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KNOCK ANALYSIS VIA NUMERICAL UNIDIMENSIONAL MODEL OF A SINGLE CYLINDER RESEARCH ENGINE CORRELATED WITH EXPERIMENTAL DATA

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Abstract. *In Brazil the focus in the renewable matrix research field gains an especial attention due to the concern about GHG (Greenhouse Gases). Besides, ethanol fuel allows exploring better spark authority and higher compression ratio. Combined with dynamometric tests, the 0/1D CFD analysis became an important tool in understanding the phenomenological models involving combustion, volumetric efficiency, heat transfer and friction. The main purpose of this paper is to develop a numerical unidimensional model using the software GT-SUITE, that represents the Single Cylinder Research Engine (SCRE) used in this work. The numerical validation will be performed by two methods: TPA (Three Pressure Analysis) and non-predictive combustion model using a Wiebe function. The correlation with the experimental data will be compared and explained for the two methods, using Hydrous Ethanol at an engine speed of 2000 rpm and load of 8 bar BMEP. The Knock detection model will be implemented for E10 (10% anhydrous ethanol / 90% gasoline) at engine speed of 3000 rpm and load of 6 bar BMEP and E22 (22% anhydrous ethanol / 78% gasoline) at an engine speed of 2500 rpm and load of 8 bar BMEP.*

Keywords: *0/1D CFD, Internal combustion engine, GT-SUITE, Knock.*

1 INTRODUCTION

The conception of a new project in the automotive sector before modern computers development always demanded previous study and hard work experimentation. However, from the technological improvements a new engineering branch was created denominated CAE (Computer Aided Engineering), which allows a better planning and execution of a new project, carrying on gains in time and money, variables with great importance in the industry (Barros, 2003; Pulkrabek, 2004).

The CFD (Computational Fluid Dynamics) analysis is a derivation of the CAE field, and focus on the numerical solution of phenomena related to the flow, heat transfer, friction and chemical reactions through the mathematical domains discretized on space and time. The CFD approach has gained a special attention in the industry and academy because it is capable to provide a great correlation with experimental data and allows exploring extrapolated maps of operating conditions (Malalasekera e Versteeg, 1995).

The application on the tridimensional form or CFD-3D has proved to solve a complex phenomenon that occurs in internal combustion engines, like turbulence, fuel injection and combustion. The CFD-3D analysis, once presenting well correlating results with experimental data, is an extremely useful tool to better understand the phenomena involved, besides generating results, often difficult or impossible to be generated experimentally. However, the CFD-3D analysis requires high computational processing cost and time (Malalasekera e Versteeg, 1995; Barros, 2003)

One-dimensional numerical models are being increasingly applied in the exploration of internal combustion engines operating maps. Due the fact of, since the mode is validated, it's possible to extrapolate operating conditions that are often not possible in the experimental engines search due to the structural limits of the engine or the unavailability of some resource such as different fuels and blends or different configurations of the combustion chamber which are often easier to be modified numerically than via experimental research (Lanzanova, 2013; Jo et al., 2014).

The exploration of engine maps operation that extrapolates the experimental conditions of an engine is extremely useful in knock analysis, since one of the bottlenecks in the study of knock is within the structural limits of the engine. Thus, some models of detection and characterization of knock are being developed, as well as, more complex models with predictive combustion capable to better understand the phenomenon (Li et al., 2015; Martins e Lanzanova, 2015).

The present work aims to develop a one-dimensional model that reproduces the operating conditions of an AVL® Single Cylinder Research Engine (SCRE). The model was validated in two different ways and the main differences were highlighted, using the first case of the Table 1. In addition, four engine operating conditions were used for a preliminary knock study, two operating on the Maximum Break Torque Spark Timing (MBTST) and two on the knock border. Cases with and without knock are operating under the same conditions except for the spark timing. In summary, the detection and characterization of the knock in this work, constitutes a first step for the development of a predictive model of combustion for a better exploration of the phenomenon, without depending on experimental data.

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2 METHODOLOGY

2.1 Experimental Setup

The engine used in this research is an AVL® Single Cylinder Research Engine (SCRE) with direct injection and the dynamometric tests were performed by the experimental CTM (Centro de Tecnologia Da Mobilidade) – UFMG (Universidade Federal de Minas Gerais) Team. The engine was operating with fuel blends from E0 to E100, on load from 2 to 8 bar BMEP and engine speed from 1250 RPM to 5000 RPM. Each case consist of 200 cycle averaged. However data was adquired with cases presented only one cycle for the knock characterization.

The geometrical engine specifications are presented by the Table 1 and Table 2 shows the selected cases for this work. The case 1 consists in a condition without knock and was used to validate the model in two different forms. The cases 2, 3, 4 and 5 were used to characterization of the knock Phenomena. The cases 3 and 5 that presented higher spark advance are the case with knock. The valve lift was also measured and is presented by Fig. 1. The ethanol/gasoline fuel blends are presented in this work by the form E following the percentage of ethanol by volume, as shown in Table 2.

