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# SPRAY BEHAVIOR ON COMPRESSION IGNITION INTERNAL COMBUSTION ENGINES: A CFD ANALYSIS OF CAVITATION IN THE FUEL INJECTOR

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**Abstract.** Cavitation is a common phenomenon in fuel diesel injectors and has a strong influence on engine's performance, of this form, research on cavitation phenomenon in fuel injectors and its effect on spray breakup is very important for reduction of emissions and fuel consumption. In this work, the flow of diesel fuel throughout a SAC type injector was numerically analyzed. Pressure, temperature, fuel liquid and vapor phases as well as surface erosion are numerically investigated inside the discharge channel of the diesel injector. Three injector operation parameters: (a) fuel pressure, (b) fuel temperature and (c) needle lift were varied in order to understand the fluid flow trend in the discharge channel of the injector. Numerical experiments were performed in AVL-AST™ software by using a simplified geometry and a simplified DOE was proposed in order to better understand the influence of injector's operation parameter on cavitation and spray behavior. Results are discussed and analyzed in terms of pressure, temperature, liquid and vapor fuel as well as surface erosion.

**Keywords:** Cavitation, AVL-FIRE™, Spray, CI Engines

## 1. INTRODUCTION

Cavitation occurs in a wide range of engineering applications such as pumps, turbines and in some components of internal combustion engines as fuel injectors, and in this case, is often associated with undesired consequences such as loss of power, fuel consumption and emissions increase. Cavitating flows are unsteady in nature with their distinct flow features exhibiting highly varying spatial topology and short time scales. Under certain flow conditions, cavitation is possible to exhibit a periodic behavior characterized by the shedding of coherent vortical structures, (Mitroglou *et al.*, 2017).

Scarcity of crude oil and high rising price represent a challenge engine developers to manufacture and model less polluting and more efficient systems in order to meet demands and restrictions imposed by governmental regulations (Kumar *et al.*, 2013). In compression ignition engines, the relationship between nozzle aperture, channel length, pressure and the injection time, besides the working temperatures are directly related to the spray development and characteristics of the combustion process in the chamber, having this parameters a big impact on engine's efficiency and emissions.

Diesel engines are increasingly used in automotive applications due to superior fuel economy, however, they have to meet stringent emission legislation on pollutants such as nitrogen oxide (NO<sub>x</sub>) and particulate matter (PM). The multiple injections and high injection pressure offered by common rail (CR) fuel system can reduce the emission of particulate matters due to improve spray atomization and fuel mixing (Zhu *et al.*, 2003).

Experimental tests focusing engine's optimization (fuel economy and pollutant emissions) requires changes in input parameter, this is highly demanding in terms of money and time. An alternative is the numerical simulation of engine performance with the help of mathematical models and powerful digital computers reducing cost and time (Kumar *et al.*, 2013). By means of numerical simulation, in this work is analyzed the spray behavior in a simplified injector and chamber geometry, the interactions between different input parameters, as well as the effect of cavitation on the injector, correlating the changes with the referred results. In this work, the numerical data of AVL-AST standard example file "Injection Nozzle: Diesel injector (910)" was used to perform this numerical analysis having as focus the of the impact / influence of changing injector operation parameters. A simplified design of experiments (DOE), was used to determine the relationship between factors affecting the process and the output of that process (Sundararajan, 2000-2019).

## 2. DIESEL INJECTORS AND CAVITATION PHENOMENON

Cavitation is a common phenomenon in fuel diesel injectors and has a strong influence on the internal flow and combustion development in the combustion chamber because it significantly influences fuel mixture preparation and combustion of IC engines, of this form, research on cavitation phenomenon in fuel injectors and its effect on spray breakup is very important for reduction of emissions and fuel consumption.

Regarding that, there are two main forms of cavitation: (a) hydrodynamic cavitation, that occurs when the pressure decrease below static vapor pressure of liquid, and (b) the geometric cavitation which is influenced by the stress concentrations imposed by the geometry, causing pressure drop and thus cavitation. These cavitation inside the nozzle increase the turbulence level and stimulate the spray disintegration.

