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THERMODYNAMIC MODELLING OF A POWER GENERATION STEAM ENGINE

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Abstract. *During the industrial revolution steam engines were the main responsible for the increase in production capacity and were used in the most diverse applications. When it comes to power generation, its efficiency for small power plants (between 75 kW and 5 MW) may exceed that of other renewable energy sources such as hydric, solar and wind. Considering that the raw material used in the boiler can be biomass or industrial waste such as rice husk, its operational cost also becomes competitive. In this context, the use of steam engines is a viable alternative in remote areas. Steam engines work by expanding the superheated fluid in the working chamber, which have their intake and exhaust through windows. Thus, its evaluation to optimize the opening and closing points of the windows and ideal operation conditions are necessary. In this sense, a computational model was developed for thermodynamic analysis to determine the ideal operation points and steam cut-off. A steam engine with a displacement of 15.6 L and fed by 1400 kg/h of superheated steam at 498 K and 1.50 MPa of pressure was modeled. The target power considering the capacity of the generator was approximately 75 kW, which was achieved with the steam cut-off occurring at 43.5° crank angle after top dead center. It was possible to increase this power by changing the cut-off points, but at the expense of thermal efficiency. The thermodynamic efficiency of the real engine based on the second law was found at 8.59%. The simulated parameters were found at 8.37%, 75.75 kW and 1392 kg/h for thermal efficiency, engine brake power and steam mass flow rate, respectively.*

Keywords: *Steam engine, Renewable source, Microgeneration, Thermodynamic system, Computational simulation.*

1. INTRODUCTION

The International Energy Agency (IEA) has published their World Energy Outlook 2017 report (International Energy Agency, 2017), revealing there will be a 30% growth in energy demand by 2040, which corresponds the addition of another China and India to the current world energy demand. In this scenario, the use of fossil fuels is becoming more restrict due to environmental issues caused by greenhouse gases emissions. Therefore, the development of new technologies that provide a more efficient energy production or the improvement of the current technologies efficiencies are proving increasingly necessary (IPCC, 2007).

The European Union in the attempt of ensuring energy supply, competitiveness and sustainability, has a policy with established brands to become a sustainable economy with low carbon emissions. The goals for the next decades include a minimum renewable energy contribution of 27% in the total energy matrix and the 30% increase of energy efficiency (Union, 2017).

In 2015 in the Intergovernmental Panel on Climate Change 121 countries benefited from high solar incidence signed the International Solar Alliance (ISA). The purpose of the agreement was to deploy solar power technology in developing countries and it aimed to implement financial instruments to mobilize over US$ 1 trillion in solar energy investments by 2030 (Macron, 2018; UOL, 2018).

In this energy and environmental panorama the employment of steam engines can be a competitive alternative due to the possibility of applying renewable energy and wastes (such as bagasse, rice husk and other wastes) as heating sources for steam generation. The steam engine is a machine that converts thermal energy into mechanical energy throughout the working fluid vapor (HAWKINS, 1904). Its emergence was due to the need to produce useful work for the pumping of water in the mining. The concept has evolved throughout the centuries thanks to the patents developed by James Watt, which converted the reciprocating piston motion into rotating motion through a crank-connecting rod mechanism. This contributed to its application in the transport and industrial segment (Amengual Mata & Saiz González, 2007).

The use of reciprocating steam engines for power generation has been successfully employed in small-scale power plants (less than 5 MW) worldwide (Bidini, Manuali, & Saetta, 1998). It stands out because of their simplified mechanical system, low periodicity of maintenance and ability to efficiently work at part–load. Given these facts, the study of steam engines is still relevant particularly for power generation in standalone regions under great solar incidence (the case of Brazil, for use with thermal collectors) or heat extraction from biomass combustion in boilers. (Bouvenot et al., 2014).

