1-D COMPUTATIONAL MODELING AND SIMULATION OF A MWM 229.4 DIESEL ENGINE OPERATING WITH BIODIESEL AND ETHANOL

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Abstract: This work analyzes the performance of the MWM 229.4 diesel engine in a 1-D computer simulation with biofuels B20 (20\% biodiesel and 80\% diesel, v/v) and D72B18E10 (18\% biodiesel, 10\% ethanol and 72\% diesel, v/v). The environmental impacts from fossil fuels has driven interest in renewable alternatives for sustainable energy to replace petroleum derivatives in thermal engines. A 4-stroke 3.92L diesel engine was modeled and validated in order to evaluate the engine's torque, power, fuel consumption and thermal efficiency. The results showed that B20 and D72B18E10 had slightly lower performance compared to pure diesel due to their properties such as lower calorific value and cetane number. However, the presence of oxygen in the mixtures improved the quality and efficiency of combustion, resulting in greater thermal efficiency in some operational conditions.

Keywords: Biofuels; Diesel Engine; Internal Combustion Engine; Numerical Modeling and Simulation; Thermal Efficiency.

MODELAGEM E SIMULAÇÃO COMPUTACIONAL 1-D DE UM MOTOR DIESEL MWM 229.4 OPERANDO COM BIODIESEL E ETANOL

Resumo: Este trabalho analisa o desempenho do motor diesel MWM 229.4 em uma simulação computacional 1-D com biocombustíveis B20 (20\% biodiesel e 80\% diesel, v/v) e D72B18E10 (18\% biodiesel, 10\% etanol e 72 \% diesel, v/v). Os impactos ambientais dos combustíveis fósseis têm impulsionado o interesse em alternativas renováveis de energia sustentável para substituir os derivados de petróleo em motores térmicos. Um motor diesel 3.92L 4 tempos foi modelado e validado para avaliar o torque, potência, consumo de combustível e eficiência térmica do motor. Os resultados mostraram que o B20 e o D72B18E10 tiveram desempenho ligeiramente inferior em comparação ao diesel puro devido às suas propriedades como menor poder calorífico e índice de cetano. Porém, a presença de oxigênio nas misturas melhorou a qualidade e a eficiência da combustão, resultando em maior eficiência térmica em algumas condições operacionais.

Palavras-chave: Biocombustíveis; Motor Diesel; Motores de combustão interna; Modelagem e simulação numérica; Eficiência térmica.

1. INTRODUCTION

The growing awareness of the environmental impacts of fossil fuels has driven interest and development in biofuels as part of clean and sustainable energy strategies worldwide. The projection is that, in a few years, fossil fuels will be replaced by clean energy sources that do not degrade the environment. This transition has been gradually occurring since the late 20th century, but there is still much to be done to make this vision a reality. Additionally, many countries still rely on the exploration of oil, coal, and natural gas for their economy, making the transition to a renewable energy-based economy challenging.

According to Vidal [1], Brazil plays a significant role in the global biofuels industry, responsible for a large share of global ethanol production. Moreover, the country has been excelling in biodiesel production, mainly from vegetable oils and animal fats. Brazil holds a prominent position as the world's second-largest ethanol producer while ranking among the top three global biodiesel producers [2].

According to ANP [3], in 2022, Brazil produced just over 30 billion liters of both anhydrous and hydrated ethanol. This impressive number is the result of decades of investment in technology and research to increase biofuels production efficiency. Additionally, nearly 7 billion liters of biodiesel were produced in the country the same year, representing a significant increase compared to previous years. Biofuels play a significant role in the current context, helping to reduce greenhouse gas emissions, diversify the energy matrix, promote economic development, and strengthen energy security.

2. METHODOLOGY

This work aims to evaluate the performance of a diesel engine operating with biofuels (biodiesel and ethanol) in blends with diesel, through simulation using the WAVE software. For this purpose, the diesel engine was modeled in a computational environment. The modeling was validated by analyzing the experimental results from Carvalho [4], using the same engine. Two biofuel blends were simulated: B20 (20% biodiesel and 80% diesel, v/v) and D72B18E10 (18% biodiesel, 10% ethanol, and 72% diesel, v/v). Subsequently, the results of the engine's mechanical performance parameters (torque, power, specific consumption, and thermal efficiency) were compared with the model operating with pure diesel as the standard fuel. These results come from the modeling and validation based on Carvalho's experimental data (2020).

The simulations were performed based on the modeling of an MWM diesel engine, 299.4, four cylinders, with a direct injection system and a naturally aspirated air intake system. Table 1 below presents some of the main technical specifications of the engine used.

