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THE IMPACT OF HFO VISCOSITY AT THE AUXILIARY EQUIPMENT ENERGY CONSUMPTION OF MARINE ENGINES AT THERMOELECTRIC POWER PLANTS

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Abstract. *The use of marine engines for energy production is an excellent alternative to meet the instantaneous demand variations because of the possibility of fast starting and its simple and reliable operation. Consequently, several countries use this technology to supply the energy demand when other sources are not able to deliver the requested power. During the operations, marine engines consume heavy fuel oil (HFO) due to the low cost and high usage. However, this fuel presents a great viscosity variability, impacting on the power consumption of the auxiliary equipment that prepares the HFO to be injected in the engine, as well as on the main engine performance. The study was developed using a model that quantifies the thermal and electrical energy consumption of the auxiliary equipment and defines, through logical control, the configuration that represents the lowest consumption of these machines and the highest global efficiency of the power plant. The auxiliary systems presented a high overall energy efficiency and it was possible to observe scenarios with satisfying results, indicating gains on the usage of controls to adjust the operations based on the viscosity and operational demand.*

Keywords: *Marine Engines, Fuel, Viscosity*

1. INTRODUCTION

The energy generation by thermoelectric power plants is an alternative that aims to complement the electricity supply when the main energy production sources are not able to meet the demand. Marine engines are the technology employed due to the capacity to deliver the demanded power in a flexible way, with fast activation and constant production. On account of their high fuel consumption, most marine engines use heavy fuel oil (HFO) for its economical aspect. However, HFO greatest disadvantage lies in the high polluting gas emissions. Additionally, the measurement of particle emission during HFO combustion has been the focus of researches (Anderson et al., 2015).

Since it is crude oil, HFO is highly viscous and needs to achieve different temperatures at each stage of the system (i.e. storage, treatment, engine injection), thus varying its viscosity and avoiding equipment damage. Park et al. (2015) carried out experiments to investigate the dependence between temperature and physical properties of HFO, evaluating the effects on fuel injection and spray development. The study showed that fuel density decreased linearly as the temperature increased and that the quantity of fuel injected on the combustion chamber and also the delay of the injection were both reduced at high temperatures. Zhou et al. (2017) conducted studies via sensitivity analysis to investigate the effects of HFO properties on spray and combustion of marine engines. The variation of ambient pressure and temperature can affect the global performance of the engine, as it can influence the penetration, density and fuel evaporation (Zhou et al., 2017).

This work analyses the impact of HFO viscosity variations on the marine engines and auxiliary system energy consumption, applied at a thermoelectric power plant. Previous studies were carried out at this power plant, aiming to achieve higher efficiency by increasing the available power (Lira Jr. et al., 2017). The work used a mathematical model to evaluate the influence of the cooling water and the admission air temperatures on the delivered power and energy efficiency of the marine engines. In another study taken at the same plant, Henríquez et al. (2017) simulated the potential for residual energy recovery in different technological scenarios concerning its destination. The results showed that in all the configurations there were significant gains and efficiency increase of the power plant.

The present study was driven by a mathematical model that optimizes the energy consumption of the auxiliary equipment (e.g. centrifugal pumps) by minimizing the difference between the demanded fuel input of the main engine and the flow delivered by auxiliary systems. The validation of the model took place at the Suape Energia power plant. Despite the small percentage of gains in absolute terms, this value is very significant due to the high engine energy consumption.

2. MATERIALS AND METHODS

This section presents the materials and the methodology to assess the impact of HFO viscosity at the auxiliary equipment energy consumption of marine engines at thermoelectric power plants.

2.1 Suape Energia Thermoelectric

Thermoelectric power plants use the heat released by the combustion to generate electrical energy. This thermal energy can be indirectly used to produce high-pressure steam which then expands, generating mechanical energy to move a steam turbine. On gas turbines, the thermal energy is used directly by the expansion of the exhaust gases. Additionally, it can also be used to move the pistons inside a cylinder, in the case of internal combustion engines.

Suape Energia is a thermoelectric plant located at Suape port terminal, in Cabo de Santo Agostinho, Brazil. Its services include generation, supply and distribution of electric energy. The plant consists of seventeen Wärtsilä 20V46F marine engines, distributed in three machinery rooms, totaling 381.2 MW of installed capacity. The power plant installations can be seen in Figure 1.