1.1 Thermodynamic fundamentals applied to thermal machines

Thermal machines perform the conversion of heat into mechanical work. This occurs when a heat source carries a working substance from a low temperature state to a higher temperature state. The working substance (usually gas or vapor in thermal expansion) transfers this energy through its expansion inside closed system by actuating the mechanical parts (piston, rotor or other) and performing work. From the work and heat supplied and / or removed from the system it is possible to find its thermodynamic efficiency as it follows:

$$\eta = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H} \tag{1}$$

In the case of external combustion engines such as steam engines, the use of the First Law of Thermodynamics is made difficult when the boiler boundary conditions are not known (intake and exhaust pressures and temperatures). The Second Law of Thermodynamics with respect to thermal efficiency is based on the irreversibility of the system. It can be described in the following equation:

$$\psi = \left(h - T_0 s + \frac{1}{2}V^2 + gZ\right) - (h_0 - T_0 s_0 + gZ_0) \tag{2}$$

The thermal efficiency by the Second Law of Thermodynamics describes how much of the maximum thermal energy was used, that is, how much of the Carnot´s efficiency is being achieved by the system. If we analyze an ideal machine the thermal efficiency by the Second Law would equal the Carnot efficiency as follows:

$$\eta = \frac{W}{(h - h_0) - T_0(s - s_0)} \tag{3}$$

1.2 Thermodynamic steam engine cycle

The thermodynamic cycle is the series of processes where the variation of the thermodynamic quantities of the system is zero. Under the Energy Conservation Law, the sum of heat and work received by the system must be equal to the sum of heat and work carried out by the system.

The thermodynamic cycles are used to understand the behavior of the stages (admission, compression, expansion and exhaustion) that involve a complete engine cycle. Figure 1 shows a theoretical thermodynamic cycle of a steam engine, where "steam cut off" is the end point of steam injection and "point of exhaust release" is the beginning of steam exhaust.

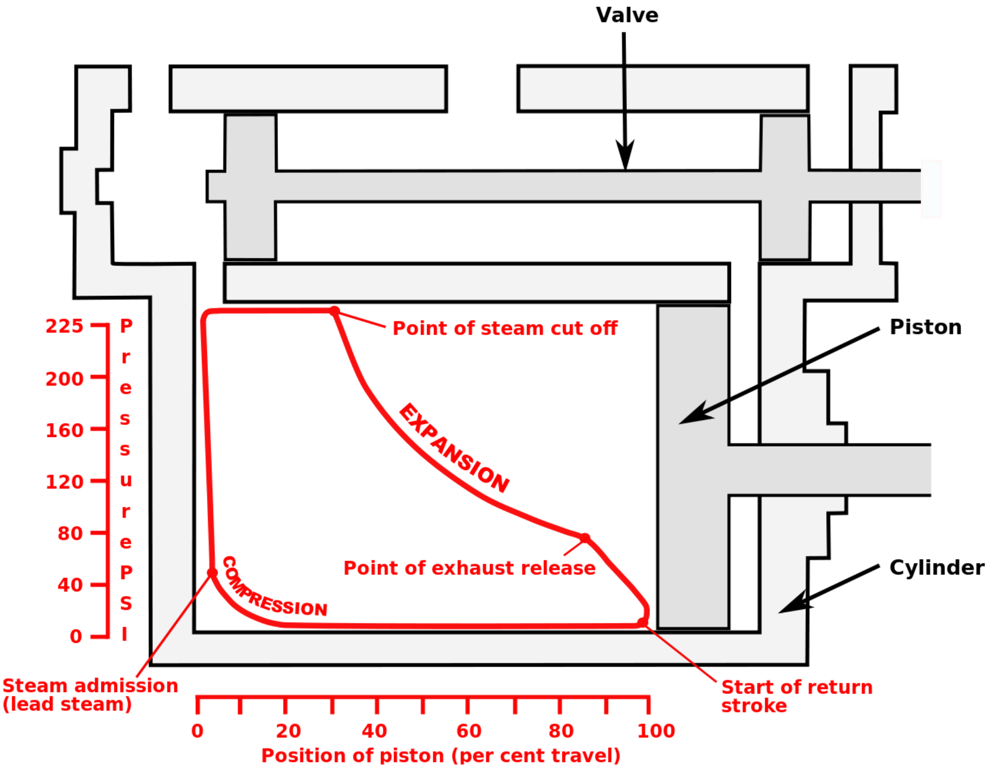

Figure 1. Theoretical diagram of pressure by volume of a steam engine to the piston. Source: Handbook for Railway Steam Locomotive Engineman (1957).

The efficiency of steam engines is related to a series of factors, such as steam inlet pressure, temperature, admission and exhaust timings and structural dimensions, since heat transfer rely on the volume-surface relation. Performance data of a steam engine powered by a wood-fired boiler system is presented in (Prasad, 1995), the study showed an engine efficiency variation of 13.0-18.0% operating in the range of 15.95-33.08kW. Another study (Dellicompagni, Franco, Altamirano, & Hongn, 2015) approached a steam engine of double effect, with 12.64kW of maximum power and found an efficiency about 21.0%. Also, (Müller & Parker, 2015) investigated the atmospheric steam engine with forced expansion and the results showed an engine efficiency of 10.2%.

