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# NUMERICAL ANALYSIS OF FUEL SPRAY ANGLE ON THE OPERATING PARAMETERS IN A LOCOMOTIVE DIESEL ENGINE

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***Abstract.*** *Railway sector is one of the leading actors in transportation services around the world. No wonder sustainability and energy efficiency studies about it have gained value in recent years, especially in rail freight industry where fuel consumption is quite high. This area is mostly driven by diesel internal combustion engines which efficiency is directly related to fuel consumption and the reduction of pollutant gases. These engine responses can be controlled by optimizing injection system parameters, such as fuel spray angle and swish and squish interaction, for example. Reducing levels of pollutants emitted by diesel engines have a direct impact on sustainable development. Thus, the purpose of this work is to analyze, numerically, the response of a typical locomotive compression ignition engine in terms of power, torque, fuel consumption and emissions operating with different injection angles (153°, 160° and 167°) in the same piston-in-bowl. By numerical simulation techniques of Computational Fluid Dynamics (CFD), the obtained results showed changing fuel spray angle direct impact on combustion behavior inside the cylinder geometry modeled and indicate the best responses at the smallest simulated angles, towards the cavity of the piston head*

***Keywords:*** *Rail Diesel Engine, Fuel Spray Angle, Emission, AVL-FIRE™*

## 1. INTRODUCTION

Sustainability and energy efficiency studies have increased in recent years, especially in the transportation sector, where fuel consumption and emissions of polluting gases are engineering challenges when dealing with internal combustion engines. In diesel engines, for example, Li *et al.* (2013) studies show that emissions have severe impact on global warming and tropospheric ozone formation, accounting for much of the environmental damage caused by this thermal machine. The main emissions are CO, $NO_X$, $SO_X$ and soot formation. Choi and Reitz (1999), Fuster *et al.* (2009) and Reitz and Rutland (1995), as quoted by Soni and Gupta (2017), affirm that emissions can be minimized by optimizing geometric and operational parameters on injection systems such as fuel spray angle and spray / piston-in-bowl interaction. Fuel spray direction must be precisely defined according to the shape of combustion chamber, swirl and squish movements, because the synergy of these parameters favors (or not) the complete development of spray which improves mixing air and fuel. Thus, better operational responses in terms of environment-friendly and power performance can be obtained by engines. Even a little fuel spray angle change of 2 degrees, already causes significant impact in soot formation and fuel consumption (Reif, 2014). According to Martins (2006), the biggest problem in diesel engine combustion is still in ensuring a sufficient mixture between air and fuel to obtain complete fuel burning. In this scenario, understanding fuel spray angle influence on the operation of a engine is promising, mostly in Brazil, with a high fuel consumption in the rail sector, for example. According to VALE (2011) and Pereira (2009), more than 90% of variable cost of Carajás Railroad came from diesel oil during 2007. Therefore, even a small reduction in fuel consumption already represents a significant save in outgoing values. Practical tests of these parameters aren't feasible at first, because of high components costs involved. Thus, Computational Fluid Dynamics - CFD appears as an interesting approach to this problem, also reducing time to achieve results. Gorji-Bandpy *et al.* (2009) have found that mixture of fuel and air becomes more complete increasing fuel spray angle for the engine geometry studied, resulting in fewer soot formation, but higher emissions of $NO_X$. Wei *et al.* (2014) simulated three different angles (146°, 150° and 154°) for another combustion chamber geometry and have concluded $NO_X$ and soot emissions are lower with 154° and 146°, respectively. Therefore, the purpose of this work is to analyze the influence of fuel spray angle variation on the response of a diesel engine with plausible geometric and operational characteristics when it's compared to the current systems used in locomotives. By CFD program, AVL-FIRE™ , a piston-in-bowl geometry similar to the DASH9-BB40W locomotive engines was simulated for three different fuel spray angles (153°, 160° and 167°) in order to evaluate the response in terms of power, torque, fuel consumption and emissions ($NO_X$ and soot formation).

## 2. RAIL ENGINES LITERATURE REVIEW

The current rail freight transport scenario requires high levels of torque and power from engines. For example, according to VALE S.A. (2018), a single train on Carajás Railroad (EFC) must transport more than 45 thousand tons of iron ore in 330 wagons. In this way, locomotives are equipped with large size and medium rotation engines, working with cylinders volume of 11000 $cm^3$, approximately at compression rates close to 12,7 to 17 and operational rotation between 400 and 1800 rpm (Heywood, 1988). Besides that, it is common to find two or four stroke engines from 8 to 16 cylinders operating in a range from 700 to 6300 hp (Borba, 2009). In a typical rail engine, there are 8 acceleration points and a consumption rate of more than 700 liters / hour of diesel at full load, resulting in a maximum thermal efficiency of close to 40% in this situation. The lower acceleration point, lower efficiency results (VALE, 2018). Looking at these numbers the importance of studies about the subject is noticeable

## 3. METHODOLOGY

This work is an exploratory research based on quantitative data used in Computational Fluid Dynamics through Engine Simulation. The geometry model was built using the AVL-FIRE™ ESE - Diesel tool. Soni and Gupta (2017) also used such tool to numerically evaluate the spray dynamics in two piston geometries and for three injection angles (120°, 140° and 160° ). The main idea of this work, is to maintain constant the piston geometry and only change the injection angle to analyze the responses of the engine.