The SCRE was instrumented according to follow steps:

- Specification of the quantities involved for the required results;
- Project and definition of the dynamometric test of the SCRE;
- Design the detail strategy of the monitoring sensor on INDICOM®;
- Perform the dynamometer bench assembly with the main monitoring sensors;
- Definition of the best alternatives of configuration available like: spark plugs, injectors and type of pistons, according to test results required;
- Configuration of the basic software and the sensor calibration;
- Definition of the calibration strategy for each fuel blends, load and engine speed;
- Run the dynamometric tests;
- Development of data processing routines;
- Analysis of the results;
- Formatting the data in spreadsheets;

Table 1 – SCRE specifications

Items	**Values**
Bore [mm]	82
Stroke [mm]	86
Connecting rod length [mm]	144
wrist pin to crank offset [mm]	0,5
Displacement Volume [L]	0,45
Number of Valves	4
Compression Ratio	11,5

Table 2 – Specifications of selected cases

Items	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
BMEP [bar]	8	6	6	8	8
Engine Speed [RPM]	2000	3000	3000	2500	2500
Fuel	E100	E10	E10	E22	E22
Equivalence Ratio	1	1	1	1	1
Average Intake Temperature [K]	308,15	302,70	302,70	301,61	301,61
Average Exhaust Temperature [K]	877	957,67	957,67	934,23	934,23
Fuel Injection Mass [mg/cycle]	41,49	23,07	23,07	29,61	29,61
Air Mass Flow [kg/h]	22	28,92	28,92	28,57	28,57
Start of Injection [°]	-299	-270	-270	-270	-270
Injection Pulse Width [ms]	3,20	1,82	1,82	2,37	2,37
Spark timing [°]	-21,0	-19,5	-22,5	-17,5	-20,5

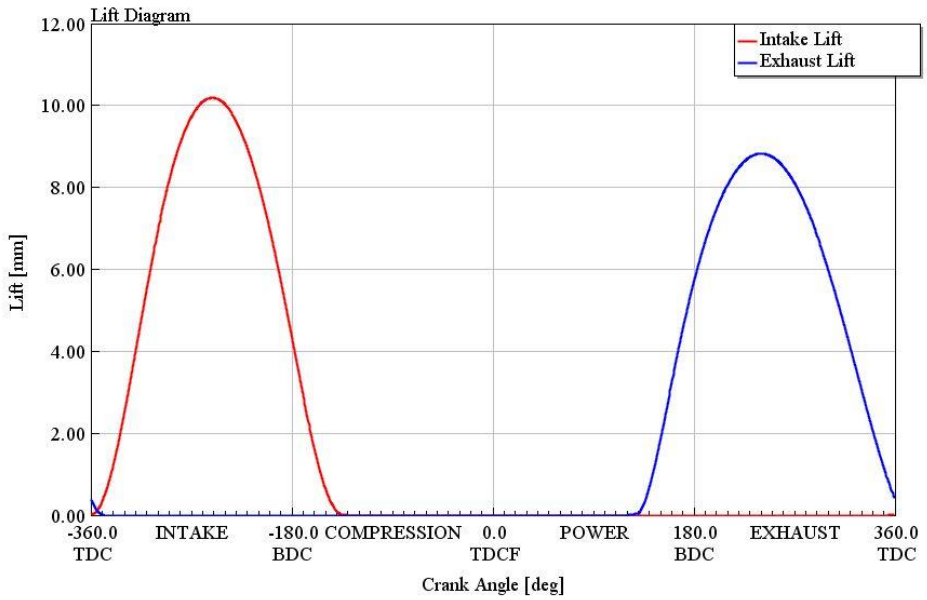

Figure 1. Lift valves diagram.

2.2 Numerical Setup

The one-dimensional numerical modeling of internal combustion engines has been widely approached on the study of the combustion phenomena, volumetric efficiency, gas exchange, heat transfer and friction. Commercial software like GT – SUITE®, which covers a variety of tools capable to manipulate mathematical models (CAD), perform the spatial and temporal discretization, numerical solution of the internal combustion engine model and the post-processing of results, have been increasingly used to obtain fast results with a good correlation with the experimental data, and also to provide boundary conditions for more complex numerical models like CFD-3D.

Fluid Dynamics Governing Equations. The software solves the one-dimensional flow integrating the Eqs. (1) (2) e (3) through the discretized domain in time and space. The numerical method used is called Finite Volume Method and the variables are solved in the center of the discretized volume, the interpolation for the boundary results in an average scalar value. According to the GT-SUITE® Flow Theory Manual, (2015b) the Eqs. (1), (2) and (3) are the Conservation of Mass, Energy and Momentum, respectively.

$$\frac{dm}{dt} = \sum \dot{m} \tag{1}$$

$$\frac{d(me)}{dt} = -p\frac{dV}{dt} + \sum(\dot{m}H) - hA_s\,(T_{fluido} - T_{parede}) \tag{2}$$

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$$\frac{d\dot{m}}{dt} = \frac{dpA + \sum(\dot{m}u) - 4C_f \frac{\rho u|u|}{2}\frac{dxA}{D} - K_p\left(\frac{1}{2}\rho u|u|\right)A}{dx} \quad (3)$$

The variables are the following: m is the volume mass; ṁ is the boundary mass flow into volume, $(m = \rho A u)$; V is the volume; p is the pressure; ρ is the density; A is the cross-sectional area; A_s is the surface heat transfer area; e is the total specific internal energy; H is the total specific enthalpy $(H = e + \frac{p}{\rho})$; h is the heat transfer coefficient; T_{flow} is the flow temperature; T_{wall} is the wall temperature; u is the velocity at the boundary ; C_f is the Fanning friction factor; K_p is the pressure loss coefficient; D is the equivalent diameter; dx is the length of mass element in the flow direction (discretization length); dp is the pressure differential acting across dx; and dt is the time differential.