2. METHODOLOGY

A computational model of the cycle was developed on GT-Power and fed by the geometric characteristics of the CAD drawing and from the data provided by the manufacturer (table 1).

Table 1. Steam Engine Outline Conditions

Brake Power [kW]	75
Steam mass Flow [kg/h]	1400
Inlet Temperature [K]	498.15
Inlet Absolut Pressure [MPa]	1.5
Exhaust Absolut Pressure [MPa]	0.15

The inlet and exhaust pressures are absolute, and the intake vapor is in the overheating zone. Duct lengths and valve times for steam inlet and exhaust were measured so that the computational model would approach the maximum of the real model. In addition to the geometric data several other factors had to be estimated such as: discharge coefficient of the valves, cylinder wall temperature, fluid outlet environment and coefficients of friction. Figure 2 is the final model 1D.

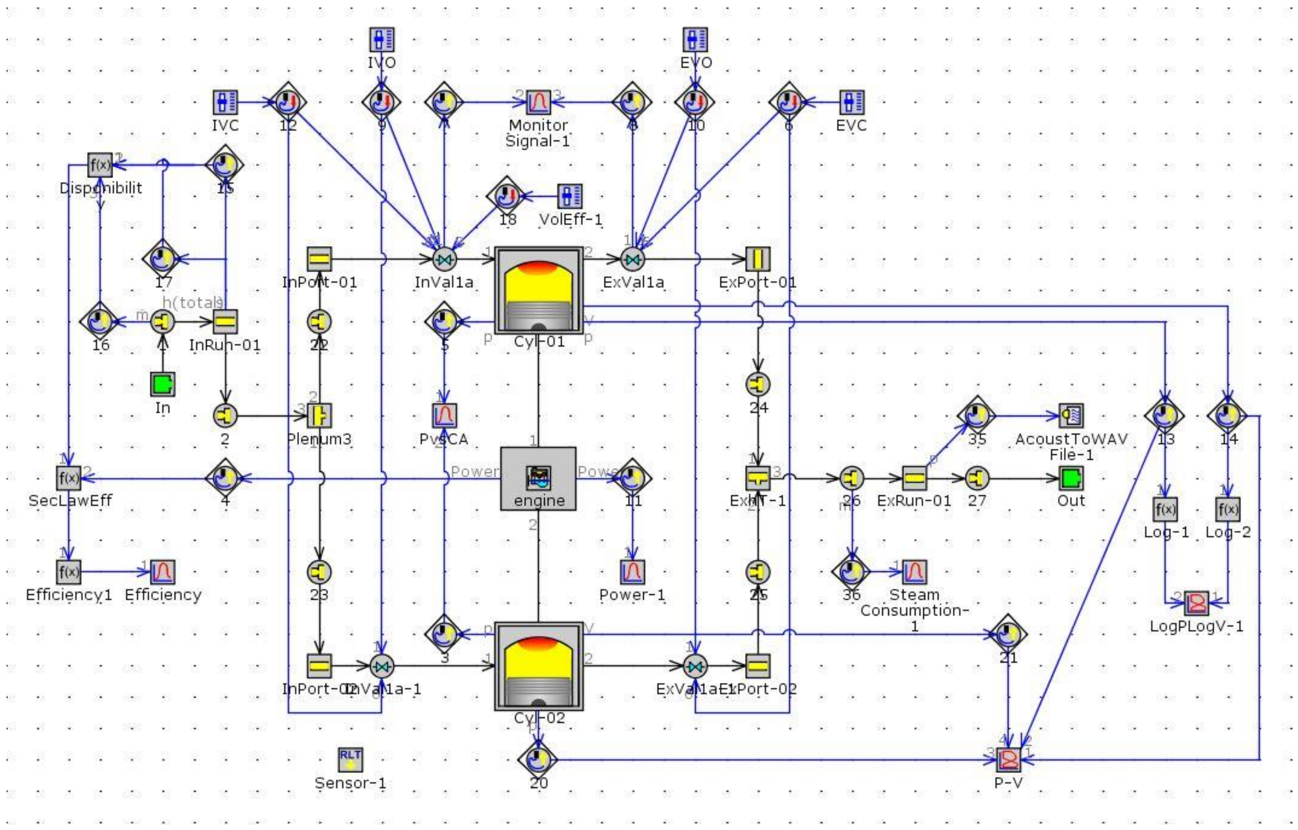

Figure 2. 1D computational model in GT-Power software

The parameters of the steam engine from the thermodynamics fundamental view were solved analytically based on the previous equations and they were used as the bottom line to know the expected maximum values for the thermodynamic cycle. The values used in the equations are shown in Table 2.