### 3.1 Geometric and operating parameters for simulation

The first step was to model geometric aspects of a typical locomotive engine based on the General Electric's GE 7FDL of DASH9-BB40W manual. Table 1 shows the global geometric parameters of the modeled diesel engine. Based on studies of internal documentation at VALE S.A, (VALE, 2011), and a technical visit to the same company, an ESE-Diesel piston-in-bowl template was adapted for this typical railroad engine as shown in Figures 1 and 2. For constructing the model, the geometric engine parameters of Tables 1 and 2 were used.

Table 1. GE 7FDL geometric parameters used in this work. (VALE, 2011)

| Parameter | Description | Parameter | Description | Parameter | Description |
|---|---|---|---|---|---|
| Strokes | 4 | Stroke Length | 266.7 mm | Valves | 4 |
| Cylinders | 16 | Compression Ratio | 12.7:1 | Rod Length | 590.50 mm |
| Configuration | V | Crank Radius | 133.35 mm | Piston Bore | 228.6 mm |

As can be seen in Table 1, the engine has 16 cylinders, but only one was modeled in order to reduce computational efforts and time. In addition, axis-symmetrical condition was used, of this form, the piston allows to divide the combustion chamber by the number of injection holes, 8. Thus, only a 45° portion of cylinder was modeled with a single fuel spray characterized.

### 3.2 Numerical model by using AVL-FIRE™

In this work, geometric parameters where collected from real engine injector and piston and then used for simulation purposes. Figure 1 shows the main geometric parameters from injector and piston for the reference case (case 0). Note that, for the other simulated injection angles, only the injection angle was altered, all the others geometric parameters where kept constant, as shown in Figure 3.

Table 1 shows the values of geometrical parameters used in the numerical approach.

Based on studies of internal documentation (VALE, 2011) and technical visit to the same company, an ESE-Diesel piston-in-bowl template was created for this typical railroad engine geometry as shown in Figure 2 below.

Figure 2 also shows the block-structured mesh and contour conditions of model. There were 348232 elements in this study domain with 9640 faces and 445 contour faces. Cell size was maintained in recommendations of computational tool. It doesn't present negative volumes or triangular faces and more than 80% of the cells with aspect ratio less than 2 during mesh mobility. In order to create the model mesh, ESE Diesel mesh generator algorithm itself was used which fundamentally respects the concepts of mobile and block-structured mesh. It was possible to create and expand different blocks that accurately described the complex geometries involved, such as spray and combustion chamber, for example, along crankshaft rotation without losing the sequential indexing of finite volumes within each block. Because of this, it was possible to optimize computational costs and achieve greater reliability in the calculations performed.