Temporal e Spatial Equations. According to the GT-SUITE® Flow Theory Manual (2015b), the solution of the flow described in the previous topic is performed by the integration of the conservation equations in space and time. The integration can be done by three methods: explicit, implicit, or quasi-steady. For this work was chosen the explicit method because it provides more accurate results of acoustic phenomena like pressure oscillation in engine air flow and injection systems. The relation between the time step and the discretization length is set by the Courant Number, showed in the Eq. (4):

$$\frac{\Delta t}{\Delta x}\left(|u| + c\right) \leq 0{,}8 * m \quad (4)$$

The variables are the following: Δt is the time step (s); Δx is the minimum discretized element length (m); u is the fluid velocity (m/s); c is the speed of sound (m/s); 0,8 is the Courant Number; and m is the time step multiplier specified by the user (less than or equal to 1.0).

Two-Zone Combustion Model. The Two-Zone Combustion Model is a methodology applied in almost all combustion models adopted by the GT – SUITE® software. The calculations are performed as follows, the cylinder is divided in two zones: the unburned and the burned zone. At the start of the combustion which in this work occurs at the spark timing, all the cylinder is filled with the unburned zone and any residual gas fraction or EGR are included in this zone from the previous cycle. The mixture of air and fuel at each time step Δt is transferred from the unburned zone to the burned zone. The burn rate is imposed or calculated by the combustion model, which defines the amount of air/fuel mixture to be transferred. According to the GT-SUITE® Engine Performance Manual (2015a) the unburned and burned zones can be expressed by the Eqs. 5 and 6 respectively:

Unburned zone:

$$\frac{d(m_u\, e_u)}{dt} = -p\,\frac{dV_u}{dt} - Q_u + \left(\frac{dm_f}{dt}\,h_f + \frac{dm_a}{dt}\,h_a\right) + \frac{dm_{f,i}}{dt}\,h_{f,i} \quad (5)$$

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Burned zone:

$$\frac{d(m_b e_b)}{dt} = -p\ \frac{dV_b}{dt} - \ Q_b + \left(\frac{dm_f}{dt}\ h_f + \frac{dm_a}{dt}\ h_a\right) \tag{6}$$

The indexes u and b refer respectively to unburned and burned zones, and the variables are the following: m is the mass; m_f is the fuel mass; m_a is the air mass; $m_{f,i}$ is the injected fuel mass; e is the internal energy; P is the cylinder pressure; V is the volume; Q is the heat transfer rate; h_f is the enthalpy of fuel mass; h_a is the enthalpy of air mass; and $h_{f,i}$ is the enthalpy of injected fuel mass.

The Wiebe Function. According to Heywood (1988), the thermodynamic approach for the mass burn fraction calculation is given by the Wiebe Function presented by the Eq. 7:

$$x_b\ = exp[\ -a\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{m+1}] \tag{7}$$

The variables are the following: x_b is the mass burned fraction; θ is the crank angle; θ_0 is the angle of start of combustion; $\Delta\theta$ is the combustion duration; and a and m are adjustment parameters, with usual values of a = 5 and m = 2. The adjustments of the parameters a and m of the Eq. 7 are performed in order to adapt the mass burn fraction curve to different geometries, fuels and other possible differences such as position of spark plugs, among others (Melo, 2012).

Three Pressure Analysis – TPA. In the TPA methodology, the necessary domain needs to cover at least from the intake to the exhaust ports. As presented in the GT-Suite® Engine Performance Manual (2015a), the methodology used for this kind of simulation can be presented by the following steps:

- In the first cycle a dummy burn rate is used and no pressure analysis is performed, so the heat transfer data and the injection profile are stored to be used in the next cycle;
- From the second case onwards, the cylinder pressure direct calculation through the mass burn fraction is paused;
- The mass burn fraction in the cylinder is calculated by analyzing the three pressures (at the intake, the cylinder and the exhaust), initial conditions defined for the gas in the cylinder (the GT-ISE® typically use the intake valve close as the start of the simulation), heat transfer rate and injection profile;
- The cylinder pressure direct calculation is restarted and recalculated using the mass burn fraction from the previous step;
- The interactions are performed until the cycles achieves the steady-state conditions;

Knock Characterization. For the knock analysis it´s necessary to define an interval that covers the whole duration of the phenomenon which was defined as being, from the moment of the spark to the 60° after the top dead center. In addition, a filter that delimits the frequency band for knock analysis with a resonance frequency band between 2 and 20 kHZ has been implemented. A multi zone knock model was implemented using the Douaud&Eyzat model for the knock detection. For this model some inputs are needed like the RON (Research Octane Number) and the MON (Motoring Octane Number) average and the specification of combustion chamber geometry, so STL files of the piston and head dome surface were used to define the combustion chamber.