Table 2. Analytic equations input values.

Brake Power [kW]	75
Steam mass flow rate [kg/h]	1400
Reference enthalpy [kJ/kg]	105.76
Reference entropy [kJ/kg K]	0.3669
Reference temperature [K]	298.15
Inlet enthalpy [kJ/kg]	2862.93
Inlet entropy [kJ/kg K]	6.5915
Inlet temperature [K]	498.15

The thermal efficiency according to the Second Law of Thermodynamics could be derived.

$$w = \frac{\dot{W}}{\dot{m}} = 75 \Big/ \left(\frac{1400}{3600}\right) = 192.857 \frac{kJ}{kg} \tag{4}$$

$$\eta = \frac{w}{(h - h_0) - T_0(s - s_0)} = \frac{192.857}{[(2862.93 - 105.76) - 298.15(6.5915 - 0.3669)]} = 21.4\% \tag{5}$$

And the Carnot efficiency.

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H} = 1 - \frac{298.15}{498.15} = 40.15\% \quad (6)$$

So, the thermodynamic efficiency of the steam engine can be calculated.

$$\eta_{termodinâmica} = \eta_{2°Lei}\ x\ \eta_{Carnot} = 0.214\ x\ 0.4015 = 8.59\% \quad (7)$$

3. RESULTS

Through the computational model it was possible to find the opening and closing points of the intake and exhaust windows, thermal cycle efficiency, steam engine power and mass flow rate (Table 3).

Table 3. Results of the computational model.

Opening window [°]	0
Admission window closing [°]	43.5
Exhaust window opening [°]	151
Exhaust window closing [°]	-46.5
Thermal efficiency [%]	8.37
Power of the steam engine [kW]	75.75
Mass flow[kg/h]	1416.5

The timing for the intake closure and the exhaust window opening were found, respectively, at 43.5°ATDC and 46.5°BTDC which is close to the literature (Ferrara, Manfrida, & Pescioni, 2013). The relationship between the exhaust and intake timings is a compromise between engine output and efficiency and can be related to the parameters of steam engines such as cut-off ratio and expansion ratio. Giving the importance of such, the cut-off point, which represents the load of steam injected in the cycle, when increased enhances the power output at the expense of a decrease in engine efficiency. On the other hand, the continuous increase in the injection of steam when it is further from the optimum point represents the loss of power output. Looking for the target power output of approximately 75 kW which is the capacity of the generator, the cut-off ratio could be obtained through the computer simulation occurring at 43.5°ATDC as it is shown in the figure 3 on the pressure-volume.

The divergence between the analytic calculation and the computational model is shown in table 4.

Table 4. Divergence between the computational model and the results obtained by the manufacturer.

Thermal efficiency difference [%]	1.03
Steam engine power difference [%]	1.27
Mass flow rate difference [%]	1.16

The power output from the simulation was found at 75.75 kW which is slightly higher than the nominal power of the generator. Giving the operation conditions and the objective of reaching a certain power from the engine, the thermal efficiency from computational model was lower in comparison with the analytic results. Which is in accordance with the theory, since there is a trade-off between enhance of power and consequently reduction of efficiency, (Ferrara et al., 2013).

As it is shown in figure 3, the area of both cylinders on the diagram is not equal, therefore the work produced by the upper half is slightly greater in comparison with the lower chamber. This can be best explained by the structural characteristics of the engine design, which comprises one piston driven by the rod that separates the upper and the bottom chambers. The volume displaced by the piston in the upper chamber is greater than the bottom one due to the volume occupied by the rod. It should be stated that both traces showed in the p-v diagram represent independent processes, illustrating the counter motion of both cylinders. One might think there is a negative work produced in the lower chamber, but such is not the case since their traces are plotted as reversal for better understanding of the double effect of the piston.