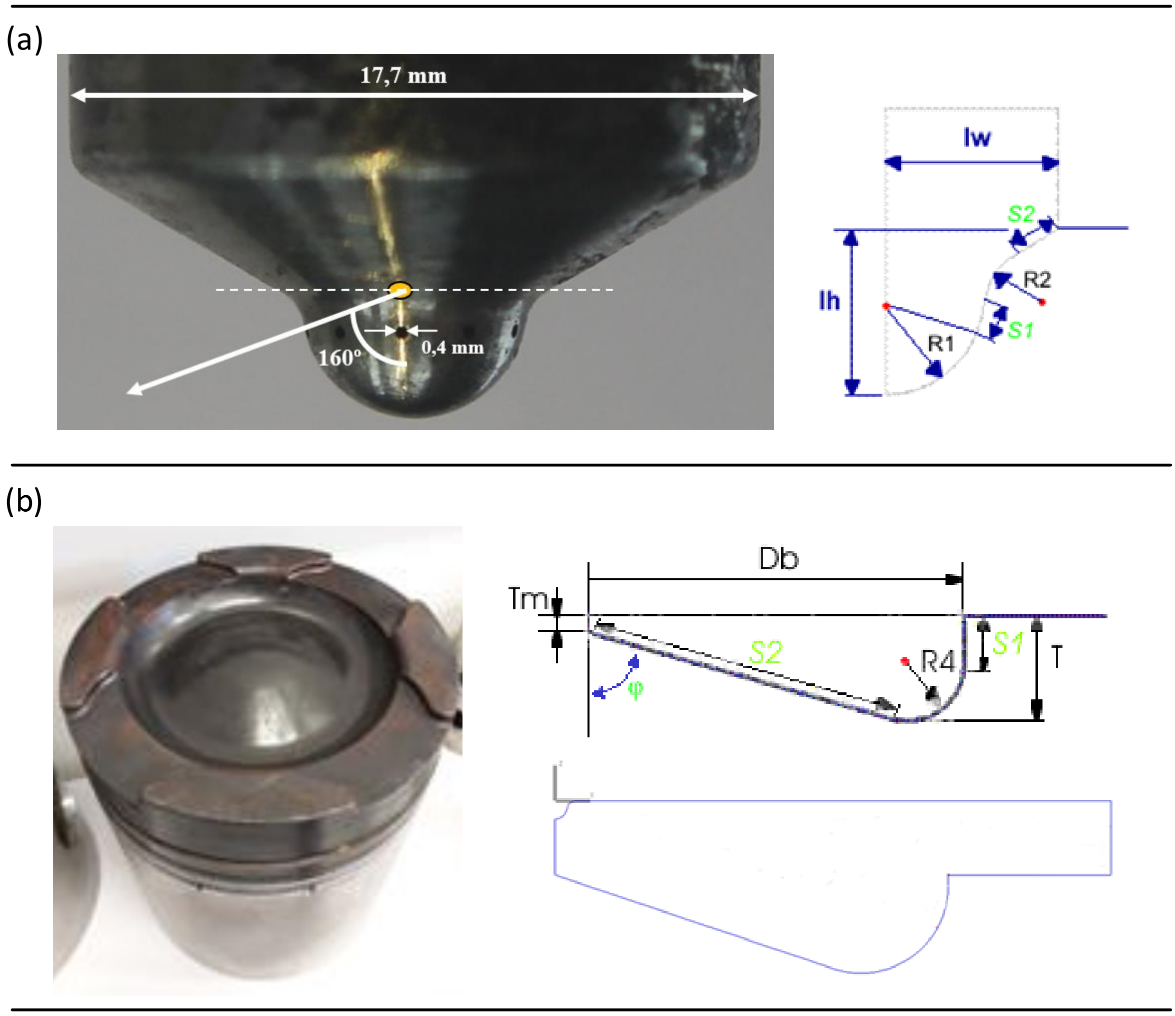


Figure 1. Geometrical parameters used in the numerical approach. (a) Injector, (b) Piston

Table 2. Injector and piston geometric characteristics used in this work

| Injector parameter | value | Piston parameter | value |
|---|---|---|---|
| **holes** | 8 | **Db** [cm] | 16.180 |
| **hole diameter** [m] | 0.040 | **T** [cm] | 2.020 |
| **injection angle** | 160° | **Tm** [cm] | 0.0 |
| **Iw** [cm] | 0.426 | **R4** [cm] | 1.800 |
| **Ih** [cm] | 0.380 | **S1** [cm] | 0.220 |
| **R1** [cm] | 0.236 | **S2** [cm] | 6.031 |
| **R2** [cm] | 0.130 | $\varphi$ | 71.38° |
| **S1** [cm] | 0.102 | | |
| **S2** [cm] | 0.088 | | |

Initial conditions were inserted into the model. It was adopted strategy of not contemplating admission cycle, so simulation begins at the closing of intake valves in order to reduce computational time. Table 3 shows the initial conditions of engine at compression cycle at the best engine acceleration point (DASH9-BB40W engine)

Finally, three case studies were created in which all previously discussed parameters were kept equal for all scenarios except for the fuel spray angle. Case 0 represents engine original configuration with 160° while Case 1 and Case 2 were 7° for less and more, respectively, when it's compared to Case 0 as shown in Figure 3. With these angles, it was already considered to obtain significant differences in engine responses.

It should be noticed that this model follows the principles of mass, momentum and energy conservation in a finite domain of control volumes. These are fundamental features of ESE-Diesel, also known as finite volume method. Also,

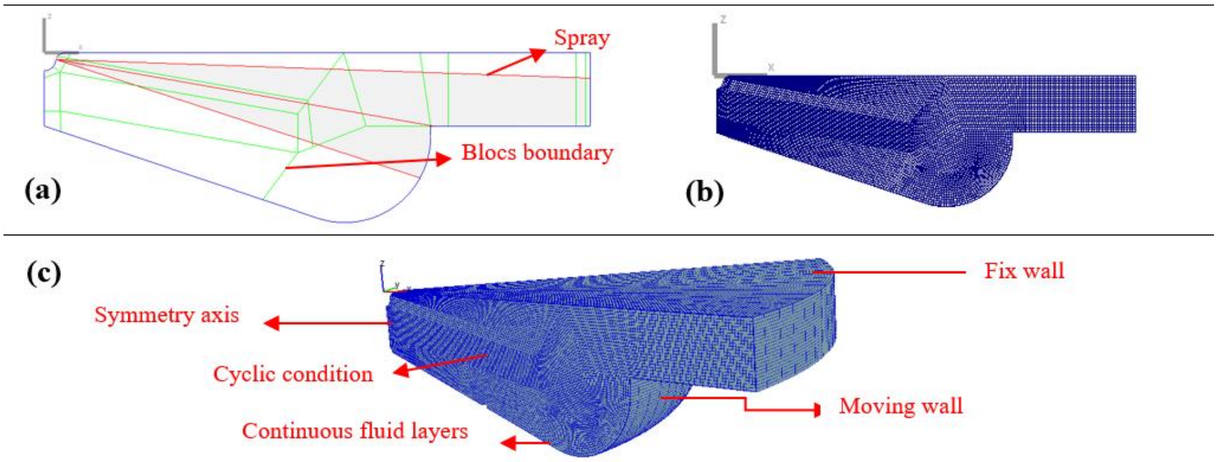


Figure 2. Combustion chamber geometry modeled at top dead center. (a) Block-structured mesh; (b) 2D model; (c) 3D model