The phenomenon in diesel fuel injectors have been analyzed by several research groups around the world by using both, experimental and numerical approaches. Figure 1(a) shows the typical full-cone spray development in a SAC - type injection hole. The first break-up is called primary break-up and results in large droplets that form the dense spray near the nozzle. At high pressure injection, cavitation and turbulence are the main break-up mechanisms (Baumgarten, 2006).

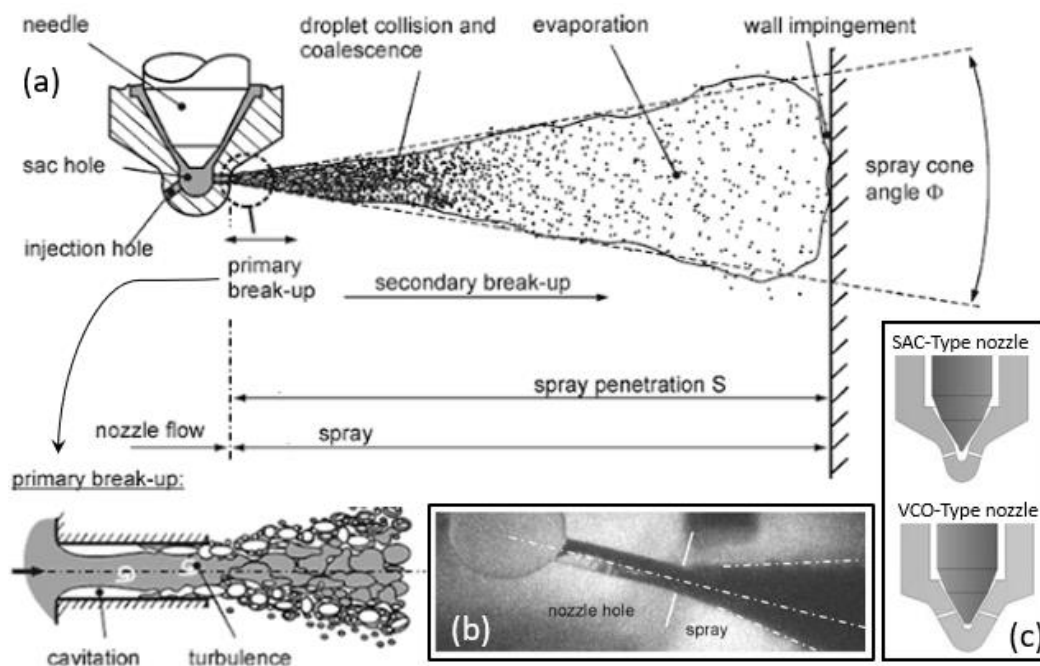


Figure 1. (a) Typical full-cone spray development in a SAC - type injection hole. (b) Effect of the cavitation / erosion process in the spray symmetry. Adapted from Baumgarten (2006). (c) Predominant diesel fuel injector nozzle designs. Adapted from TechnoYam (2019)

As spray develops, the droplets with low kinetics are pushed to the outer spray region, forming the conical design. The further away from the initial cone, the more steam and less liquid are witnessed. In the dilute spray further downstream, the main factors of influence on further spray disintegration and evaporation are the boundary conditions imposed by the chamber as gas temperature and density as well as gas flow (Baumgarten, 2006). Cavitation develops inside the nozzle holes because of the decrease of static pressure due to the strong acceleration of liquid, different from boiling, where there is an increase in temperature. Figure 1(b) shows the effect of the cavitation / erosion process in the spray symmetry.

### 2.1 SAC and VCO injectors

Two basic types of nozzles can be classified depending on the design of the needle seat and nozzle hole inlets, Figure 1(c) shows both the predominant diesel fuel injector nozzle designs, the nozzle SAC type - which will be the model used in the numerical experiment, and the valve covered orifice VCO type.