2.1. WAVE

WAVE is a software that allows engine performance analysis. This software is a state-of-the-art 1D gas dynamics simulation tool. It is used around the world in industry sectors including land transport, rail, motor sports, marine and power generation. WAVE allows acoustic and performance analysis to be performed for virtually any intake, combustion and exhaust system configuration [5].

Table 1. Engine specifications MWM 229.4.

Struct	4 cylinders in line
Bore x Stroke	102 x 120 mm
Displacement volume	3.92 L
Compression ratio	18:1
Maximum power	54 kW at 2500 rpm

2.2. FUELS

The mixtures used in the simulation were: B20 (80% diesel and 20% biodiesel) and D72B18E10 (72% diesel, 18% biodiesel, and 10% ethanol) and pure diesel was the reference fuel. The choice of these blends was made in reference to Carvalho's work [4]. Table 2 presents the properties of the basic fuels for the mixtures mentioned above, collected within the WAVE software itself.

Table 2 – Physicochemical properties of fuels according to the WAVE software database.

Property	Diesel	Biodiesel (FAME)	Ethanol
Chemical formula	$C_{15}H_{25,05}$	$C_{18,86}H_{37,72}O_2$	C_2H_6O
Lower heating value (MJ/kg)	42.8	38.0	26.83
Latent heat of vaporization (kJ/kg)	220	352	910
Density at 25 ºC (kg/m³)	762.55	880.0	789.37
Viscosity at 25 ºC (cSt)	2.13	3.62	1.10
Stoichiometric fuel/air ratio	1/14.30	1/12.70	1/9.00
O (wt %)	0	10.79	34.73

Since it was necessary to make comparisons between the experimental results obtained in Carvalho [4] and the results obtained in this work, it is crucial to highlight the similarity between the properties of the fuels used in both studies. Table 3 presents the properties of the fuels used in Carvalho [4].

With some notable exceptions, such as the heat of vaporization of biodiesel, the density of diesel, and the viscosity of both diesel and biodiesel, the values of all other properties are very similar and can be directly compared. Therefore, we have adopted the same cetane numbers (CN) presented by Carvalho [4] as another key data point for the analyses, as this information is not available in the WAVE database.

Table 3 – Physicochemical properties of fuels used in Carvalho.

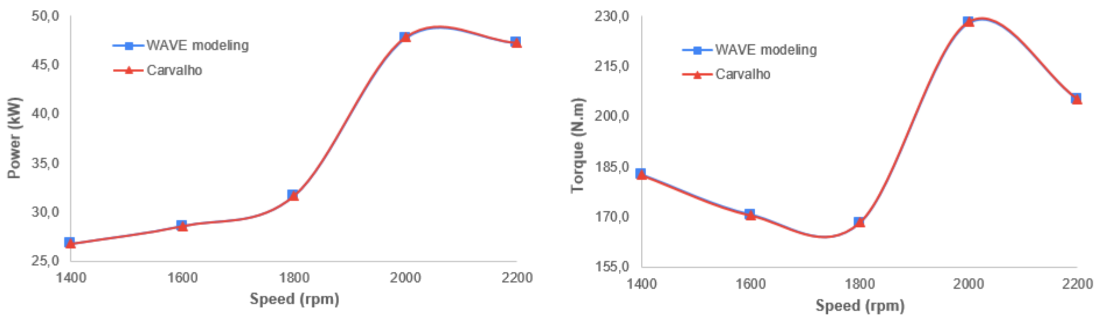
Property	Diesel	Biodiesel (FAME)	Ethanol
Lower heating value (MJ/kg)	42.5	37.46	28.40
Latent heat of vaporization (kJ/kg)	260	200	836
Density at 25 ºC (kg/m³)	840.0	877.8	786.0
Viscosity at 25 ºC (cSt)	3.30	4.95	1.20
Flash point (ºC)	96	158	15
Cetane Number	46.0	55.9	6.5
O (wt %)	0	10.8	34.7

2.3. MODEL VALIDATION

From the computational modeling of the reference engine (MWM 229.4), validation was performed considering the torque and power values obtained in Carvalho [4], using diesel as the reference fuel. In the validation process, variables were adjusted for some engine characteristics, and by varying these variables, tests were conducted to approximate the expected behavior. The adjusted variables were: rotational speed (rpm), fuel-air ratio (F/A), fuel injection duration, and constant injection timing angle.

The validation of the model, as shown in Figure 1, describes the power and torque behavior curves, performed at rotations of 1400, 1600, 1800, 2000, and 2200 rpm. The results obtained indicate a relative deviation of only 0.1% in the power curve and 0.1% in the torque curve.

Figure 1 – Validation of power and torque curves.



