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Development of a virtual bench for the analysis of the physical processes of internal combustion engines

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Abstract. Currently, internal combustion engines face the challenge of reducing fuel consumption and reducing polluting emissions due to their significant impact on the environment. Therefore, it is necessary to use tools that allow us to evaluate the operating characteristics of this type of thermal machines. In the present investigation, the development of a virtual bench was proposed for the analysis of the behavior and performance characteristics of an internal combustion engine for use as a learning tool in higher education students. From the results obtained, it could be demonstrated that the pressure curves of the combustion chamber and the rate of heat release obtained by means of the virtual bench presented a high concordance with the experimental records. The maximum deviation obtained was 5% and 15% for the pressure curve and the heat release rate. Comparing the performance parameters of the brake specific fuel consumption of the engine and energy efficiency, a maximum deviation of 2.96% was shown compared to the real engine. In general, the virtual development bank can describe the behavior of the engine, allowing the characterization of physical phenomena, as well as evaluating the effect of auxiliary technologies such as turbo-compression systems.

1. Introduction

Nowadays, internal combustion engines (ICE) have the need to overcome several challenges related to reducing fuel consumption and reducing polluting emissions, without compromising the mechanical performance of the engine [1]; this is a consequence of increasingly strict governmental environmental regulations and the need for more efficient energy management due to the economic cost of fuels [2,3]. Despite the emergence of new technologies such as electric motors, it is estimated that ICE will continue to be relevant in the industrial and transportation sectors [4,5]; due to the above, the evaluation and analysis of the operation of internal combustion engines is still important today.

In order to improve engine performance, different types of technologies and changes in engine design have been studied, such as direct injection systems, turbochargers, exhaust gas after-treatment, valve actuation, among others [6,7]. The understanding and evaluation of the engine and the different types of technologies is a key factor to minimize fuel consumption and reduce polluting emissions, for which, experimental methodologies and simulation tools are increasingly important, since they allow to identify the effect that the various physical processes of the engine have on its consumption and performance; due to the importance of knowing the engine's operation, it is necessary to develop tools that allow students to become familiar with the physical processes present in the operation of ICEs [8,9]. The practical applications for the analysis of ICEs require the use of large and sophisticated laboratories, which implies a high economic cost [10–12]. This leads to the development of learning activities that do not stimulate critical thinking in students.

Due to the above, the present research proposes the development of a virtual bench of an internal combustion engine, based on mathematical models that allow describing the behavior of ICEs. The virtual bench is built using MATLAB software and is validated by comparing the results obtained experimentally under different operating conditions. In this way, the development of a tool is sought to characterize the physical phenomena associated with the engine combustion process, considering variables such as combustion pressure, exhaust gas temperature, heat release rate, fuel consumption, and NOx emissions.

2. Methodology

The construction of the model of an internal combustion engine is based on a set of sub-models, which are based on physical models that allow replicating the real operation of the engine; The diagram of the developed model of the internal combustion engine is shown in Figure 1. The development of the user interface was carried out using the MATLAB software, because it is a tool generally available in higher education centers and highly used in various disciplines for the construction of computational models. The MATLAB graphical user interface (GUI) was designed with the general interface of the benchmarks in mind. The programming structure of the virtual bench is shown in Figure 2.

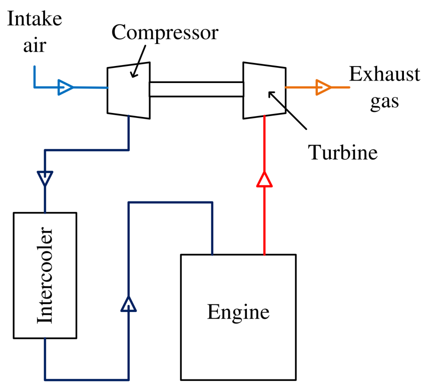

Figure 1. Diagram of the developed model.