Developments in the design of the injector nozzle have led to a reduction in SAC volume with the introduction of mini-SAC and VCO nozzles and a consequent improvement in engine hydrocarbon emissions. The major difference between the two designs lies in the fact that in SAC or mini-SAC the needle closes the nozzles in a region above the holes. In VCO type the needle covers the holes when it is closed.

## 2.2 Cavitation phenomena in fuel injectors

In fuel injectors, if the liquid fuel pressure falls locally, below the vapor pressure, vapor fuel bubbles are formed in that region. If the cavitation is extremely strong, the erosion caused by cavitation may occur in the proximity of the phenomenon. When the surface is eroded, the process continues at a higher rate than the initial one. Increasing the roughness promoted by erosion increases the cavitation bubbles and weakens the already deteriorated surface. If this occurs within the holes of a diesel injector, the result of the geometry change would negatively influence the injection process (Lindtröm, 2009).

The hydrodynamic cavitation is the most important effect in diesel engine fuel injection nozzles. At localized pressure changes inside the nozzle cavitation, bubbles and cavities originate. The visual observations of the cavitation process are extremely difficult due to high flow velocities in the spray hole and the typical spray hole dimensions (Blessing *et al.*, 2003). Cavitation in such nozzles has been identified in two distinct forms. The geometric-induced cavitation is a relatively well-known phenomenon initiating at sharp corners where the pressure may fall below the vapor pressure of the flowing liquid (Andriotis *et al.*, 2008).

The second form of cavitation is referred to as string or vortex cavitation, these structures have been observed in the in the bulk of the liquid inside sac and mini-sac type nozzles, where the relatively large nozzle volume allows the formation of large-scale vortical structure. Studies have provided evidence that geometric-induced and vortex cavitation structures can interact, thus increasing the inherent instability of such transient flow fields (Mitroglou and Gavaises, 2013). Duan *et al.* (2016) studied the injection performance and cavitation analysis of an advanced 250 MPa common rail diesel injector, they used 1-D and full 3-D CFD computation in order to determine the fuel mass flow rate and velocity fields thorough the injector holes.

A new and optimized injector geometry was proposed and numerically tested showing better injection conditions in terms of cavitation performance. Wang *et al.* (2016) analyzed the effects of structure parameters on flow and cavitation characteristics within control valve of fuel injector for modern diesel engine, they reported the effects of the seal cone angle on pressure and velocity as well as on cavitation characteristics by using numerical models. He *et al.* (2016) performed a visual experiment of transient cavitating flow characteristics in a real-size diesel injector nozzle. In their study, experimental test under different pressures were performed in order to analyze the evolution of cavitation inside diesel nozzle, and it was found that higher injection pressure leads to earlier cavitation inception.

Liu *et al.* (2019) study the cavitation dynamics and primary breakup by using highly resolved microscopic imaging technique with an enlarged transparent nozzle and a real-sized nozzle under various throttling conditions. Salvador *et al.* (2013) performed an extended computational study in a multi-hole nozzle modeling 10 different fixed needle lifts. In their work, the internal flow was modeled with a continuum nozzle flow model that considers the cavitating flow as a homogeneous mixture of liquid and vapour, due to high Reynolds numbers, turbulence effects were taken into account by RANS methods using a RNG  $k-\epsilon$  model.

Mouvanal *et al.* (2018) presented a a CFD based numerical technique to predict potential erosion due to cavitation, several cavitation models for erosion are reviewed and the numerical approach was performed in ANSYS FLUENT. Mitroglou *et al.* (2017) experimentally investigates the development and collapse of cloud cavitation and its link to surface erosion, the characterization was performed by using the high-speed imaging technique in a transparent test single-orifice nozzle operating with a closed Diesel fuel hydraulic circuit. Gao *et al.* (2017) studied the effects of cavitation flow and stagnant bubbles on the initial temporal evolution of diesel spray by using a optically transparent nozzle simulating a sac and spray orifice.