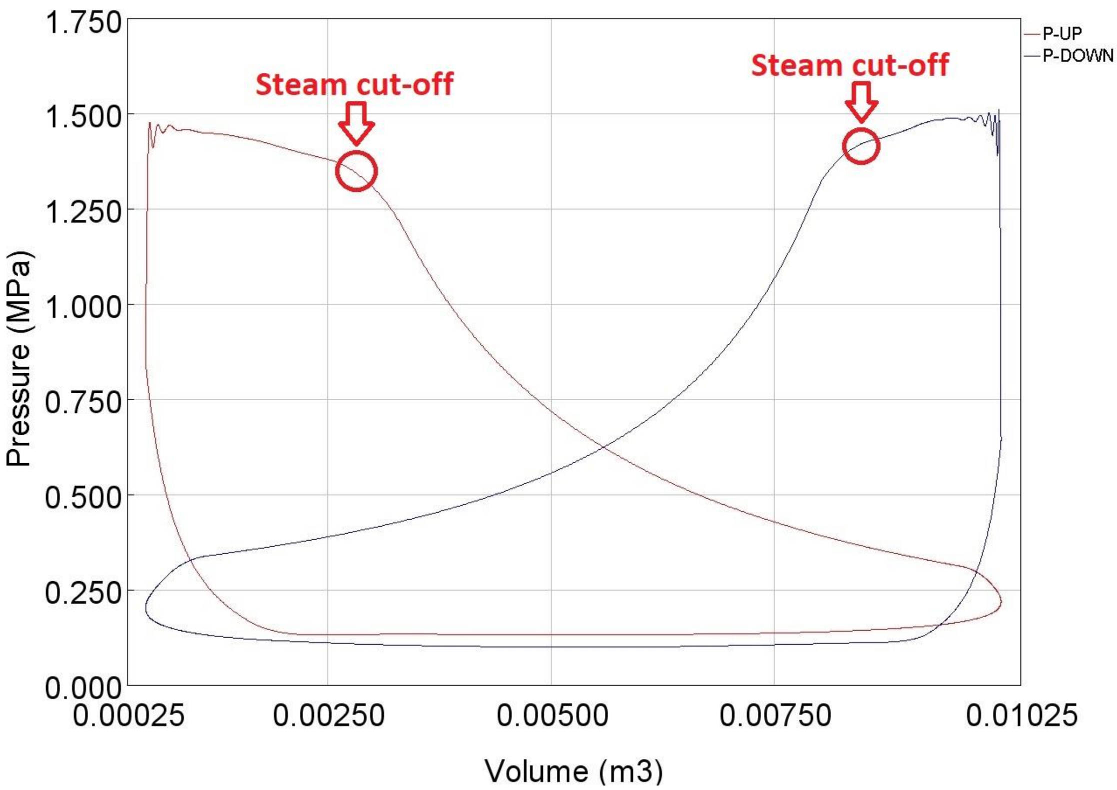

Figure 3. Pressure-volume diagram.

4. CONCLUSIONS

From the computational data obtained it is possible to notice the reliability of the thermodynamic model built and its correspondence to the real engine expected performance. Through the simulation it was possible to estimate the cut-off ratio which provided the rated power of 75.75 kW and its window timing. The error of the thermodynamic model for simulation can be considered extremely low which shows the high correlation between the real engine and its model.

The calculated second law efficiency is about one third of the Carnot efficiency, which represents the maximum output that can be reached from a thermal machine operating between two stated temperatures. This engine efficiency could be improved, if so desired, by the increment on the steam inlet temperature and pressure, although the power performance may be reduced. Even though the condenser is not approached in this paper, it is known that its pressure affects the parameters of performance and efficiency of a steam engine and it could be exploited for further improvement.

The thermal efficiency obtained in this work couldn't meet the expected values held by the literature of reciprocating and double effect steam engines. Considering the divergence between the computational model and analytic calculation, the engine's efficiency didn't exceed 8.6%, which is corresponding in magnitude to atmospheric steam engines reviewed in the literature. Although the efficiency obtained is lower in comparison to engines with similar design, it must be stated that the objective was to target the required power output of 75kW and the optimization of the efficiency was not the priority of this paper.

Considering the thermodynamic model as satisfactory and well representative of the real engine, it could be a useful tool in terms of further improvement of the engine. I.e., the possibilities provided by the computer simulation allows the input of several conditions and variables that affect engine performance, whether the objective is the maximum power output, efficiency or the best synergy between them.

5. ACKNOWLEDGEMENTS

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