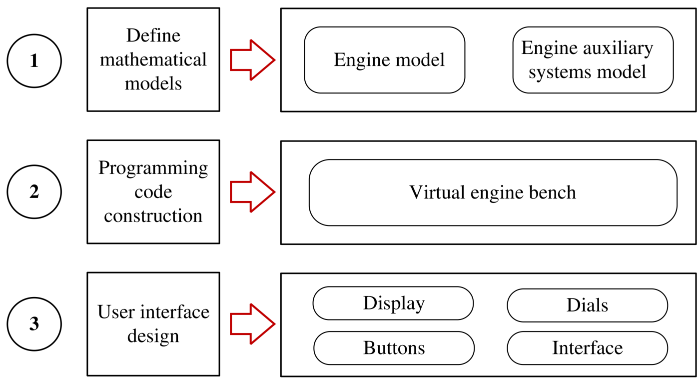

Figure 2. Structure of the virtual bench.

The volume of the combustion chamber (V_c) is determined by Equation (1) [13].

$$V_c = V_{cc} + \frac{V_{cc}\cdot(r_c-1)}{2}\cdot\left(\frac{l}{a} + (1-\cos\alpha) - \sqrt{\frac{l^2}{a^2} - \sin^2\alpha}\right), \quad (1)$$

where V_{cc} is the clearance volume, a is the radius of crank, l is the connecting rod length, r_c is the compression ratio and α is the crank angle; the heat release rate $(\frac{dQ}{d\alpha})$ in relation to the crankshaft angle is described by Equation (2) [14].

$$\frac{dQ}{d\alpha} = \frac{\gamma}{\gamma-1} P \frac{dV_c}{d\alpha} + \frac{1}{\gamma-1} V_c \frac{dP}{d\alpha} + \frac{dQ_h}{d\alpha}, \quad (2)$$

where γ is the ratio of specific heat, P is the pressure of the combustion chamber and Q_h is the heat transfer to the cylinder walls; Q_h is determined from Equation (3) [13].

$$\frac{dQ_h}{d\alpha} = (T - T_w)\cdot h \cdot \frac{dA}{d\alpha}, \quad (3)$$

where T_w is the mean cylinder wall temperature, T is the temperature of the cylinder gas, A is the heat transfer area and h is the convective heat transfer coefficient. h is determined by the correlation proposed by Woschni, as shown in Equation (4) [15].

$$h = C_o \cdot B^{-0.2} \times P^{0.8} \times w^{0.8} \times T^{-0.53}, \quad (4)$$

where B is the cylinder bore and w is the average gas velocity, respectively; the outlet temperature (T_s) and the power (P_c) of the turbo-compression system of the engine is determined from Equation (5) and Equation (6) [16].

$$T_s = T_e \cdot \left(1 + \frac{\left(\frac{P_s}{P_e}\right)^{\frac{\kappa-1}{\kappa}} - 1}{\eta_c}\right), \quad (5)$$

$$P_c = \dot{m}_c \cdot c_p \cdot (T_s - T_e), \quad (6)$$

where $\dot{m}_c$ is the mass flow rate through the compressor, c_p is the specific heat, η_c is the compressor isentropic efficiency, and κ is the specific heat ratio of the incoming gas. The subscripts e and s refer to the stagnation conditions at the compressor inlet and outlet, respectively; the temperature inside the combustion chamber is calculated using Equation (7) [17].

$$T = \frac{P \cdot V_c}{\dot{m}_{mix} \cdot R_{mix}}, \quad (7)$$

where $\dot{m}_{mix}$ is the mass flow rate of the mixture (mass flow rate of fuel + mass flow rate of air) and R_{mix} is the gas constant of the mixture.

The mathematical model used to describe the behavior of the engine requires a validation process to ensure its reliability. Due to the above, experimental tests were carried out on a test bench of a single-cylinder diesel engine. The technical characteristics of the engine are described in Table 1. The experimental tests were established at a constant rotational speed of 3600 rpm and four engine torque conditions (3 Nm, 5 Nm, 7 Nm, and 9 Nm). The fuel used in the experimental tests is diesel.