The cases 3 and 5 described in Table 2 were used to made the knock characterization, both are constitute of a single cycle which shows the more representative knock on the cylinder pressure per crank angle of the 200 cycles. The comparative cylinder pressure per crank angle of the cases on MBTST and with Knock border will presented on the results, besides the respective pressure oscillations inside the cylinder of the cases with knock coming from the filter of the of this phenomenon analysis implemented in the TPA model.

The SCRE Model. The engine CAD was provided by the AVL® company, the other components by the experimental team. The entire geometry is shown in Fig. 2.

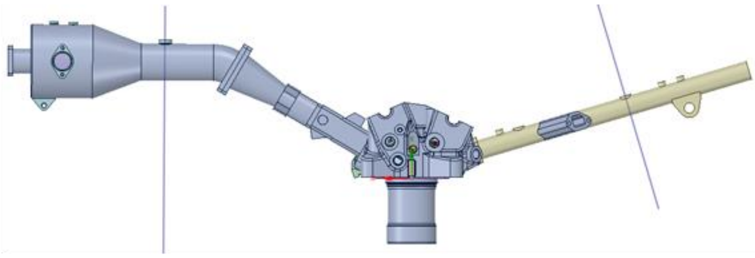

Figure 2. Complete engine geometry with the cut planes delimiting the TPA domain.

The Internal Volume Extraction. In engines CFD simulation, even in more simplified approaches like 0/1D, that is adopted in this work, the volume of interest is where the air and fuel flow through. Then the internal volume needs to be extracted from the complete geometry. The software SpaceClaim® has tools to accomplish that, as shown in Fig. 3.

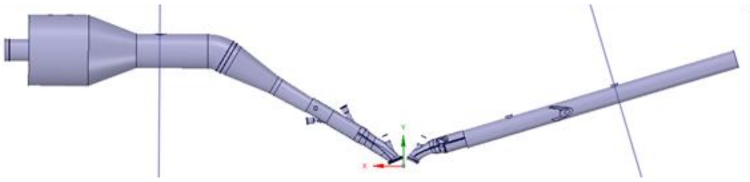

Figure 3. Internal volume of the complete geometry with the cut planes delimiting the TPA domain.

The Spatial Discretization of the Domain. The spatial discretization can be done in two ways, creating volumes to represent the pipes or splitting the pipes in more sub volumes. The software GEM-3D® is used to import the internal volume, define the boundaries, and create the blocks model performed by software GT-ISE® (Integrated Simulation Environment), software mainly dedicated to 0/1D engine simulations. In this conversion, some simplifications are done, like the shown in Fig. 4 and Fig. 5.

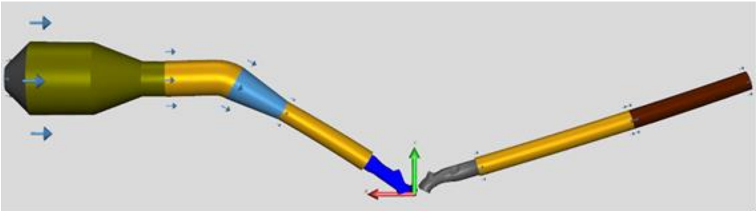

Figure 4. Complete discretized volume.

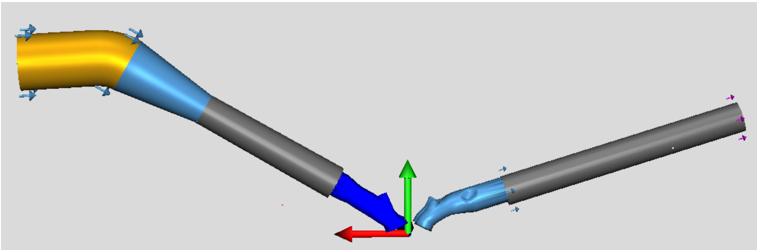

Figure 5. Delimited volume in the frontier of pressure sensors.

The SCRE model. From spatial discretization and conversion to the software GT-ISE® (Integrated Simulation Environment), it is possible to build the one-dimensional model to represent the engine studied. GT-ISE® has a library of specific blocks to simulate internal combustion engines the covers from objects to represent physical boundaries to objects that represent valves, injectors, sensors, actuators, cylinders, and the engine block.

Aiming to build a better user/software interface, each block can be completed with initial and boundary conditions and additional models intended to be coupled. Each block is thought of to solve a specific equation or set of equations and connect with the others in a logical manner to represent the engine. The two models developed in this work are presented in Fig. 6 and Fig. 7.