## 3. METHODOLOGY

In this work, the flow of diesel fuel throughout an SAC type injector was numerically analyzed. Pressure, temperature, fuel liquid and vapor phases as well as surface erosion are numerically investigated inside the discharge channel of the diesel injector. Three injector operation parameters: (a) fuel pressure, (b) fuel temperature and (c) needle lift were varied in order to understand the fluid flow trend in the discharge channel of the injector.

### 3.1 Simplified geometry

Figure 2 shows the simplified geometry of the computational domain used in this work. Figure 2(a) shows a SAC-type injector tip indicating the needle and SAC hole. Figure 2(b) shows the fluid domain composed by the fluid inside the injector and the discharge volume.

Figure 2(c) shows an overall view of the computational mesh. Note that, the geometry used in this work is not plenty in details, this is a preliminary study in order to better understand the capability of AVL software to represent cavitation phenomenon.

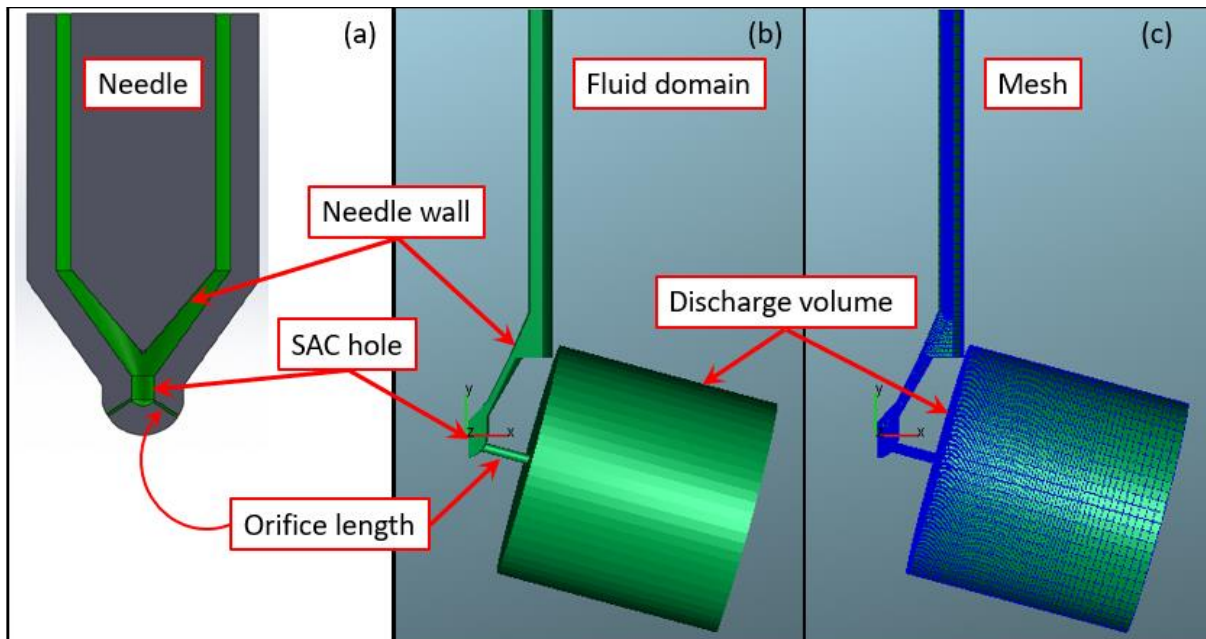


Figure 2. Geometry. (a) SAC-type injector, (b) simplified geometry, (c) Mesh

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

The AVL software represents an advanced and fully integrated virtual engine simulation tool with models for predicting accurate engine performance (Ion and Anisor, 2011). It is used for design and optimization engineering process, involving complex geometries, chemical and physical modeling and particularly developed for internal combustion engines. The solver allows heat transfer, exchange gases, combustion process, fuel injection, emission, as well as other functionalities (Lucasz *et al.*, 2012). There are different approaches of models for IC diesel engines (Merker *et al.*, 2012).

