin and Szybist (2010) to raise relevant data that would enable the calculations, once only a few prototypes have been developed.

Some considerations were made for the purpose of simplificating the calculations:

- The fuel (gasoline) is modeled as octane (C_8H_{18});
- The duration of pressurized water injection, vaporization and subsequent mixing with the exhaust gases is instantaneous and occurs when the piston is at top dead center;
- The exhaust gas is composed by the products of complete combustion octane;
- Pressure and temperature when the crank angle is at 900° do not exceed 1 bar and the temperature in the dew point;
- The air is modeled as an ideal gas;
- The temperature of 500 °C was considered for the exhaust gases of the four-stroke engine (Conklin Szybist, 2010).

For the control volume showed on Figure (2), the exergy is given by the Equation (1):
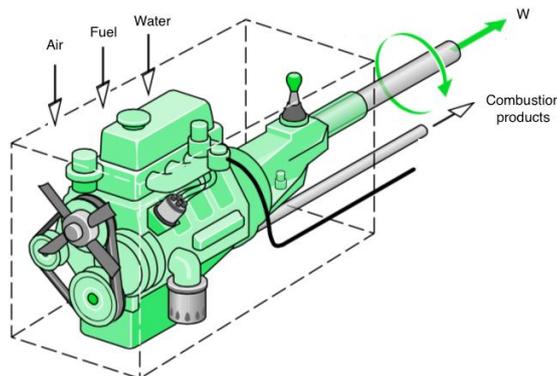

Figure 2 – Control volume analyzed – Representation of six-stroke engine. Adapted from (Moran and Shapiro, 2009)

$$\left\{\left[\sum n_r \, \bar{e}_r\right] + \bar{e}_{comb}^{CH} + \bar{e}_{ar}^{CH}\right\} \cdot \frac{\dot{m}_c}{M_c} + \dot{m}_a\left(e_{e\,a_{liq}} + \frac{\bar{e}_{a_{liq}}^{CH}}{M_a}\right)$$
$$= \left\{\left[\sum n_p \, \bar{e}_p + \bar{e}_{gases}^{CH}\right]\right\} \cdot \frac{\dot{m}_c}{M_c} + \dot{m}_a\left(e_{s\,a_{vap}} + \frac{\bar{e}_{a_{vap}}^{CH}}{M_a}\right) + \dot{W} + \dot{Q}_{perd}\left(1 - \frac{T_0}{T_S}\right) + \dot{E}_d$$

(1)

$[\sum n_r \, \bar{e}_r]$: It represents the flow exergy multiplied by the number of moles of each reactant;
$\quad \bar{e}_{comb}^{CH}$: Fuel's chemical exergy;
$\quad \bar{e}_{ar}^{CH}$: Air's chemical exergy;
$\quad e_{e\,a_{liq}}$: It represents the flow exergy of the input water;
$\quad \bar{e}_{a_{vap}}^{CH}$: Input water's chemical exergy
$[\sum n_p \, \bar{e}_p]$: It represents the flow exergy multiplied by the number of moles of each product;
$\quad \bar{e}_{gases}^{CH}$: Gases' chemical exergy;
$\quad e_{s\,a_{vap}}$: It represents the flow exergy of the output water;
$\quad \bar{e}_{a_{vap}}^{CH}$: Output water's chemical exergy;
$\dot{W}$: Net work;
$\dot{Q}_{perd}$: Heat lost by the engine;
$\dot{E}_d$: Destroyed exergy;

$\dot{m}_c$: Mass fuel flow;
$\dot{m}_a$: Mass water flow
M_c: Molar mass of fuel.
M_a: Molar mass of water.
T_0: Reference temperature.
T_s: Engine Superficial temperature

The net work may be calculated from the Mean Effective Pressure (MEP):

$$MEP = \frac{W_c}{V_{disl}} \tag{2}$$

$$\dot{W} = \frac{W_c N}{n_R} \tag{3}$$

From substituting Equation (2) in (3), the net work is calculated as:

$$\dot{W} = \frac{MEP.(V_{disl}).N_m}{n_R} \tag{4}$$

Where n_R represents the number of rotations of each power cycle. The six-stroke engine has n_R equals 3 (Conklin and Szybist, 2010).