Figure 1. Suape Energia power plant. Available from: http://www.suapeenergia.com.br/quem-somos.html.

2.2 Fuel Oil System

The present work was taken at a marine engine fuel oil system of a thermoelectric power plant. A basic flowchart is shown in Figure 2. The system starts receiving fuel oil from four stations with two pumps each, which will forward it to storage tanks. Then, HFO is sent to a transfer system, consisting of two stations of three pumps and one heat exchanger to maintain the ideal fuel temperature. Subsequently, the fuel oil is stored in buffer tanks and moved to the separation system, which consists of four stations of three pumps, three heat exchangers and three separators. There, the fuel is treated and sent to two daily tanks. HFO is then conducted to three engine rooms, of which two are made up by six engines and the other one, five.

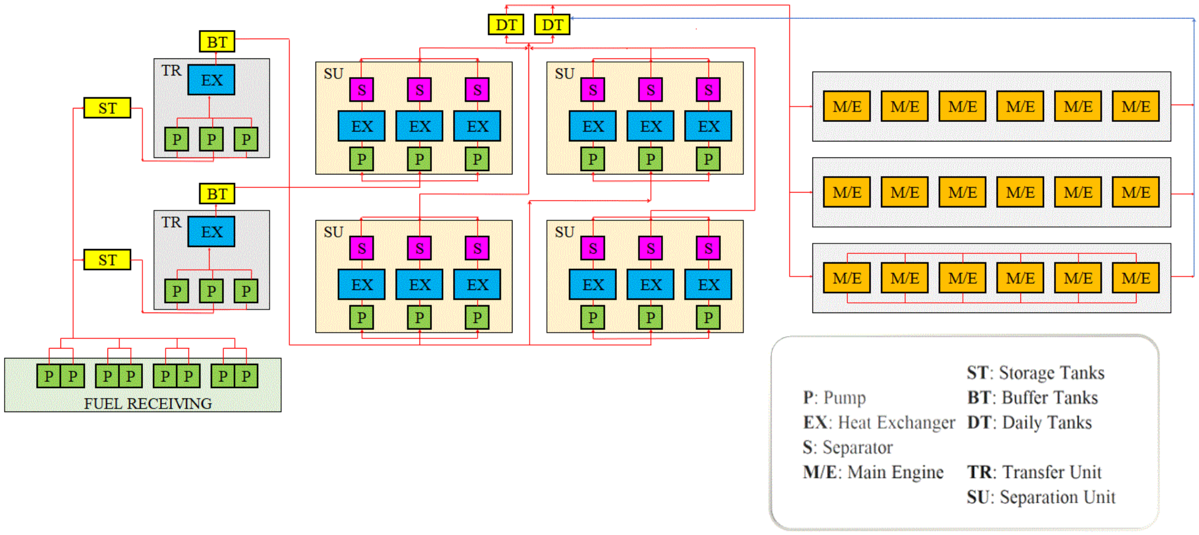

Figure 2. Basic flowchart of the system

2.3 Model Development

The used methodology for the development and parameterization of the mathematical model is presented in this topic.

2.3.1 Database

Data regarding the operation of the fuel oil system was collected in order to initiate the mathematical model construction. Additionally, the specification of the equipment (e.g. engines, pumps and heat exchangers) was obtained from catalogs. The model implementation was made through the creation of equipment curves of each subsystem of the plant as a function of HFO viscosity.

Figure 3 and Figure 4 show the flow rate and power, respectively, of the pumps as a function of HFO viscosity. Each curve represents a pressure difference in kPa.