Table 1. Pneumatic network simulation parameters.

Characteristics	Value
Manufacturer	SOKAN
Model	SK-MDF300
Displacement	300 cc
Cycle	4
Maximum power	3.43 kW at 3600 rpm
Compression ratio	20:1
Cylinder stroke/bore	63/78
Number of cylinders	1

3. Results

Next, a comparison was made between the engine's different characteristics and performance parameters for the different load conditions obtained through the virtual bench and the experimental results. Figure 3 shows the pressure curve during the combustion cycle for a rotation speed of 3600 rpm and a load of 5 Nm, obtained by means of the mathematical model of the virtual bench and the experimental tests. In general, it was observed that the largest deviations of the model are found during the processes of intake and exhaust of the engine; however, during the compression phase, a high concordance was observed between the results obtained by the model and the experimental tests.

The relative error during the combustion cycle is within a range of 0.4% - 5.0%; since the smallest error is in the compression stage, the determination of the performance characteristics of the engine and emissions are not significantly affected. From the pressure curves and the combustion chamber volume calculation, the heat release rate (HRR) is determined during the combustion cycle. The HRR comparison of the model and the experimental tests are indicated in Figure 4. In general, it was observed that the model can represent the actual behavior of the engine throughout the combustion cycle.

The maximum relative error obtained was 15% for a rotation speed of 3600 rpm and a load of 5 Nm; however, the trend described by the virtual bench is enough to describe a realistic behavior of the engine, which guarantees the potential of the model for use in analyzes focused on learning environments. The results obtained in Figure 3 and Figure 4 show that the peak of the combustion pressure and the rate of heat release occur for an angle of 360°, which corresponds to the transmission between the compression and expansion stage; similar results are reported in the literature [18]

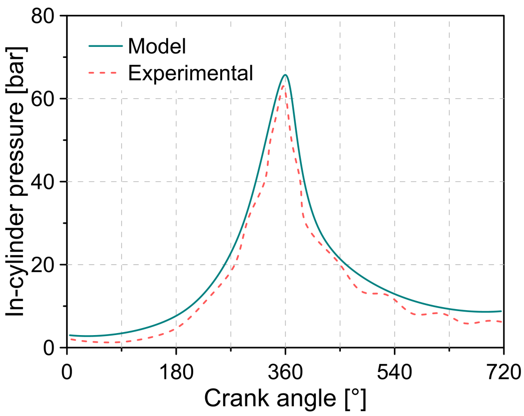

Figure 3. Pressure curve of the combustion chamber for a load of 5 Nm.

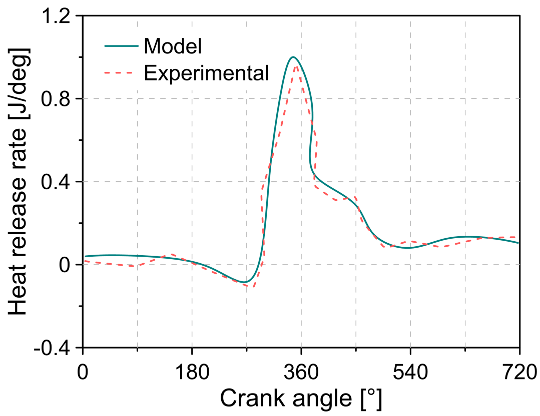

Figure 4. Heat release rate curve for a load of 5 Nm.