The exergetic efficiency is calculated by the ratio of net work and chemical exergy of the combustible:

$$\varepsilon = \frac{\dot{W}}{\bar{e}_{comb}^{CH}} \tag{5}$$

4. SIX-STROKE ENGINE BY WATER INJECTION

The six-stroke engine in question was developed by Bruce Crower (Crower, 2005). The four first strokes are the same as in a typical four-stroke engine, only before the fifth stroke, vapour water is injected direclty into the heated cylinder (Conklin e Szybist, 2010). The injected water absorbs the produced heat in the cylinder, and converts it into superheated vapour which causes an expansion by 1600 in volume, therefore the piston is forced downwards creating an additional power cycle (Saidur et al., 2012), (Dads, 2015).
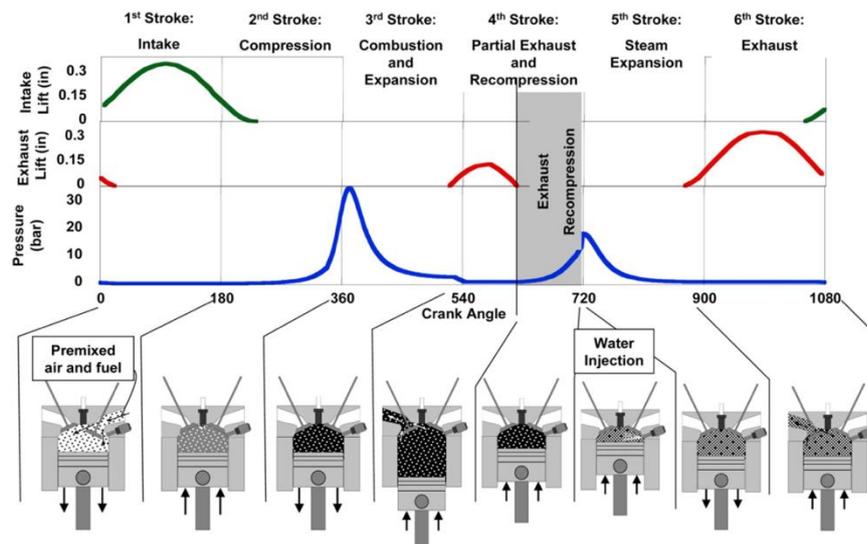

Figure 3. Representation of each stroke and valve events of a six-stroke engine (Conklin and Szybist, 2010).

The six-stroke cycle adds two strokes in order to increase the extracted work by unit of fuel. Figure (3) represents the difference between a typical diagram for a four-stroke engine where the work performed by the engine is (W_{out}) and the work consumed by the engine is (W_{pump}), and for a six-stroke engine where the additional work generated by the water injection is showed as ($W_{OUT, water injection}$).
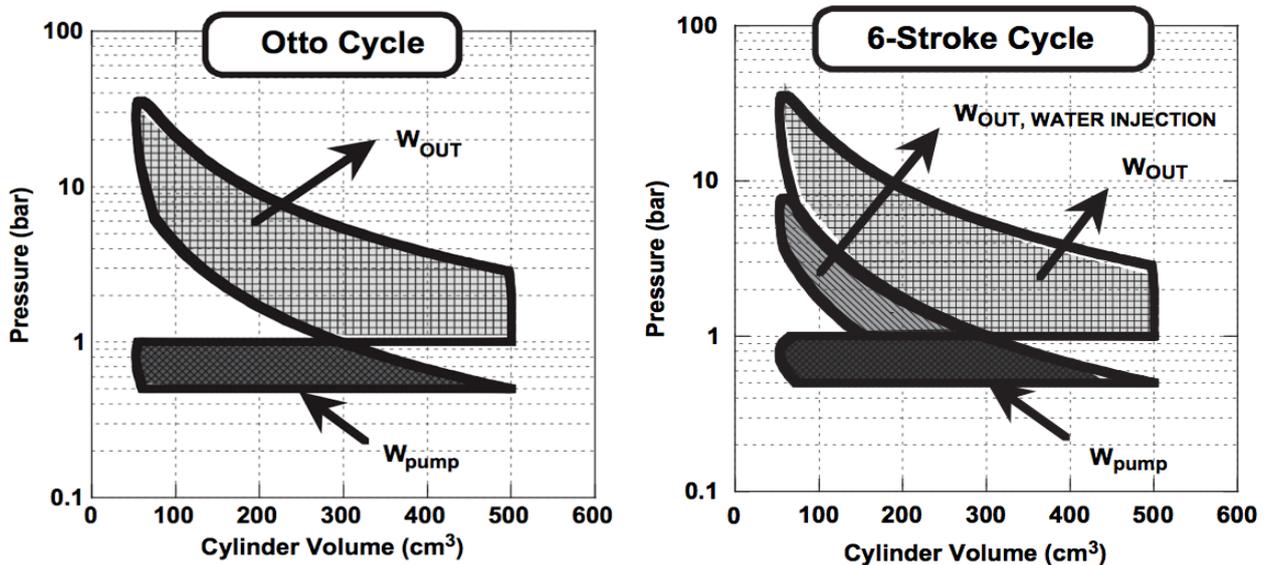