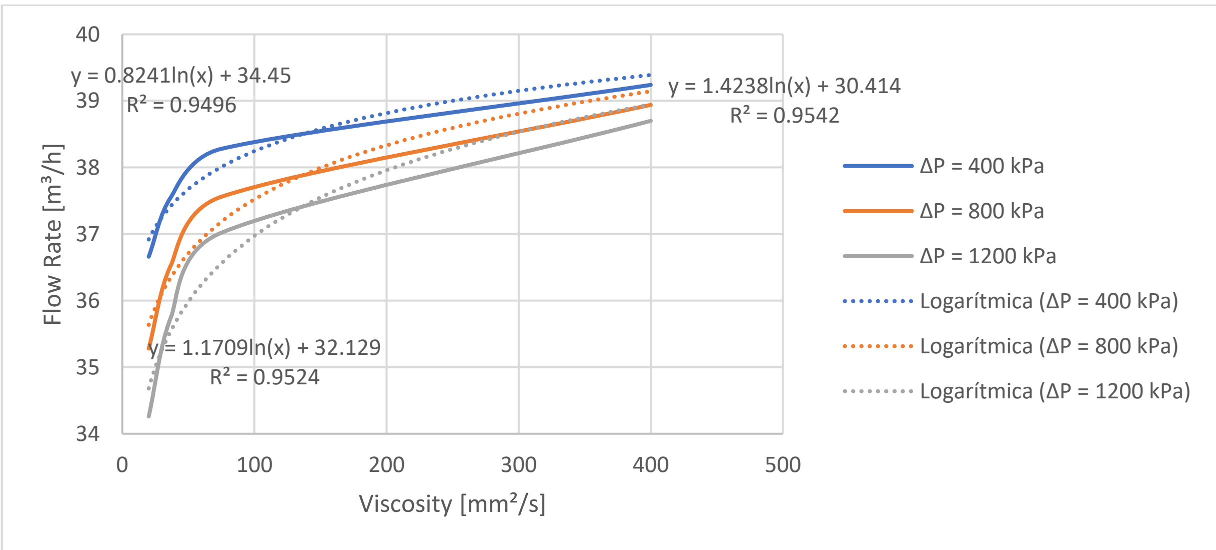

Figure 3. Flow rate (pumps) x Viscosity

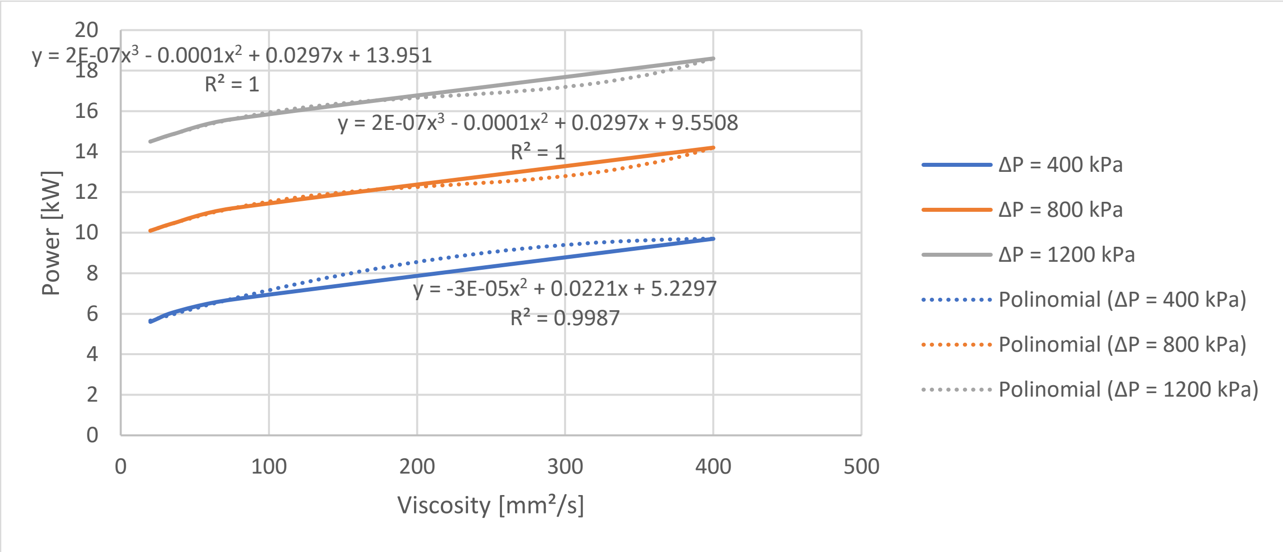

Figure 4. Power (pumps) x Viscosity

The provided pump data from the manufacturers have a significant variable profile at a viscosity value under 100 mm²/s, interfering with the adjustment of the curves with the generated data. Thus, it was not possible to obtain a higher correlation index, as shown in Figure 3.

Another important parameter for the model construction is the viscosity of the HFO and how this physical property behaves as a function of the temperature. Figure 5 shows a graph obtained from the manufacturer catalog, and it represents the ideal temperatures for each stage (e.g. storage, transfer, treatment and circulation) of the HFO in the system.