Table 3. Initial conditions - DASH9-BB40W engine

| Parameter | Description | Parameter | Description | Parameter | Description |
|---|---|---|---|---|---|
| Rotation [rpm] | 996 | Movement wall temp. [K] | 570.15 | EGR Mass fraction | 0.049 |
| Cylinder pressure [Pa] | 255000 | Fixed wall temp. [K] | 470.15 | Rotation direction Z | -1 |
| Air temp. [K] | 355 | Fuel | Diesel-D1 | Turbulent kinetic energy [$m^2/s^2$] | 10 |
| Fuel temp. [K] | 350 | Injected mass [kg] | 1.10E-03 | Injection duration [ms] | 6.35 |
| Swirl [1/min] | 2880 | Turbulent length scale [m] | 0.0045 | Crank angle injection start [°] | 342 |

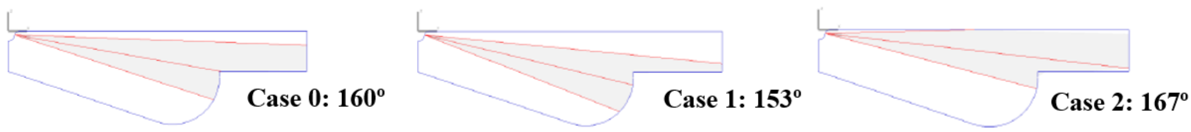


Figure 3. Case studies. (a) Case 0 (160°); (b) Case 1 (153°); (c) Case 2 (167°)

sub-models recommended by AVL-FIRE™ (2017) and published and used for other authors in the literature, (Soni and Gupta, 2017), were used to describe important phenomena involved such as combustion (ECFM-3Z), spray droplets (Wave), drag (Schillar Naumann), evaporation (Dukowicz), cylinder wall interaction (Wall Jet 1), NO formation (Extended Zeldovich) and soot formation (Kinetic Model).

The fuel incorporated in the ESE-Diesel model, Diesel-D1, has a LHV of 42.3 MJ/kg close to B10 used in Brazil for locomotives, which has 41.5 MJ/kg (VALE, 2011). The fuel in the model does not accurately reflects the actual case, as it does not present the percentage of biodiesel used, which in itself already modifies the properties of the fluid. Further studies on the numerical model would be needed to change the fuel in the ESE - Diesel. It was not possible to obtain data on the fuel temperature at the time of injection, so the recommended 350 K was maintained. Rafidah *et al.* (2012) discuss the effects of this parameter on the responses of a diesel engine, varying the fuel temperature at the time of injection from 300 K to 500 K and found maximum reductions of 1.39% and 1.13% in power and torque respectively.

The numerical simulations were performed in a computer with 8 cores, 3.4 GHz processing and 16 GB of RAM, which lasted around 24 hours (each simulation)

## 4. Results and discussion

### 4.1 Temperature fields

The numerical data shows a direct relationship between fuel spray angle and combustion process, especially on the air and fuel mixture temperature. It's known temperature is a dominant parameter in pollutants formation. Thus, it was considered to evaluate temperature in different regions of combustion chamber as shown in Figure 4. There is a significant difference in the rate of heat release in simulated cases. Linked to temperature, it is known that they are dominant parameters in the formation of pollutants. In this way, it was considered to evaluate the temperature in different regions of the combustion chamber. Strong interaction wall-spray with the upper cylinder wall was found in Case 2 which is at a much lower temperature than air and fuel mixture according to Figure 4. This interaction wall-spray causes temperature drop of mixture and doesn't allow full development of spray what causes incomplete burning and, consequently, performance losses in terms of power, torque and fuel consumption. On the other hand, Case 1 showed higher levels of mean temperature when it's compared to the other cases. Because of this, there are improvements in engine responses cited above. However, there is an increase on NO emissions, as shown in Figure 5. From values above 1800 K there are accelerated formation of this pollutant as is the engine modeled, especially in Case 2 where regions exceed 2500 K and stays for longer.