Figure 4. Schematic representation - Pressure x Volume for a conventional four-stroke engine and six-stroke engine by water injection (Conklin and Szybist, 2010).

Figure 4 proposed by Conklin and Szybist (2010), illustrates the difference between a typical diagram for a conventional four-stroke engine and a six stroke one, it is noted the work done by the engine (W_{out}) and the work consumed by the engine (W_{pump}), on the diagram for the six stroke engine it is possible to observe the extra portion of work due to the water injection ($W_{OUT, water}$).

4.1 Combustion reaction

For the Octane with a 20% of air excess, the combustion reaction is balanced as shown in Equation (6).

$$C_8H_{18} + 15 (O_2 + 3,76N_2 + 0,0922H_2O) \rightarrow 8CO_2 + 9H_2O + 47N_2 + 2,5O_2 \qquad (6)$$
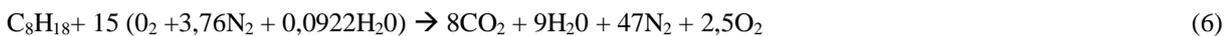
4.2 Calculation of fuel's mass flow ($\dot{m}_c$) injected in the third stroke

Accordingly to the FTP-75 test, the vehicle must cover a distance of 8,01km in 721,8s (FTP-75, 1998). The volume of fuel (V_{comb}) used in the test is equivalent to 1,7L (Conklin and Szybist, 2010). Then the consumed fuel (C_c) can be computed as 0,00235L/s. The octane's density (ρ_c) is 0,703kg/l at 25 °C (Moran and Shapiro, 2009).

$$C_c = \frac{V_{comb}}{721,8}$$

$$\dot{m}_c = \rho_c . C_c \quad => \quad \dot{m}_c = 0,0017 kg/s \qquad (7)$$

4.3 Parameters of the fifth and sixth stroke

From Figure 5 is possible to collect the additional MEP generated by the water injection and also the exhaustion gases temperature, both will be used to calculate exergy efficiency and net work of a six stroke engine.
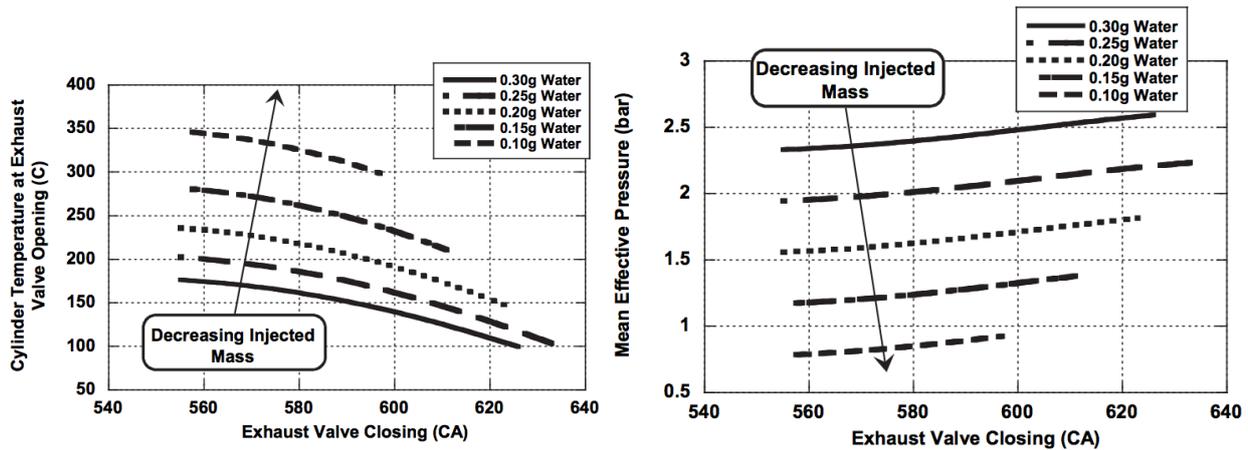
Figure 5. Temperature and Mean Effective Pressure due to the second expansion (Conklin and Szybist, 2010)