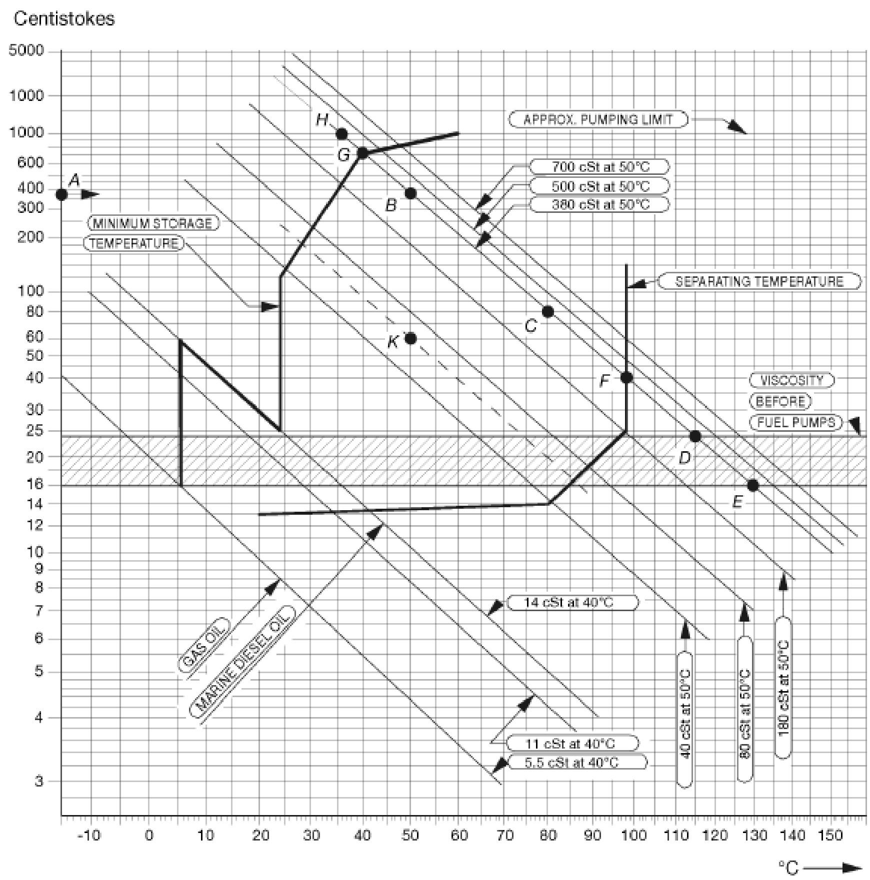

Figure 5. Fuel oil viscosity as a function of the temperature. Source: Wärtsilä, 2007

The points of the graph were taken and used as input in the software Graph, resulting in curves as shown in Figure 6. The curves represent HFO viscosities of 700, 500, 380 and 180 mm²/s, at the receiving unit.