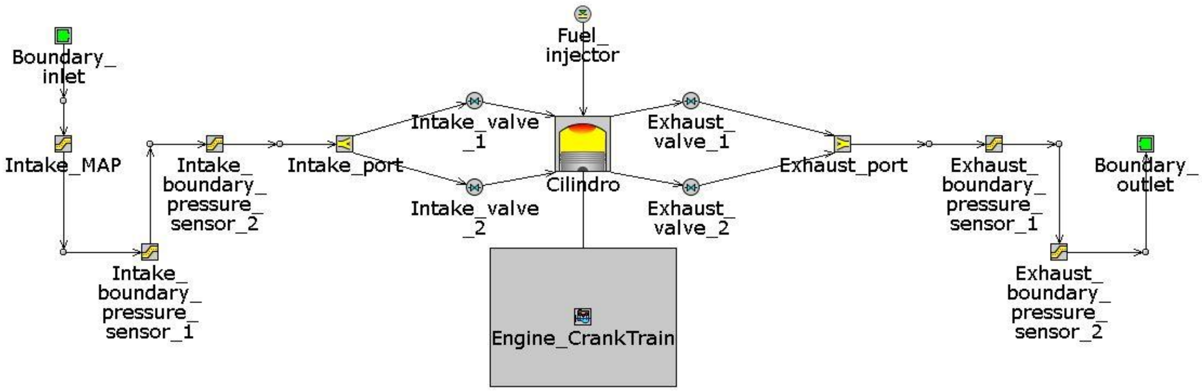

Figure 6. The Full SCRE Wiebe model

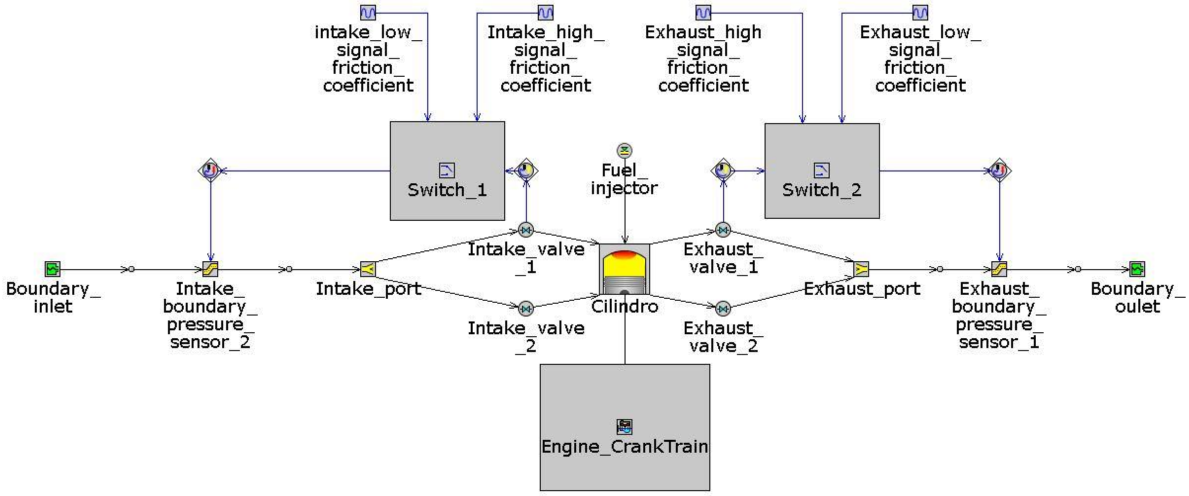

Figure 7. TPA model

3 RESULTS AND ANALYSIS

For the results, will be presented model validation by two different forms and the main divergences will be highlighted. In addition, case in the same condition with and without knock will be compared.

3.1 Comparative Validation

The validation of the TPA and Wiebe models was performed using the case 1 presented in the Table 2.

TPA Model Validation. Beyond the main parameters used by the software for the steady-state convergence, like the mass flow, the pressure and temperature in each component of the model presented by the Fig. 7, were adopted more five parameters. The percentage difference of the additional convergence parameters numerical results in relation to the experimental data are shown in Table 3.

Table 3. Percentage difference of numerical and experimental validation parameters

Item	**Percentage [%]**
IMEP [bar]	2,73
Maximum Pressure in-cylinder [bar]	2,83
Angle Maximum Pressure in-cylinder [bar]	0,58
Mass air flow [mg/cycle]	0,13
Mass fuel flow [mg/cycle]	0

A very useful way to perform the model validation analysis is through the measured and calculated cylinder pressure curves per crank angle degree as well as the LogP-LogV diagram. These results are illustrated in Fig. 8 and Fig 9.

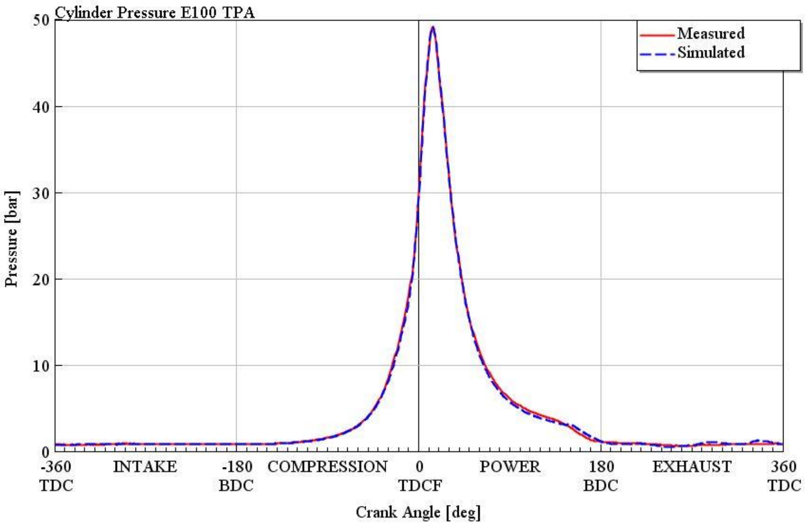

Figure 8 – Numerical and experimental cylinder pressure

In a general form the Fig. 8 show a great numerical and experimental correlation. The main divergences is in exhaust time and can be better observed in the Fig. 9 that shown the LogP-LogV diagram.