Table 1– Exhaust temperature and MEP addition due water injection at 100°C (Conklin and Szybist, 2010)

T (°C)	Water mass (g)	MEP$_{water}$ (bar)
146,2	0,1	0,71
177,8	0,15	1,25
200	0,2	1,67
253,7	0,25	2,07
326,9	0,3	2,43

Data from Tab. (1) is exclusively to an water injection temperature of 100°C, however Conklin and Szybist (2010) still make analysis for water injection temperatures at 25 °C and 175°C. They discover a decrease of 40% in the additional mean effective pressure when the vapour water is injected at 25 °C comparing to the temperature of 100°C, they also note an increase of 40% in the additional mean effective pressure when the vapour water is injected at 175°C over the temperature of 100°C. Figure 6 is generated by Tab.(1).
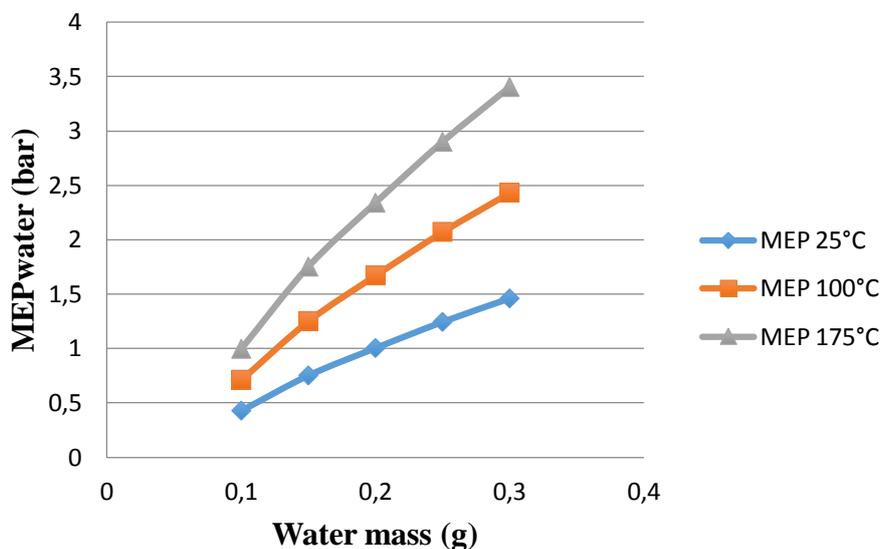

Figure 6. Additional MEP due to the injection of water vapour

Net work calculations are done by the Equation (4), hence is necessary to know some engine parameters showed on Tab.(2).

Table 2 – Engine parameters (Conklin and Szybist, 2010).

Piston diameter (d)	86 mm
Piston stroke (L)	86 mm
Number of cylinders (Ncil)	4
MEP	10 bar

Equation (4) may now be rewritten using data from Table (2).

$$\dot{W} = \frac{MEP.(0,00198).3000}{3} \quad => \qquad \dot{W} = 1,98MEP \tag{8}$$

In possession of the data required, one exergy analysis was performed in order to discover the exergy destroyed with different mass amounts of water injected and to analyze the net work gained due to water injection.