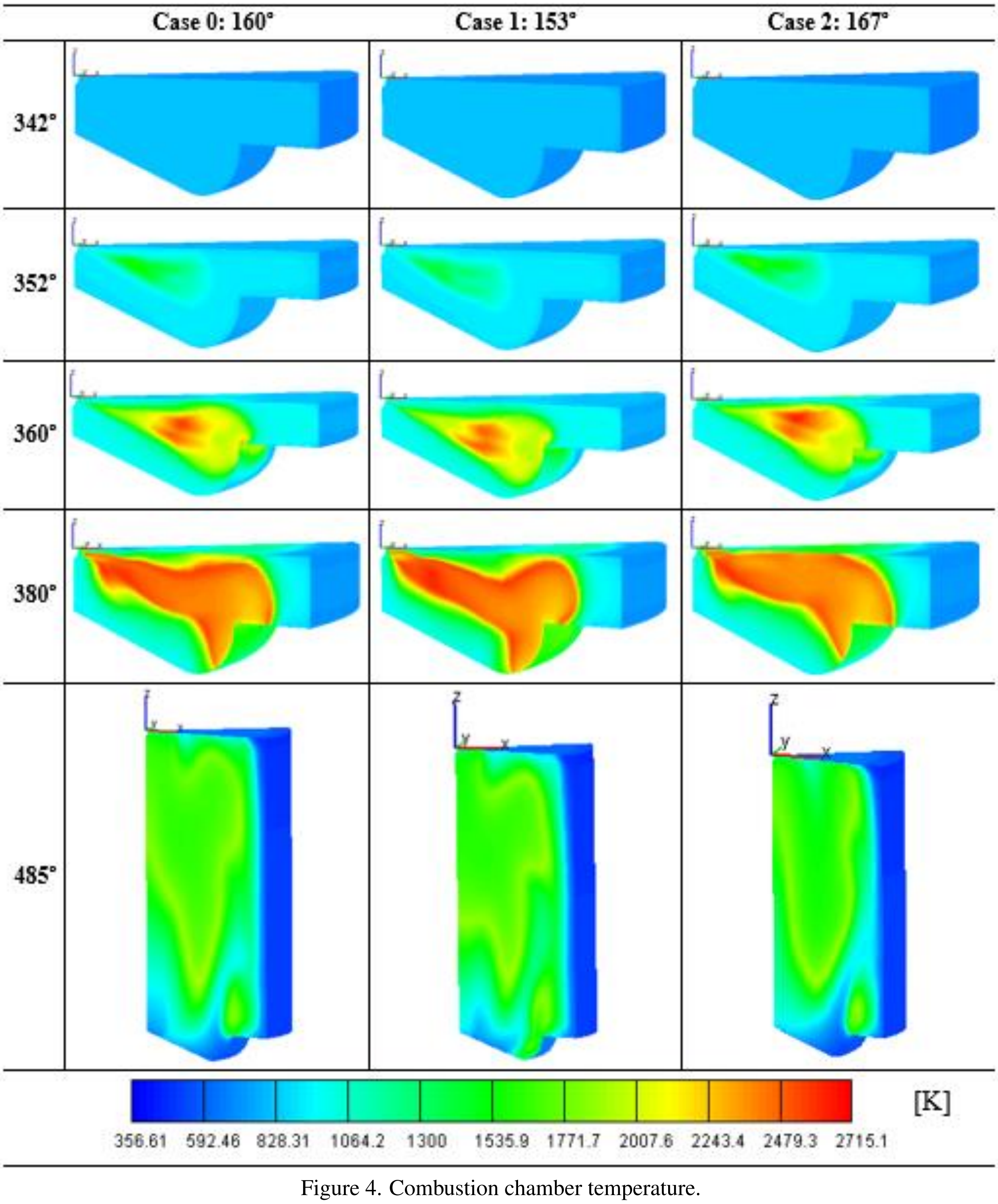


Figure 4. Combustion chamber temperature.

## 4.2 Emissions

### 4.2.1 Nitrogen oxides

Nitrogen oxides are the main constituent of known NOx gases, which must be avoided as they are harmful to humans, leading to problems of acid rain, intoxication, hemorrhage and even death by asphyxiation. According to Merker *et al.* (2012) and Baumgarten (2006), the NO formation rate is practically insignificant at temperatures lower than 1600 and 1800 K, as can be seen in Figure 5, in periods when combustion is not as poorly developed (342° to 360°).

It is only from temperatures above 1800 K that the formation of this pollutant is accelerated, as shows the numerical results of this work where regions that exceed 2500 K are found, mainly around the spray. At 380° of rotation of the crankshaft, there are high temperatures in the cylinder and, consequently, the most expressive mass fractions of NO. Two cutting planes are presented in this period to evaluate the concentrations of the pollutant, the already used across the central axis of the jet and another that seeks the top view of the spray. The highest and lowest concentrations are observed in Case 1 and Case 2, respectively.

Soni and Gupta (2017) also found smaller fractions of NO reducing the fuel spray angle when simulating 120°, 140° and 160°. But Wei *et al.* (2014) reduced fractions of this pollutant with an increase in fuel spray angle from 146° to 154°. These conflicts only prove the interaction of spray with piston-in-bowl, swirl and squish movements into combustion chamber, what predominates on engine final responses. Therefore, this kind of investigations must be evaluated from motor to motor and can not provide generalized solutions, because there are a lot of parameters simultaneously interacting. CFD appears as an interesting approach to this kind of problems.