In this work, the thin spray model described in Kumar *et al.* (2013), and previously implemented in AVL-AST was used. With respect to the liquid phase, spray calculations are based on a statistical method referred to as the discrete droplet method (DDM). Using the single zone model, are obtained from ordinary differential equations trajectory, momentum, heat and mass transfer of single droplets as well as the cylinder pressure, temperature and mass. The dual zone combustion model provides better results in face of single zone.

Otherwise, multizone model use the temporal and spatial variations of temperature and concentration to permits calculations of exhausted gas composition. The droplets are tracking in a Lagrangian way through the computational grid used for solving the gas phase partial differential equations. Full two-way coupling between the gas and liquid phases is taken into account (AVL LIST, 2014). Using multiphase models, it is possible to simulate phenomena in various injection devices, including non-linear cavitation effects and taking into account the movement of the injection needle (Lucasz *et al.*, 2012). Complete details about numerical model can be find at Adao (2018)

#### 3.2.1 Mesh, boundary and initial conditions

The meshing AVL-AST is a relatively easy process. AVL has an automatic mesh generator composed mainly by three tools: FAME™ Hybrid, FAME™ Advanced Hybrid and FAME™ Motion. In this work, an hexa mesh with a total number of cells of 153.896, allowing 167.646 nodes was created. Note that, the needle movement allows the total number of cell and nodes to keep constant for all the needle positions along the lift, just changing the aspect-ratio parameter of all meshes, Figure 3 shows some pictures with the mesh at tree needle lifts. Skewness higher than 0.71 was not detected in the meshes for all needle positions along the needle lift.

Boundary conditions were placed as moving wall (needle), symmetry, inlet and outlet for liquid fuel, fuel vapor and air respectively. Note that, the fact of three phases (see Table 1) be present in the numerical simulation, demand specification of boundary conditions for all of them.

Table 1 shows the initial conditions for all numerical experiments based on the reference case adopted for this work. By using the multiphase model, only pressure is defined for phase 1, because in the multifluid simulations the numerical model share the same pressure field by all phases (AVL-DOCUMENTATION, 2014).

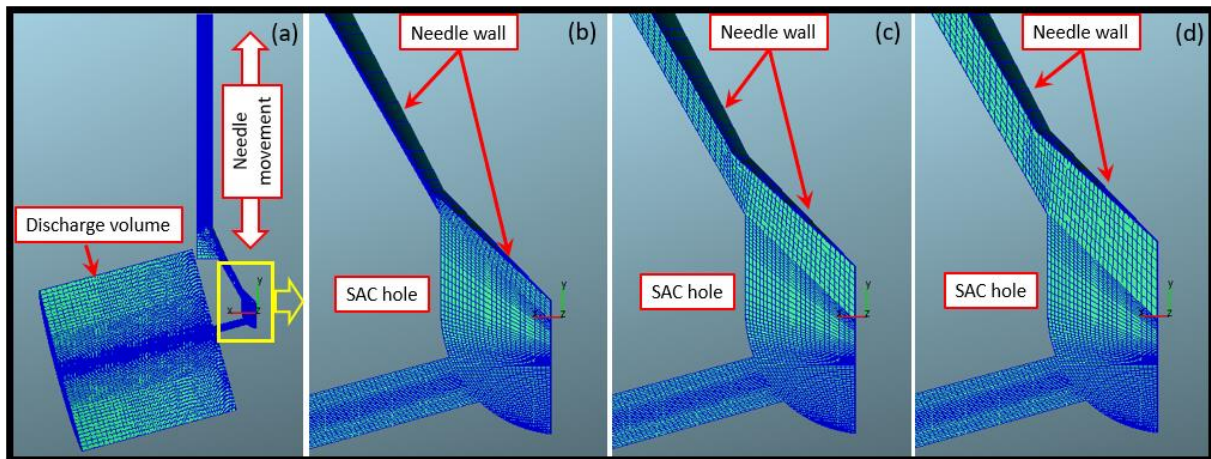


Figure 3. Computational mesh used in this work. (a) full domain, (b), (c) and (d) meshes at tree lift position showing the effect of changing the aspect-ratio.