5. RESULTS

Based on the methodology described on this work, it was possible to compute some results. Figure (7) was plotted using Equation (5), (8), and Tab.(2).
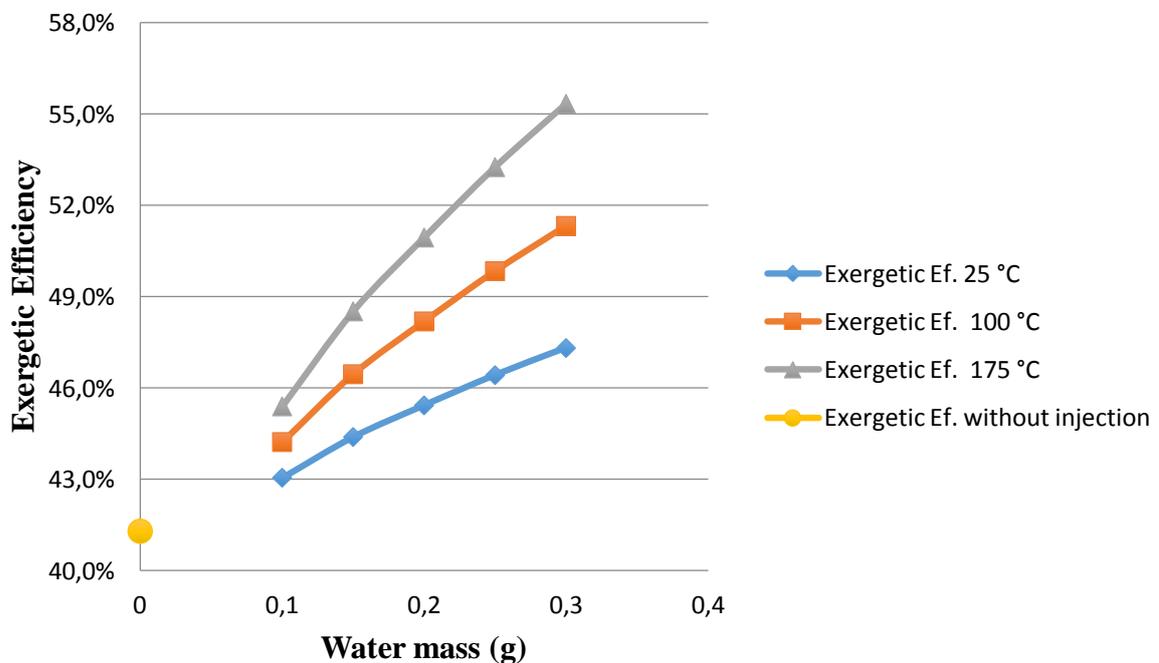

Figure 7. Comparison of six-stroke exergetic efficiencies to different temperatures of water injection and four-stroke engine without injection

The graph of Figure (7) shows that at higher temperatures there is an increase in the net work, therefore an increase of the exergy efficiency. This increase can be explained, as to achieve higher temperatures of water injection, exhaust

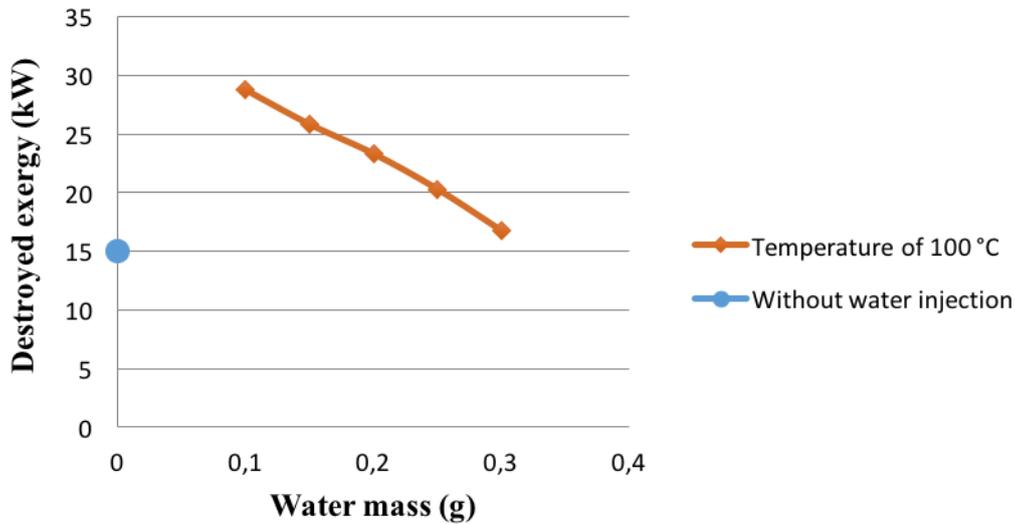gases are used to heat water, thereby it happens the recovery of a portion of exergy that would be lost.