In this case, the simulation attest to the principle of higher NO formation with the higher chamber temperature, located around the spray, where the vaporization of the mixture has already occurred, and displaced laterally to the x-axis, where there is more air coming of the swirl. Turning clockwise in Z, as the air moves, it is consumed by the fuel, to the point where the minimum air quantity for the formation of the mixture begins to be lacking and thus not to burn completely, favoring the formation of soot.

### 4.2.2 Soot

Highly toxic to humans, particulates also cause serious damage to the engine, increasing wear on the components and, when deposited in the injector nozzles, hamper the development of the fuel jet inside the combustion chamber. The formation of soot occurs with greater intensity at temperatures below 1650 K, at which point complete combustion begins to prevail (AVL-FIRE™, 2017; Merker *et al.*, 2012; Baumgarten, 2006). Following the same methodology of analysis carried out for nitrogen oxides, it is possible to observe the higher formation of soot, in Case 2 in regions of lower temperatures and concentration of available air. Figure 6 shows the numerical prediction.

The interaction of the fuel jet with the cylinder wall and the direction of rotation of the swirl as the dominant factors for this pollutant is also highlighted. At the end of the combustion (485°), a significantly larger fraction is observed in Case 2 compared to the other cases. Discussions on the pollutants emitted so far are based on cutting planes within the cylinder. However, there is a volume of control under study and these plaques can mask the results and lead to false statements. In order to avoid this problem, we evaluated the mean mass fractions throughout the cylinder volume, as shown in Figure 6, where we can confirm the conclusions of higher soot fraction and NO for the injection angles 167° and 153°, respectively. Figure 6

## 4.3 Mean Effective Pressure, Indicated Power and torque, Specific Fuel Consumption and Indicated Thermal Efficiency

Table 4 shows the numerical predictions for all the cases simulated in this work. As can be seen in Table 4, when changing the injection angle, there is a different behavior of the combustion inside the diesel engine, characterized by the different values found in the simulations. The air / fuel ratio and stoichiometric ratio remained the same in both cases, because the amount of air and fuel mass injected were not altered in the proposed methodology. According to Borba (2009), the stoichiometric ratio of GE-7FDL diesel engines is not less than 1.3 at full load, and may increase according to the operation of the turbochargers and injection system.

Table 4. Global operation parameters - Numerical predictions

| Run case | Mean Effective Pressure [bar] | Indicated Power [kW] | Indicated Torque [Nm] | Air-Fuel Ratio ($\lambda$) | Specific Fuel Consumption [kg/kWh] | Indicated Thermal Efficiency |
|---|---|---|---|---|---|---|
| Case 0 | 15.95 | 145.94 | 1399.25 | 1.77 | 0.2269 | 0.38 |
| Case 1 | 16.00 | 146.33 | 1402.92 | 1.77 | 0.2263 | 0.38 |
| Case 2 | 14.68 | 134.38 | 1288.35 | 1.77 | 0.2466 | 0.35 |