Table 1. Initial condition table for base model

Parameter	Phase 1 (fuel liquid)	Phase 2 (fuel vapor)	Phase 3 (air)
Pressure	$2.0^8$ Pa	-	-
Temperature	293.15 K	293.15 K	293.15 K
Velocity ( $u, v, w$ )	0.0	0.0	0.0
Volume Fraction	0.999998	$1.0^{-6}$	$1.0^{-6}$

### 3.3 Simplified DOE analysis

A simplified design of experiments with pressure, temperature and needle lift as main target variation parameters was performed. Table 2 show the DOE approach of the study. It was opted to not use all the combinations of the two-level factorial design, because based on previous studies, their effect is not important and already understood, like work with half the pressure and half the initial temperature. Fifteen numerical experiments were performed in order to complete this simplified analysis, Table 2 summarizes all the simulated conditions.

Table 2. Simplified design of experiments used in this work

Numerical experiment #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pressure factor	0.5	-	2	-	-	-	-	-	0.5	2	0	2	2	2	2
Temperature factor	-	2	-	0.5	-	-	2	0.5	-	-	0.5	2	2	0.5	0.5
Needle lift variation (%)	-	-	-	-	0.25	-0.25	-0.25	0.25	0.25	-0.25	0.25	-0.25	0.25	-0.25	0.25

The set-up diesel injector example 910 was used as started point (reference) to the others numerical experiments. The comparison strategy was based on initial pressure, initial temperature and needle lift changes. For temperature and pressure, was varied half on the value up and down (pressure and temperature factors on Table 2), from 283.15 K to 313.15 K and 100 MPa to 200 MPa, respectively. The needle opening treatment should have an increase of 0.25% greater and 0.25% smaller compared to the initial opening, causing a greater or lesser closure of the passage of fluid through the nozzle hole.

## 4. RESULTS AND DISCUSSION

The comparison strategy was based on initial pressure change, initial temperature and needle lift. For temperature and pressure, we varied half on the value up and down, from 283.15 K to 313.15 K and 100 MPa to 200 MPa, respectively. The needle opening treatment should have an increase of 0.25% greater and 0.25% smaller compared to the initial opening, causing a greater or lesser closure of the passage of fluid through the nozzle hole.

#### 4.1 Injection pressure

Figure 4 shows the influence of pressure on the volume fraction of vapor phase and in the mean depth of penetration rate of surface erosion (MDPR). Figures 4 (a), (c) and (e) are numerical results for the reference case (200 MPa), and Figures 4 (b), (d) and (f) for the modified value of pressure 100 MPa, corresponding to the numerical experiment #1 on Table 2.