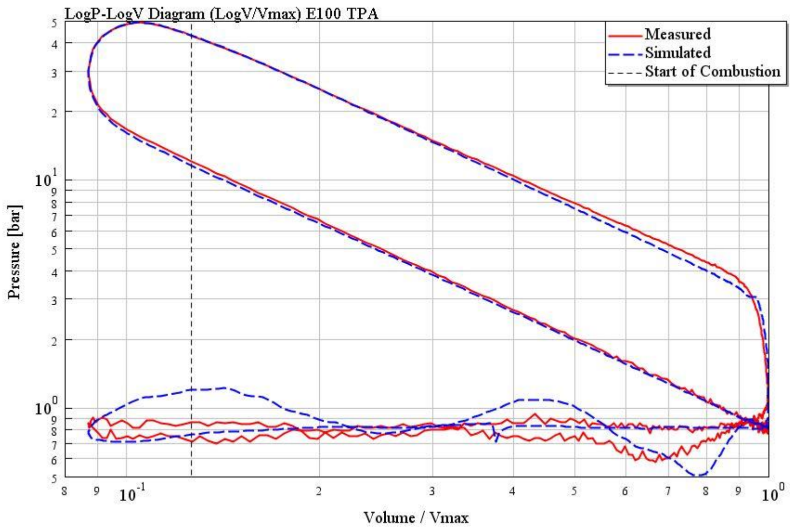

Figure 9 – Numerical and experimental cylinder LogP-LogV diagram

In the diagram presented by the Fig. 9, the numerical and experimental divergence in the pumping area is evident. It´s noted that, despite the acoustic phenomenon influence, which are observed mainly in the exhaust time due to the large pressure oscillations, the curve follows the same experimental trend.

The presence of such phenomena can be explained due the fact the domain used in the TPA model is limited according to the intake and exhaust sensor location. Then, from this premise, a model with an extended domain was developed, as shown in the Fig. 6, to evaluate and better reproduce the exhaust phase, since the compression and expansion phases of the gases inside the cylinder, are well correlated.

For this model was implemented the non-predictive combustion model that performed by the Wiebe Function to impose the mass burn fraction. The results of this analysis will present in the next topic.

Wiebe Model Validation. For this model was adopted the conditions of the case 1 as previously mentioned and the percentage difference of the additional convergence parameters numerical results in relation to the experimental data are shown in Table 4.

Table 4. Percentage difference of numerical and experimental validation parameters

Item	**Percentage [%]**
IMEP [bar]	3,77
Maximum Pressure in-cylinder [bar]	1,43
Angle Maximum Pressure in-cylinder [bar]	1,11
Mass air flow [mg/cycle]	2,64
Mass fuel flow [mg/cycle]	0

In Fig. 10 is shown the measured and calculated cylinder pressure curves per crank angle degree. As expected, the use of a large domain significantly improved the reproduction of the experimental results in the intake and exhaust gases phases inside the cylinder. These results can be better visualized in Fig. 11, where the comparison of the numerical and experimental LogP-LogV diagrams in the cylinder is presented.