Figure 8. Destroyed exergy comparison between a six-stroke engine at 100 °C water injection temperature and a conventional four-stroke engine

According to Figure (8), it is clear that the four-stroke engine has a lower exergy destroyed than the six-stroke one. Equation (3) shows that destroyed exergy is related to thermomechanical exergy, net work and chemical exergy, thereby the destroyed exergy is related to irreversible processes occurring in the engine (friction, heat transfer, expansion, compression, etc.). The six-stroke engine by water vapor injection has more processes involved due to the two additional strokes, so it has a destroyed exergy higher than that of combustion engines to four-stroke.

The lost exergy by the engine can be calculated by the sum of thermomechanical exergy and the exergy portion due to the heat lost by the engine.
Figure (9) was obtained in order to compare the lost exergy of a six stroke engine with 0.2g of water injection at a temperature of 100 ° C, with a four-stroke engine without water injection.
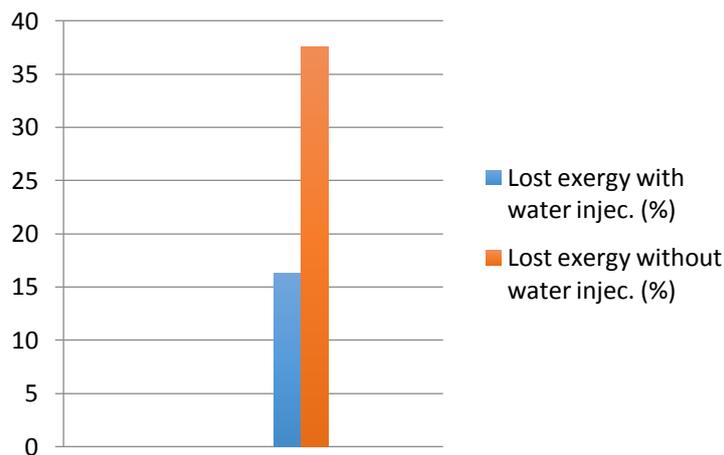

Figure 9. Comparison of lost exergy in relation to the total exergy between a six-stroke with water injection and temperature of 100 ° C, and a four-stroke engine.

According to Figure 9, the four stroke engine loses about 37.5% of the exergy, which is 33.26 kW, whereas the six-stroke engine loses only 16.2% of the total exergy totaling 16.12 kW. Although the four-stroke engine having a smaller destroyed exergy than the six-stoke, it presents upper lost exergy in more than 100%, this fact is justified because the six-stroke engine has higher exergetic efficiencies, regardless of the amount of water injected.

6. FINAL CONSIDERATIONS

Using a thermodynamic analysis, it was realized an increase in the exergetic efficiency of up to 14% achieved through the additional cycle power carried by the water injection engine that uses heat from the exhaust gas not only to achieve a further expansion which produces an extra cycle power but also for preheating the injected water.

There was a reduction of 21.3% of the lost exergy, this reduction was achieved because the exergy of the products is lower in the six-stroke engine, since the products come out at a lower temperature than in four-stroke engine. The loss of heat and cooling are also lower in the six-stroke engine, a fact that also contributes to the reduction of lost exergy. The reduction in lost exergy is something significant, because unlike the exergy destroyed, it can be reused in some way.

The destroyed exergy in six-strokes engines increased up to 17%, a fact that can be explained due to the number of additional processes carried out during the six-stroke engine cycle, resulting in increased friction losses and heat transfer. However, there is a reduction of lost exergy as there is addition of net work due to water injection which makes the exergetic efficiency of six-stroke engines higher than that of four-stroke ones regardless of the amount of water added.

It can be argued that the six-stroke engine has the potential to make significant gains in exergetic efficiency which results in a better utilization of the exergy released by the fuel.

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