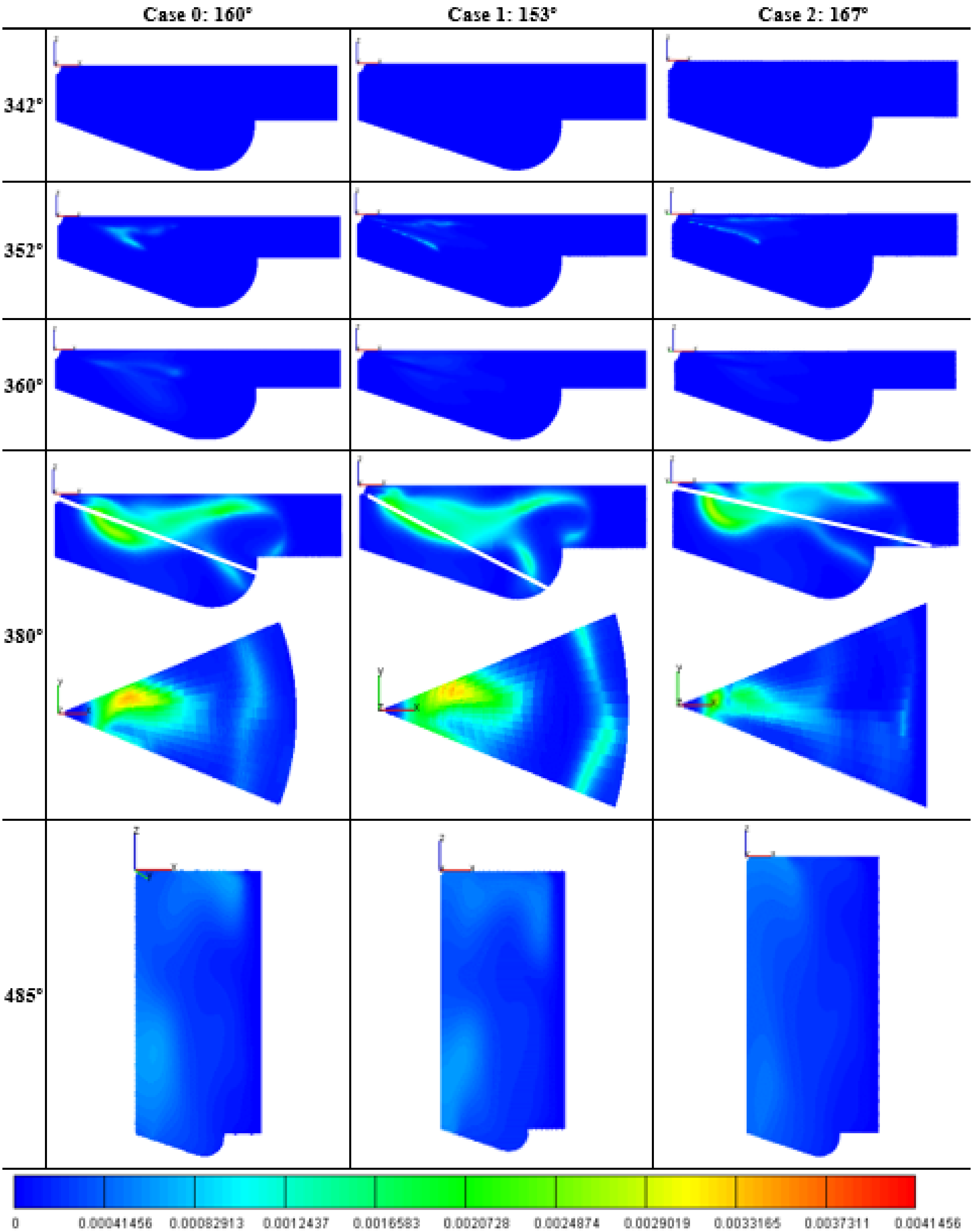


Figure 5. Combustion chamber - NO mass fraction.

Comparing Table 4 and 5, it can be seen that the effective mean pressure of Cases 0, 1 and 2 are: 15.95 bar, 16 bar and 14.68 bar, respectively. These values are within the range of maximum and minimum values found in locomotive 'A' in this work, which qualify the present work. Based on Case 0, we can see an increase of 0.31% in the effective mean pressure with the reduction of the proposed injection angle and 7.96% decrease with 7° angle modification.

Following the same comparison procedure for the indicated power, there are 0, 1 and 2 cases: 145.94 kW, 146.33 kW and 134.38 kW, respectively. These values are in agreement with the studies in Table 9, however, a sharp fall of 7.92% in