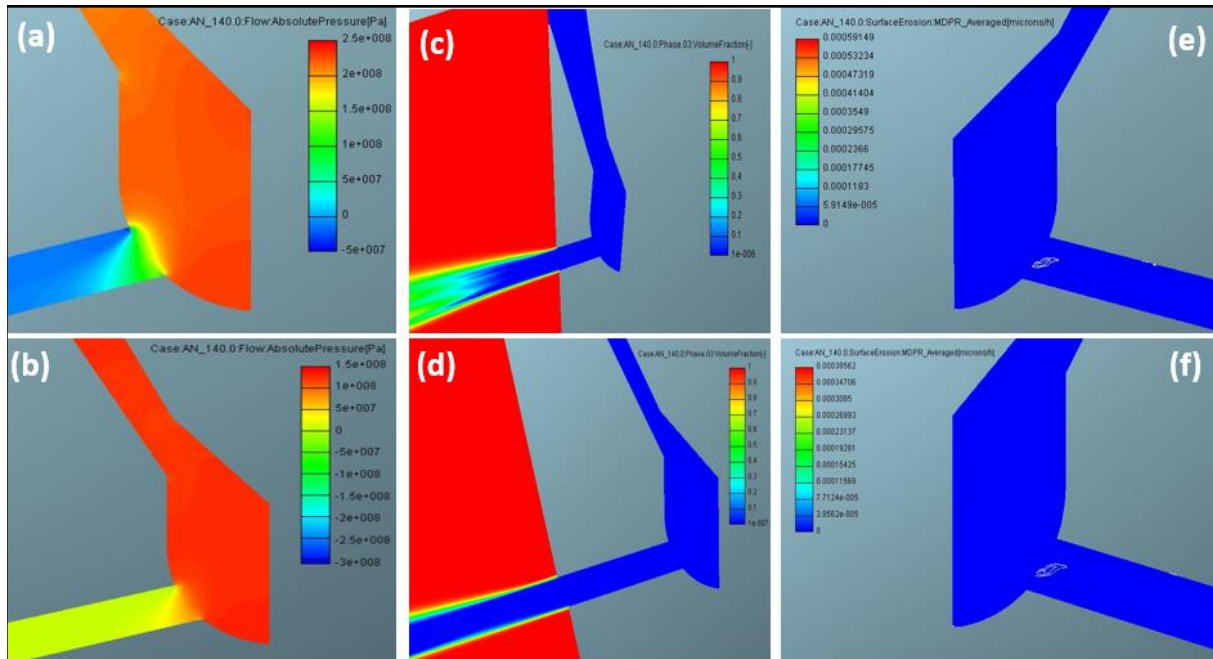


Figure 4. Pressure field: (a) 200 MPa inlet pressure, (b) 100 MPa inlet pressure. Volume fraction of vapor phase: (c) 200 MPa inlet pressure, (d) 100 MPa inlet pressure. Mean depth of penetration rate of surface erosion (MDPR): (e) 200 MPa inlet pressure, (f) 100 MPa inlet pressure.

Using the pressure as 100 MPa, we can see in Figure 4(b) that near the injection hole is a value below the initial number. This is expected because with lower inlet pressure, the forces involved are smaller, resulting in lower losses due to geometry difference. In this comparison it can be assumed that lower inlet pressure may help to minimize the effects of cavitation, but when implemented, the combustion process is negatively affected, low pressures prevent the fuel droplets from being completely broken, as well as inefficient atomization inside the piston bowl.

The velocity involved in this case follows what was previously achieved, smaller velocities in the hole, having a reduction of 39% in liquid velocity, 15% in gas velocity and 15% in vapor velocity. This is observed Figure 4(c), the volume fraction on vapor phase is higher when compared to 4(d). This vapor is important to combustion because this help the ambient to achieve a better mixture to reach the ignition condition.

The development of pressure throughout the experiments followed a pattern where the highest pressure is in the injector body, passing at the intersection of the injector hole with SAC volume we have a pressure in the order of 208 MPa. It may be noted that for increasingly higher pressures, absolute pressure values tend to increase. From the variations performed, the data that had the greatest impact were the speed of development of the vapor and erosion in the injector hole. The development of the jet is somewhat similar, but the values involved differ. In experiment #13, with high pressure and high temperature and higher rise of needle, we have a more gas phase and decelerated in the final parts of the injected plume.

With the data obtained by the study, is possible to obtain a quantitative prediction of the mean erosion, in microns/h, is higher where the velocity and pressure are higher, resulting from the larger forces involved, Figure 4(e). This is acceptable because higher velocities induce greater pressure drops, facilitating the effect of dynamic cavitation. This variable indicates the probability for erosion due to cavitation. The values represent the amount of material removal per unit time during the steady part of the erosion process.

#### 4.2 Fuel temperature

Fuel temperature is also a very important parameter to be analyzed. In this work, were performed several simulation changing the fuel temperature at inlet, as show in Table 2, by using the half or doubling the value in relation to the reference case (293.15 K - 20 °C). Figures 5(a) and (b) shows that doubling the fuel temperature the overall field of flow

changes dramatically, the averaged pressure the hole system increased when temperature rise. As the inlet flow ratio was not modified the higher temperature provided an increase in the pressure of the system. Comparing the Figure 5(c) to Figure 4(c), it is possible to elucidate the temperature influence in volume of vapor penetration and development.