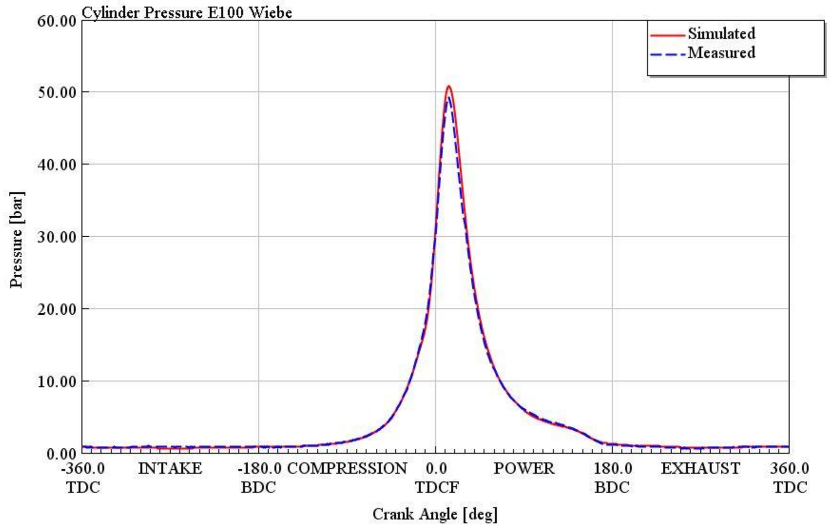

Figure 10 – Numerical and experimental cylinder pressure

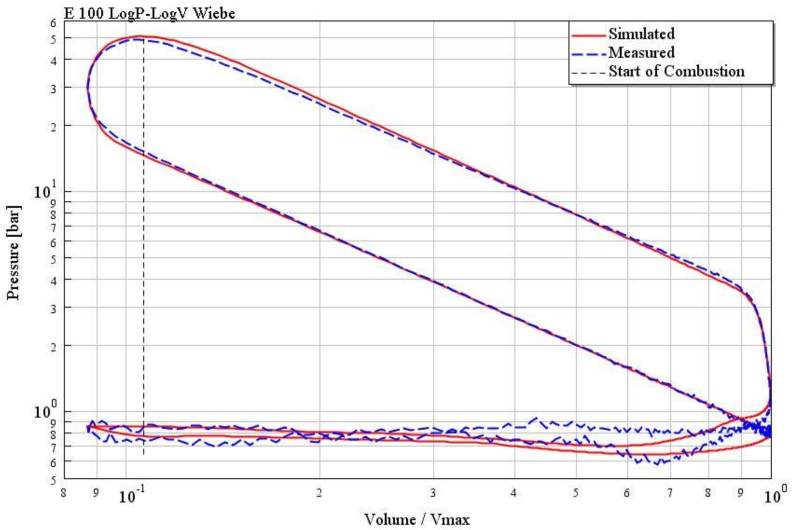

Figure 11 – Numerical and experimental cylinder LogP-LogV diagram

In summary, the expectations on the creation of a model with an extended domain was reached, proving that the difficulty of reproducing the exhaust phase using the TPA model, was in the domain delimited in the intake and exhaust sensor locations.

From this premise, it would be very interesting to explore new ways of acquiring experimental data, whose instrumentation allowed implementing a large computational domain in a TPA methodology. In this way, it would be possible to perform a more accurate analysis, capable of calculating some data that are difficult to obtain experimentally, like the trapped mass, and from this result, some important data can be extracted as the mass burned fraction and the cylinder pressure.

3.2 Knock Characterization

For a preliminary numerical analysis of the knock, the experimental cases 2, 3, 4 and 5 presented in Table 2 were chosen. The effects of the ignition advance on the pressure curve in the cylinder are shown in Fig. 12 and Fig. 14. Thus the characterizations of the knock phenomenon are presented in the graphs of pressure curve oscillation inside the cylinder shown in Fig. 13 and Fig. 15.

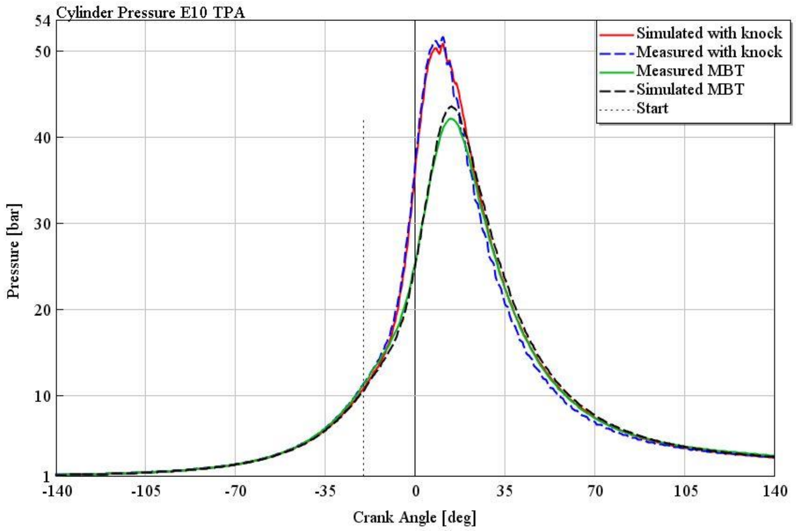

Figure 12 – Numerical and experimental cylinder pressure of cases 2 and 3.

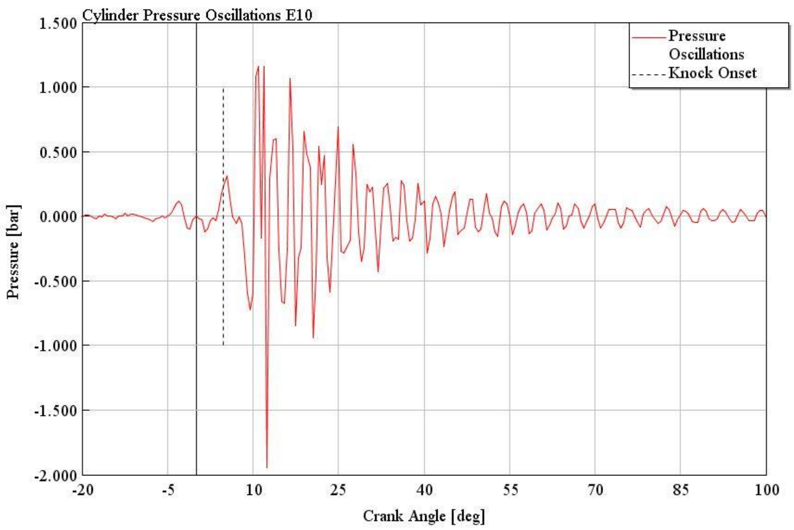

Figure 13 – Pressure oscillation in-cylinder in the case 3 for the knock characterization.