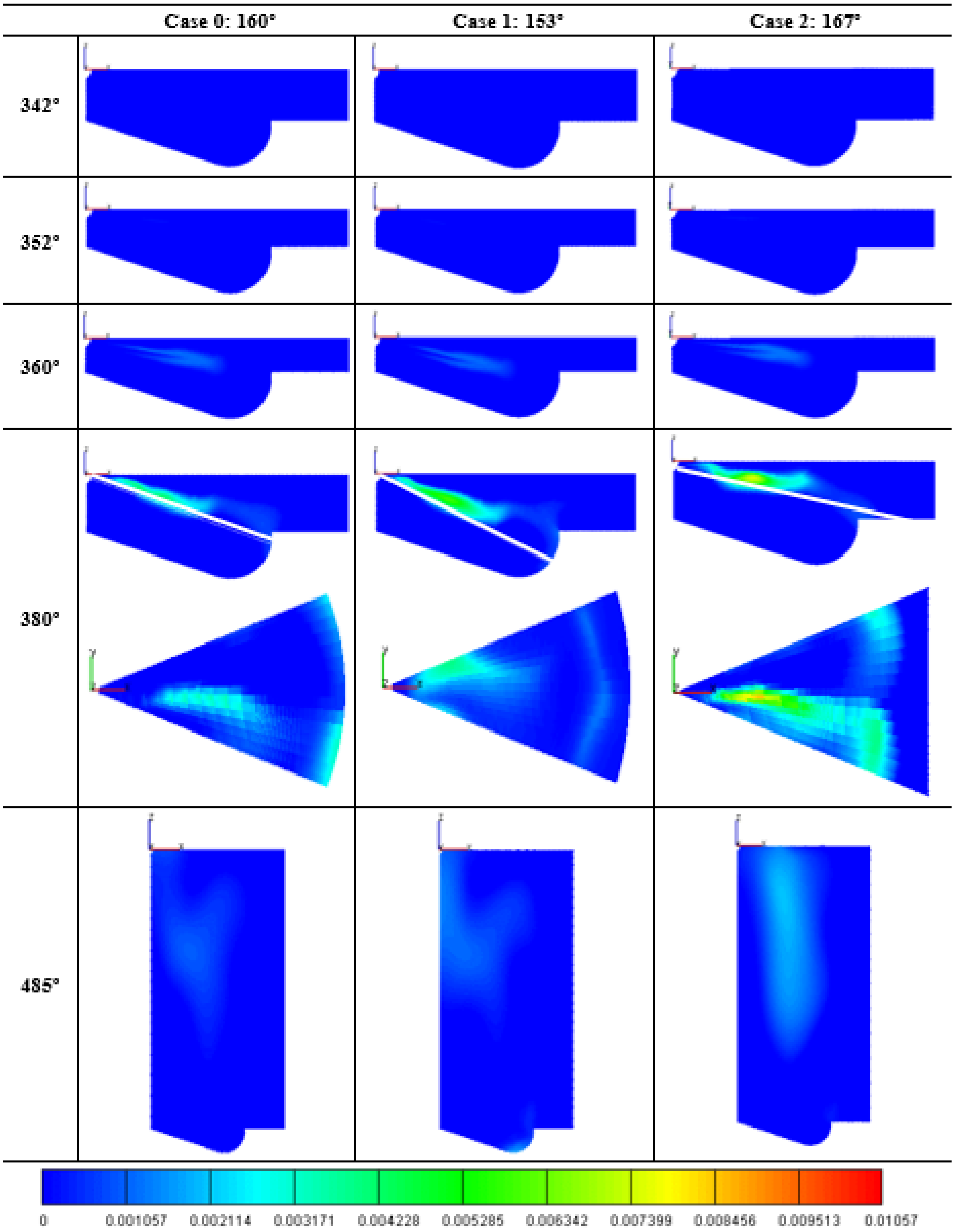


Figure 6. Combustion chamber - Soot formation.

power is observed with the increase of the proposed angle modification, with reference to Case 0. As for Case 1, there is an increase of the indicated power.

Torque and specific consumption follow the same behavior as indicated power as they are related. Increasing the injection angle has a drop of 7.92% in the indicated torque and increase of 7.98% in the specific fuel consumption. On the other hand, as the angle decreases, there is an increase of 0.26% in the indicated torque and a reduction of 0.26% in the indicated consumption. The change in injection angle alters the interaction with the flow motions in the combustion

Table 5. Averaged measured parameters, per piston - Dash 9 BB40W - locomotive 'A'. (VALE, 2011)

| | **Mean Effective Pressure [bar]** | **Indicated Power [kW]** |
|---|---|---|
| **Average** | 15.79 | 154.17 |
| **Maximum** | 16.96 | 169.27 |
| **Minimum** | 14.13 | 140.88 |

chamber. The results show that in case 2 the worst use of swirl and squish was obtained, since the jet was directed outside the cavity of the piston, region in which there is the smallest movement of gases in this model. In this way, differences are observed in the responses of the engine, as in the average effective pressure, indicated power, indicated torque and specific fuel consumption, as already mentioned.

In addition, the injection angle determines the point of impact of the spray with the cylinder wall. By directing the spray at the highest angle change, the results indicate that most of the fuel will not be vaporized during the combustion process, i.e., it will remain in liquid or solid form because it is in close contact with cooler walls at the top of the cylinder. This unused fuel favors the emission of pollutants from incomplete burning, as well as provoke the power reduction observed in Case 2.

## 5. CONCLUSSION

The obtained results indicate the best responses at the smallest simulated angles, towards the cavity of the piston head, because it is where the greatest gas circulation is and the necessary conditions for the droplet breaks until the vaporization and burning of the mixture, generating more power and lower fuel consumption. New studies may point out from when you begin to reflect negatively the decrease of the angle of injection, because it is necessary to arrive at the moment when the jet will lose development space when being directed exclusively to the piston head. It was possible to reproduce the engine geometry (cylinder, piston and combustion chamber) to carry out the numerical analyzes in a similar way of the DASH9-BB40W engine characteristics, as well as to cohesively portray the operating conditions of the system to be used in terms of pressure, temperature and other input variables for the numerical simulation at the best engine acceleration point. Changing fuel spray angle showed direct impact on combustion behavior inside the diesel locomotive engine cylinder modeled. Results indicate different responses in terms of power, torque, fuel consumption and emissions (NO and soot formation) for three different fuel spray angles (153°, 160° and 167°) in the same piston-in-bowl combustion chamber geometry. Engine was modeled in ESE-Diesel by AVL-FIRE™ simulation tool and it was validated based on actual locomotive DASH9-BB40W operating data. It's believed that negligible changes in power, torque and consumption are found with reduction of fuel spray angle from 160° to 153°. On the other hand, by raising this parameter to 167° there are reductions of 7.92% in power and torque produced and increase of 7.98% in specific consumption. For emissions, the largest mass fraction of NO and soot were found at 153° and 167°, respectively. Obtained results indicates the best response at the smallest simulated angle toward piston-in-bowl. There are higher levels of gas circulation in this area and the necessary conditions for droplet breaks until vaporization and mixture burning which insure greater power and lower fuel consumption. New studies can point out from which angle less than 153° the engine will begin to present worse responses since spray will lose its development space when it's directed to piston head. Finally, it is emphasized this is an exploratory study. As proposal for future work, it is recommended to repeat the study with different piston-in-bowl combustion chamber geometry and other fuel.

## 6. ACKNOWLEDGEMENTS

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