Figure 5 depicts the exhaust gas temperature for the four engine load conditions; it was evidenced that the experimental data describe an increase of 14.05% in the temperature of the gases when there is an increase of 2 Nm in the engine load. In the case of the virtual bench, an increase of 14.17% was registered, which indicates a high concordance with the experimental results. Additionally, both curves describe a similar trend with increasing engine load; similar results are reported in the literature [19]; to analyze the performance of the engine, the calculation of the brake specific fuel consumption (BSFC) and the energy efficiency (n_c) were performed using the Equation (8) and Equation (9) [20].

$$\mathrm{BSFC}\left(\frac{\mathrm{kg}}{\mathrm{kWh}}\right) = \frac{\dot{v}_f\left(\frac{m^3}{s}\right)\cdot\rho_f\left(\frac{kg}{m^3}\right)}{N_e\ (kW)} \times 3600, \tag{8}$$

$$n_c\ (\%) = \frac{N_e\ (kW)}{v_f\left(\frac{m^3}{s}\right)\cdot\rho_f\left(\frac{kg}{m^3}\right)\cdot LHV_f\left(\frac{kJ}{kg}\right)} \times 100, \tag{9}$$

where $\dot{v}_f$ is the volume flow rate, ρ_f is the density of fuel, LHV_f is the lower heating value lower and N_e is the brake engine power; the N_e is determined by the Equation (10).

$$N_e(kW) = \frac{2\pi\cdot n\ (rpm)\cdot M_e(Nm)}{60\times 1000}, \tag{10}$$

where n is the engine rotation velocity and M_e is the brake engine torque, respectively; the results of the BSFC and n_c for the engine under the selected conditions are shown in Figure 6 and Figure 7. When comparing the BSFC of the engine obtained through the virtual bench and the experimental tests, an adequate agreement in behavior was evidenced; in both cases, it was observed that the BSFC of the engine decreases with the increase in engine load, which is a consequence of the greater efficiency in the engine's combustion process at high loads, as indicated in the research by Mubarak, *et al.* [21]. The relative error of the BSFC was found between a range of 1.67% - 2.96%. In the case of n_c, it was observed that the results obtained by the virtual bench describe the real trend of the engine. The largest deviation compared to the experimental tests occurred in the highest load condition; however, the relative error was less than 3% in all the operating conditions analyzed.

Finally, the ability of the virtual bench to describe the NOx emissions of the engine is evaluated; the results in behavior with the experimental data are presented in Figure 8; the analysis shows that the maximum deviation presented was 7%, which is high for a precise analysis of the engine. However, high precision is not essential for a study focused on learning general engine behavior; in general, the behavior and magnitude described by the model is enough to mimic real engine conditions. On the other hand, the variables simulated by the virtual bench, such as chamber pressure, heat release rate, fuel consumption, energy efficiency and NOx emissions, describe behaviors like the studies available in the literature. In this way, the ability to predict the physical phenomena of the internal combustion engine is guaranteed.

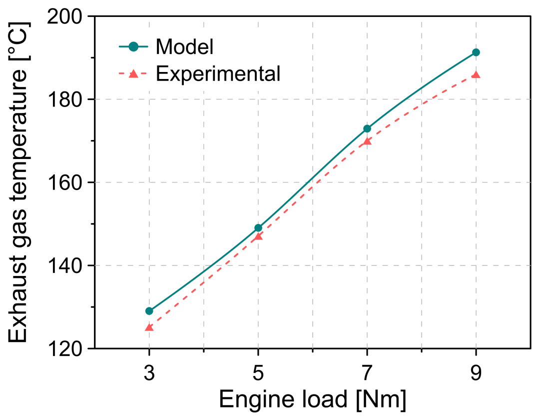

Figure 5. Exhaust gas temperature for different loads.

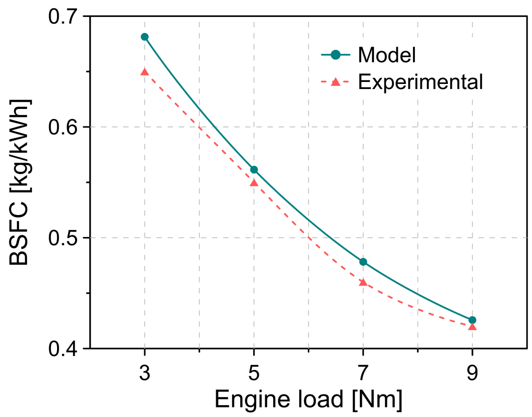

Figure 6. Brake specific fuel consumption for different loads.