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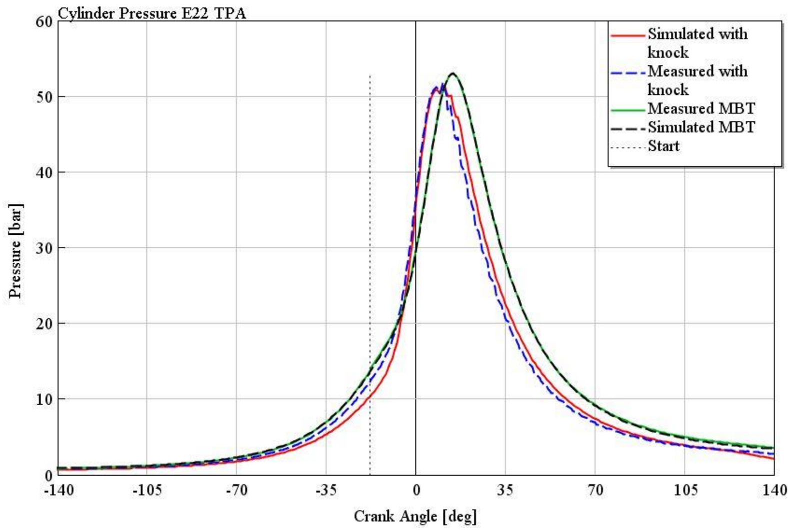

Figure 14 – Numerical and experimental cylinder pressure of cases 4 and 5.

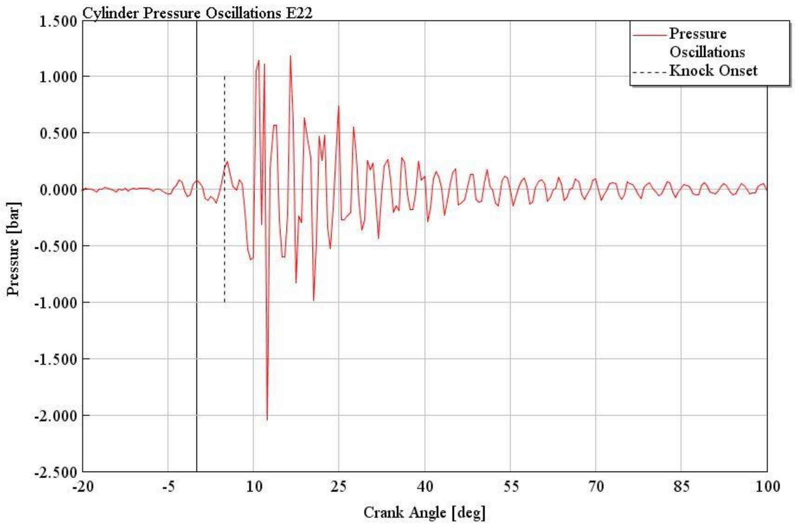

Figure 15 – Pressure oscillation in-cylinder in the case 5 for the knock characterization.

Beyond the spark timing, the main divergences of the cylinder pressure curves in the Fig. 12 and Fig. 14 is due the fact that the cylinder pressure cycle with the highest knock intensity is not necessarily the curve more similar to the curve averaged of 200.

The results presented in this topic constitute a valid and promising analysis, but, not conclusive. However, it can be considered that the knowledge acquired in the elaboration of these results is of extremely importance for the elaboration of a predictive combustion model that allows a better exploration the phenomenon of detonation.

4 CONCLUSION

In this work, through a study of the GT-Suite® software was developed a one-dimensional numerical model that represents the SCRE of the AVL® Company at the Mobility Technology Center - CTM, at the Federal University of Minas Gerais - UFMG.

The numerical model was validated against to the experimental data. The experimental data acquisition was performed according to the domain used in CFD-3D simulations, whose the boundaries are delimited in the the inlet and exhaust pressure sensors location. Due to the fact of the CFD-3D analysis are quite expensive computationally, the SCRE was instrumented to cover a relatively small domain of analysis.

In the TPA method the domain of study must also be delimited in the pressure sensors, for a good correlation with the experimental data and consequently, to perform the correct calculation of the trapped mass, mass burn fraction and pressure in the cylinder. The use of this domain in this analysis caused a great oscillation of pressure waves, mainly in the exhaust system, resulting in numerical divergences in relation to the experimental data.

The theory mentioned above could be confirmed by the development of a different and more simplified model using a non-predictive combustion model performed by the Wiebe function to impose the mass burned fraction. Therefore, due to the fact of this approach allows the expansion of the intake and exhaust domains, it was used in order to improve the correlation of the numerical results in relation to the experimental data.

The Three Pressure Analysis (TPA) also allowed the development of a methodology for the knock characterization. For this analysis was four cases were chosen for preliminary study of knock, two operating with knock border and two on the Maximum Break Torque Spark Timing (MBTST). Cases with and without knock are operating under the same conditions except for the spark timing.

In summary, one of the main challenges encountered in the development of this work, was the elaboration and validation of the TPA model. Since the CAD treatment for the internal volume extraction, to solution the errors solution indicated by the solver of the software. However, the main goals of this research is the exploration of the knock phenomenon for the development in the near future a predictive combustion model that reproduce the phenomenon and extrapolate the experimental data.

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