As WAVE performs simulations only in 1D, there is no possibility of obtaining performance data for 40 as a function of a single power, that is, under the same load and speed conditions. Therefore, the only direct comparisons made with Carvalho's work [4] are the results of torque and power as a function of the motor's rotation speed.

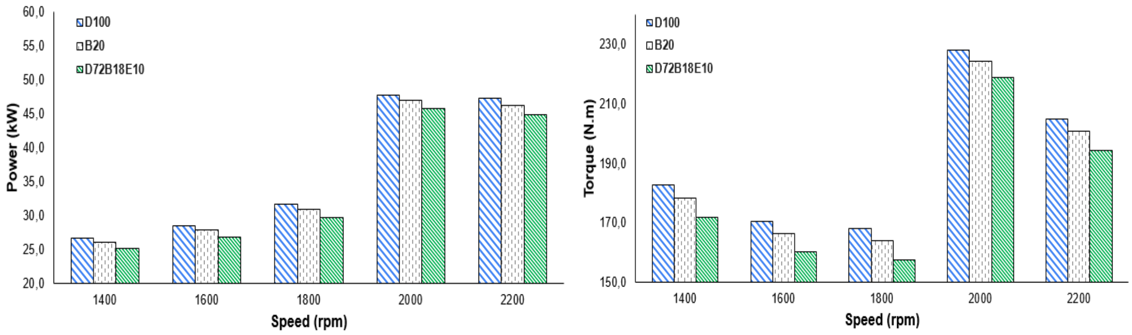
3. RESULTS AND DISCUSSION

The validated model was assessed through its performance with different fuels with the aim of better understanding the behavior of the biofuels tested in this engine and comparing them to the results observed by Carvalho [4].

3.1 TORQUE AND POWER

The torque and power results obtained with the fuels are presented in Figure 2, based on the validation obtained with Carvalho's results [4].

Figure 2 – Results of torque and power.



A gradual decrease in torque between 1400 and 1800 rpm is observed, followed by a sudden increase at 2000 rpm. This behavior is consistent across all fuels. According to Carvalho [4], this phenomenon is attributed to the motor's design characteristics, which likely optimize the volumetric efficiency for the 2000 rpm rotation, where the peak torque occurs. The biofuels performed below pure diesel, with B20 showing an average deviation of 2.1%, while D72B18E10 had 5.5%.

The power behavior observed for all fuels is analogous. As the rotational speed increases, the power rises until it reaches its maximum at 2000 rpm, and then gradually declines. The biofuels showed lower performance than D100, with an average deviation of 2.1% for B20 and 5.5% for D72B18E10. Since there is a relationship between power and torque, the justifications for the obtained results are the same. The lower heating value (PCI) is the main property that explains these values for both fuels. In the case of B20, the increase in viscosity and density reduces the combustion efficiency, but the high calorific value somewhat compensates for this effect. However, in D72B18E10, the low calorific value of ethanol combined with the characteristics of biodiesel significantly reduces the combustion power, resulting in less torque delivered by the engine.

Table 4 – Comparison of torque and power data from the simulated model and Carvalho's results.

RPM	Fuel	WAVE modeling		Carvalho [4]		RD (%)
		Torque (N.m)	Power (kW)	Torque (N.m)	Power (kW)	
1400	B20	178.4	26.2	181.7	26.6	1.8
	D72B18E10	171.8	25.2	168.9	24.8	1.7
1600	B20	166.6	27.9	168.3	28.2	1.0
	D72B18E10	160.3	26.9	156.2	26.2	2.6
1800	B20	164.1	30.9	165.2	31.1	0.7
	D72B18E10	157.7	29.7	155.2	299.2	1.6
2000	B20	224.5	47.0	221.7	46.4	1.2
	D72B18E10	218.9	45.8	210.3	44.1	4.1
2200	B20	201.0	46.3	205.8	47.4	2.3
	D72B18E10	194.6	44.8	189.6	43.7	2.6

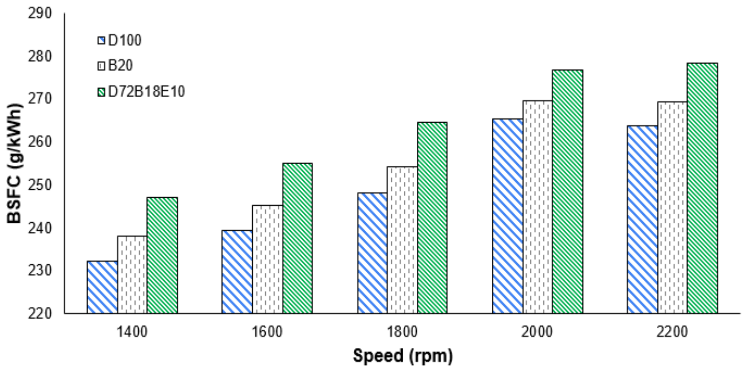
In comparison with B20, an average deviation of 1.4% was obtained. In Carvalho [4] the behavior of the B20 is much closer to the D100 and reaches a higher torque at 2200 rpm, while in the modeling an almost linear relationship between the fuels is visualized, where the B20 delivers on average 2% less torque relative to the D100. Placing D72B18E10 in evidence, an average deviation of 2.5% was obtained. The behavior between both is very similar, however, in the modeling, the torque delivered by the engine is greater. In fact, there are two properties that can have a direct influence on these results when comparing Tables 3 and 4, in the modeling the D100 used has a much lower density reflecting a better burning of the fuel, while the B100 used has a much higher heat of vaporization and consequently obtaining lower burning power.