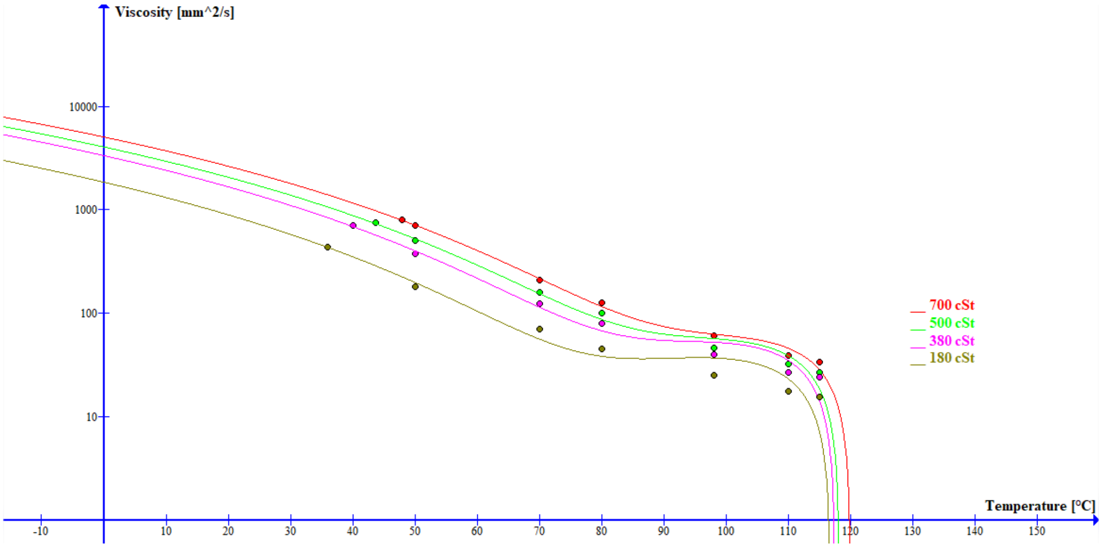

Figure 6. HFO viscosity-temperature curves plotted on *Graph*

The following equations were obtained for fuel viscosity values of 700 Eq. (1), 500 Eq. (2), 380 Eq. (3) and 180 Eq. (4):

$$f(x) = -0.0049911341x^3 + 1.4894017x^2 - 149.07187x + 5065.1994;\ R^2 = 0.9992 \quad (1)$$

$$f(x) = -0.0043938457x^3 + 1.2711533x^2 - 123.17707x + 4055.5299;\ R^2 = 0.9972 \quad (2)$$

$$f(x) = -0.0039040471x^3 + 1.1041709x^2 - 104.30673x + 3344.4293;\ R^2 = 0.9971 \quad (3)$$

$$f(x) = -0.002418626x^3 + 0.66093273x^2 - 60.053999x + 1851.019;\ R^2 = 0.994 \quad (4)$$

Additionally, it is important to consider the steam consumption of heat exchangers. The values from the saturated steam table (

Table 1) were used to plot curves and obtain equations for the steam saturation energy for a given pressure. The curve is shown in Figure 7.

Table 1. Enthalpy and internal energy of saturated steam. Source: Çengel; Boles, 2013.

Pressure [kPa]	Enthalpy [kJ/kg]	Internal Energy [kJ/kg]
0.6	2501.3	2375.3
1	2514.2	2385.0
1.5	2525.3	2393.3
2	2533.5	2399.5
2.5	2540.0	2404.4
3	2545.5	2408.5
4	2554.4	2415.2
5	2561.5	2420.5
7.5	2574.8	2430.5
10	2584.6	2437.93
15	2599.1	2448.7
20	2609.7	2456.7

25	2618.2	2463.1
30	2625.3	2468.4

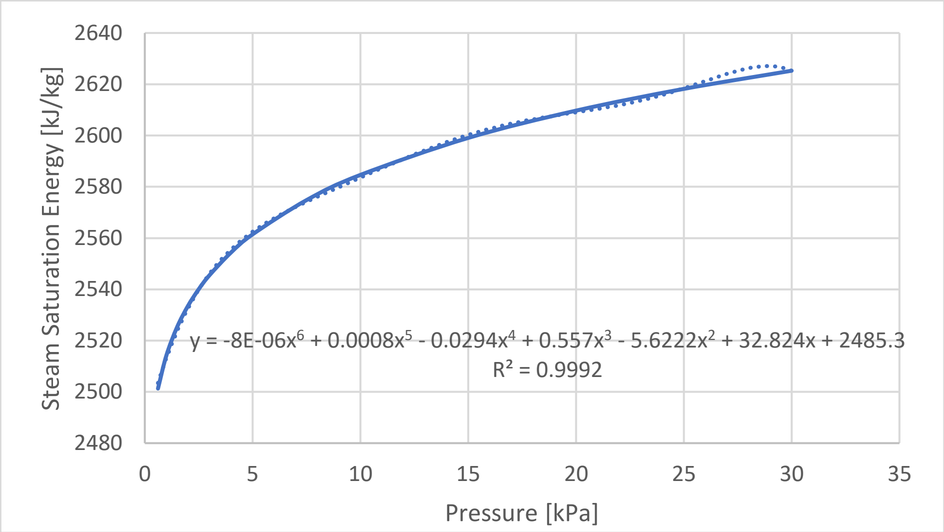

Figure 7. Steam Saturation Energy

After obtaining the curve and the flow rate of the equipment, the consumption of steam can be estimated by Eq. 5.

$$\text{Consumption}_{\text{Steam}}[\text{kg/h}] = \frac{\text{Flow Rate}_{\text{Steam}}[\text{kJ/h}]}{\text{Energy [kJ/kg]}} \quad (5)$$

In Eq. 5, the term $FlowRate_{steam}$ is obtained from the required energy to heat the fuel oil, and *Energy* denotes the steam saturation energy.