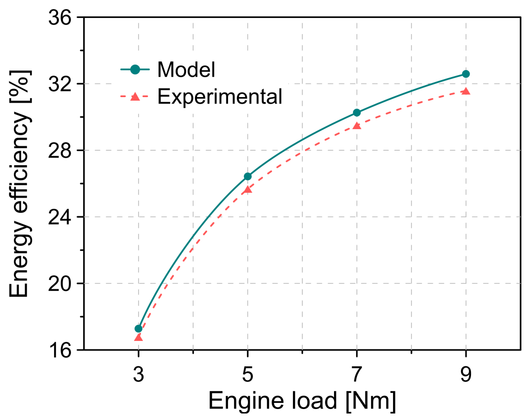

Figure 7. Energy efficiency for different load conditions.

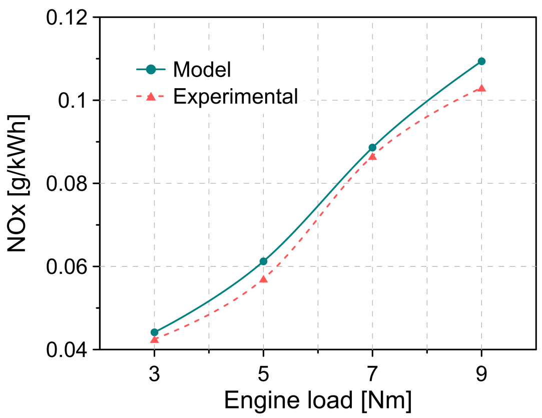

Figure 8. Nitrogen oxide emissions for different loads.

4. Conclusions

This research describes the development and validation of a virtual bench built using MATLAB software for the analysis of performance characteristics and emissions of internal combustion engines in an environment focused on the learning and practice of higher education students; in this way, it is possible to recreate and facilitate the experience acquired in the experimental test benches. The virtual laboratory is built from mathematical models that describe the combustion process of the engines; from the comparison with the experimental results, it was shown that the virtual bench can describe the trends present in the real engines. The validation was carried out for a constant speed condition (3600 rpm) and four load levels on the engine (3 Nm, 5 Nm, 7 Nm, and 9 Nm).

From the results obtained, it was possible to demonstrate that the pressure curves of the combustion chamber and the rate of heat release obtained through the virtual bench presented high concordance with the experimental records, especially during the compression stage of the combustion cycle; the maximum deviation obtained was 5% and 15% for the pressure curve and the heat release rate. Analysis of engine performance parameters such as brake specific fuel consumption and energy efficiency determined from the virtual bench for different load conditions described a similar trend with real engine behavior. In the case of these parameters, the maximum relative error was 2.96%. For NOx emissions, it was shown that the magnitudes and trends of the virtual bench are in accordance with the experimental results.

In general, the virtual bench can describe the trends present in real internal combustion engines, which allows evaluating the different processes and parameters in this type of heat engine; the development of the virtual bench allows to provide physics with a tool to characterize the physical phenomena associated with the engine's combustion process, facilitating analyzes focused on the variability of the engine's boundary conditions. Additionally, the use of this type of tool allows evaluating the effect of auxiliary technologies such as turbochargers, thermoelectric generators, Rankine cycle, among others. In this way, the influence of these technologies on the performance of internal combustion engines can be investigated in a preliminary way, in order to achieve an improvement in consumption and reduction of emissions. Future research aims to improve the research capabilities of the virtual bank by adding new sub-models that allow the study of systems such as hydrogen generators.

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