3.2 SPECIFIC CONSUMPTION

The results of specific consumptions obtained with the fuels are presented in Figure 3, based on the validation obtained with Carvalho's results (2020).

The consumption showed an increase as the rotational speed increased and remained constant after 2000 rpm, with a proportional growth pattern of the curve for all fuels. However, the biofuels showed higher values compared to pure diesel. The average deviation for B20 was 2.2%, and for D72B18E20, it was 5.9%. The lower lower heating value (LHV) of biodiesel and ethanol is the main factor contributing to the increase in specific consumption, as the engine requires a higher mass flow rate of fuel to obtain the required power due to the lower burning power.

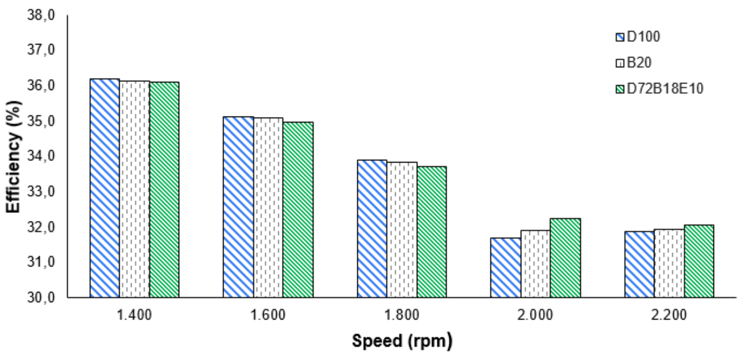
Figure 3 – Results of specific consumption.



3.3 EFFICIENCY

The thermal efficiency results obtained with the fuels are presented in Figure 4, based on the validation achieved with Carvalho's results [4].

Figure 4 – Results of thermal efficiency.



The engine efficiency decreases with an increase in rotational speed between 1400 and 2000 rpm. After this decline, it starts to increase again, reaching its peak efficiency at the lowest speed for all fuels. At low rotations, between 1400 and 1800 rpm, Diesel proves to be slightly more efficient, even though by a small margin. At higher rotations, 2000 and 2200 rpm, D72B18E10 stands out with significantly higher efficiency, while B20 performs at an intermediate level across all rotations. At lower rotations, the high LHV makes Diesel more efficient, but at higher rotations, the oxygen content present in the mixtures, along with the elevated temperature inside the cylinders, makes the combustion of fuels more efficient, especially D72B18E10. The efficiency values of all fuels are very close, with B20 and D72B18E10 being more efficient than D100, by 0.3% and 0.70% respectively.

4. CONCLUSION

The tests conducted with a diesel engine, model MWM 229.4, in a 1-D computational simulation with the aim of evaluating its performance when operating with biofuels, B20 and D72B18E10, showed behavior within the expected parameters.

In the model developed based on the power and torque parameters obtained in the dynamometer experiment by Carvalho [4], the deviations were less than 1.0%. The engine operating with B20 had only a slight average decrease of 2.1% in torque and power compared to diesel, along with a slight increase in specific fuel consumption by 2.2% and a 0.3% increase in efficiency. On the other hand, the D72B18E10 had a larger decrease in torque and power compared to pure diesel at 5.5%, a significant increase in specific fuel consumption by 5.9%, and a 0.7% increase in engine efficiency.

In a general analysis of the fuels, the results showed a slight decrease in performance (torque and power) of the diesel engine operating with B20 and D72B18E10, mainly due to the lower LHV in the biofuel blends. However, these biofuels proved to be more efficient, especially at high rotations, even when operating in an engine designed for pure diesel, thanks to the higher oxygen content in the mixture, which enhances the fuel burning despite the lower LHV. Future research will extend engine's performance analysis with in-cylinder pressure, exhaust gas temperature and heat release rate results. Also, it is planned to investigate the influence of these simulated conditions on the engine exhaust.

5. REFERENCES

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