2.3.2 Model Operation

The optimization of the system was made through *Solver* supplement, enabling simulations and hypothesis tests in different scenarios. It runs by placing an objective cell, while the variable parameters are modified until the ideal situation is achieved, maintaining the imposed restrictions. In the present case, the objective was to reach the minimum difference between the delivered fuel flow by the auxiliary system and the main engine demanded flow. For that, auxiliary system parameters were changeable within a restricted range of values.

The model aims to reach the smaller difference between the flow delivered by the pumps of the separation system and the consumed flow of the engines, to guarantee that there is no production surplus. This objective will be achieved through the control of the equipment operation, which has a functioning variable that indicates if the equipment is running. Each subsystem has at least one equipment that will be used to supply the demand in an interval of 20 to 100% of its operation.

Restrictions were imposed on the model variables in order to guarantee the optimal configuration of the system. These restrictions are related to the equipment functioning and they delimit the interval on which each equipment may operate at a given engine fuel demand.

2.3.3 Model validation

To validate the model, comparison tests were carried out between operational data from the power plant at 700cSt and the optimized model, in order to demonstrate the pumps consumption difference in each case and enabling a parametric analysis.

3. RESULTS AND DISCUSSION

The total consumption of the auxiliary equipment is shown in Figure 8. In total, 68 cases were simulated, considering each viscosity for each number of running engines. As expected, the behaviour of the curves indicates that the higher the viscosity, the lower the energy consumption. The higher the number of running engines, the flow rate from the pumps increases, consequently its demanded power. However, the pumps operate in higher efficiency and in less time to meet the oil volume demand, meaning that the total consumption will be lower. This can also be seen from Figure 4, where the pump power is higher when the viscosity decreases at higher flow rate output.

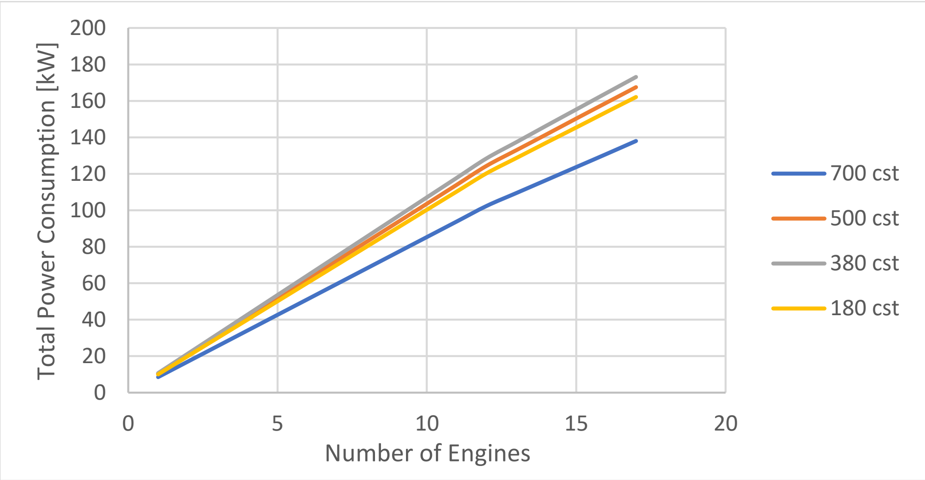

Figure 8. Auxiliary Equipment consumption as a function of the number of running engines, for each analysed viscosity.

Another visualization of the results is shown in Figure 9, where the power consumption is a function of the viscosity and each curve represents the number of running engines.

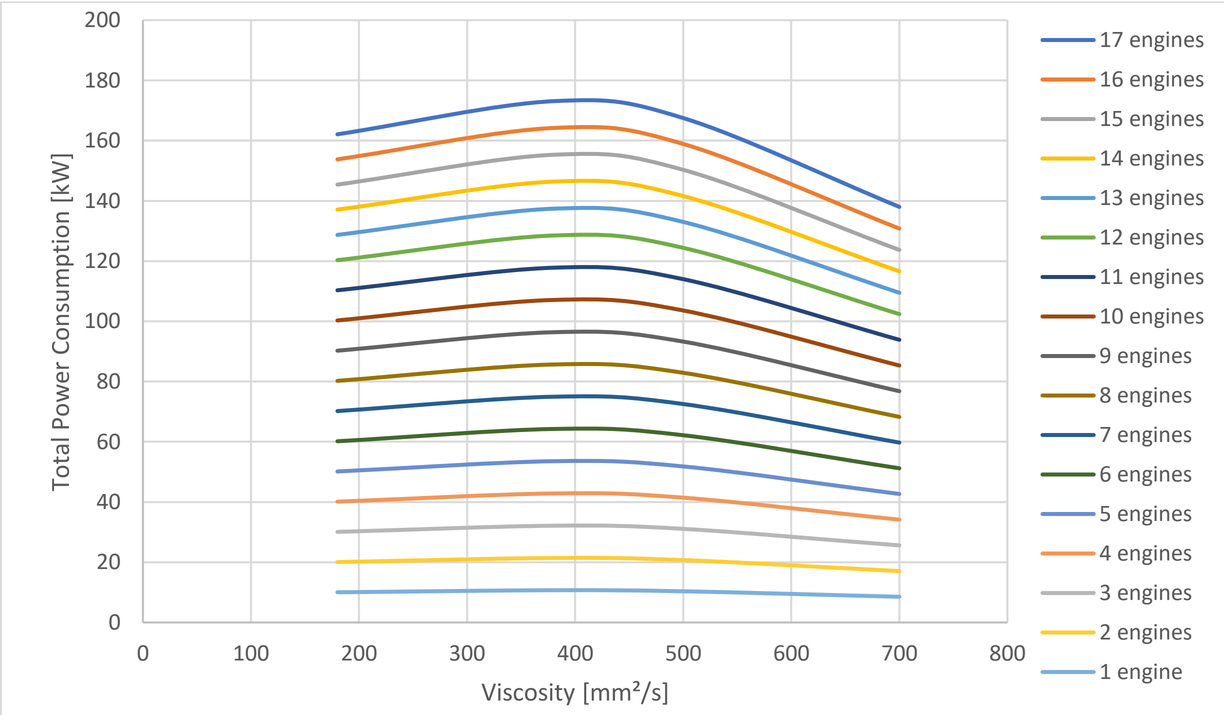

Figure 9. Total power consumption as a function on the fuel viscosity for each number of running engines.

The curves present a parabolic behaviour with the increase of functioning engines, meaning that the power consumption varies with the viscosity. To that end, the influence of the viscosity on the Reynolds number and the friction factor f (dimensionless) was analyzed, aiming to find its impact on the pressure drop considering an average flow speed of 1 m/s and a flow rate of 100 m³/h, for 100 m of pipes (a standard commercial value to quantify pressure losses in pipe sections). The results are shown in the table below.

Table 2. Pressure drop results for each viscosity value

Viscosity [mm²/s]	Reynolds	f	H [m]	Pressure [kPa]
700	268.66	0.238	5.165	50.649
500	376.13	0.170	3.689	36.178
380	494.90	0.129	2.804	27.495
180	1044.80	0.061	1.328	13.024

Based on Tab. 2 results, the pressure loss is higher for fluids with greater viscosity. However, this variation is negligible on the flow rate curves of the pumps. This can be seen from Figure 3, where a higher variation takes place at viscosity values smaller than 180 mm²/s. In conclusion, even though it will result in higher consumption, a differential pressure caused by the viscous fluid will not affect the operation efficiency of the auxiliary equipment, since the required operation time will decrease in order to achieve the demanded flow rate output.

4. CONCLUSION

As proposed, the study shows that a variation on the fuel oil viscosity has an influence on the flow rate of the auxiliary equipment, thus on its energy consumption. Considering the real operation condition, such impact is mitigated by the temperature control of HFO at each stage of the process, therefore enabling the temperature adjustment throughout the fuel preparation system. A detailed knowledge of the variations, however, would enable a better adjustment of the conditions to ensure a lower energy consumption.

It is suggested, as a complement, a study considering a transient analysis, which would allow the evaluation of the autonomy of the system. Additionally, a model parameterization including the impact of the fuel viscosity variation on the steam consumption of the plant is proposed as future work.

5. ACKNOWLEDGEMENTS

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