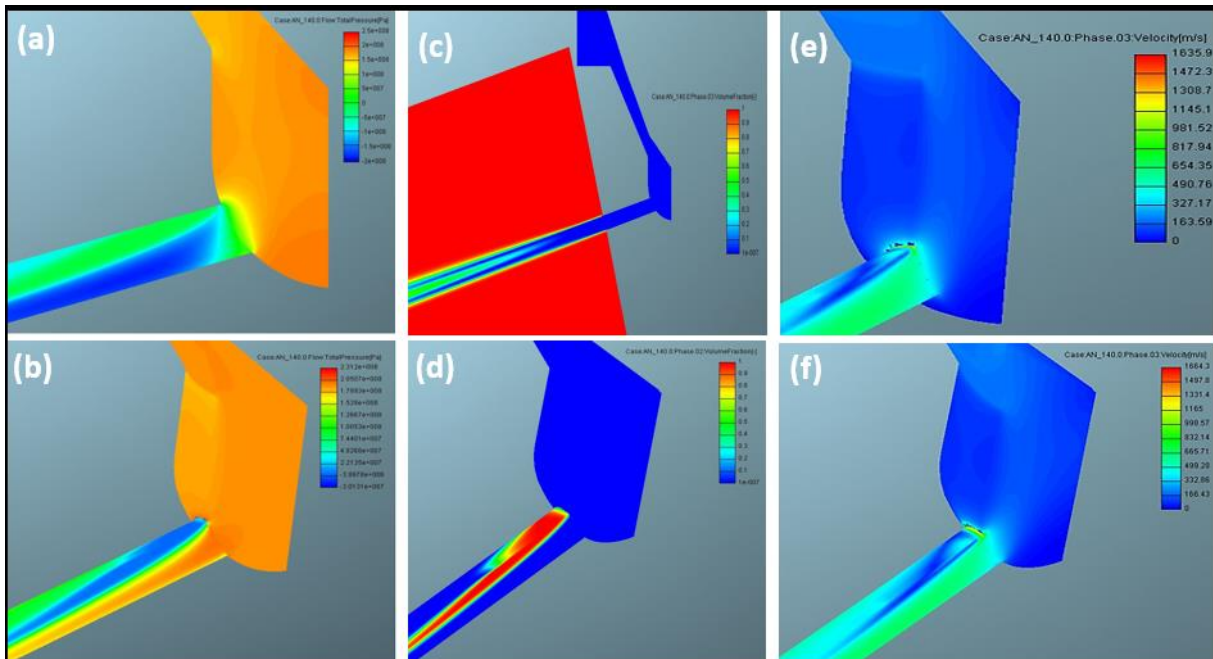


Figure 5. Temperature influence: (a) Total pressure at reference (200 MPa inlet pressure and 20 °C), (b) Total pressure at double fuel temperature (200 MPa inlet pressure and 40 °C). (c) Volume fraction of vapor with doubled initial temperature (200 MPa inlet pressure and 40 °C). (d) Volume fraction of gas on injector hole with doubled temperature (200 MPa inlet pressure and 40 °C). (e) vapor phase velocity at the injector hole at reference (200 MPa inlet pressure and 20 °C). (f) vapor phase velocity at the injector hole, doubled temperature (200 MPa inlet pressure and 40 °C).

The fuel temperature of 313.15 K (40 °C) disturbed the amount of vapor who gets inside the piston because the phase of gas has increased in this case, see in Figure 5(d). With the modified temperature, when the fuel pass through the hole, the average velocity has a discrete increase, as shown in Figures 5(e) and (f). This condition provides a worse scenario for cavitation, the value of erosion (MDPR) is much higher in this case due to the velocity, implying a pressure drop and consequently favoring cavitation.

Experiment #14 follows the same pattern as the others, with little final variation, but what we established in experiment #15 is different. The reduced temperature and the higher rise caused slower vapor phase velocity development than the other experiments, with a central velocity of 20% less. The main part about erosion is that the higher the lift associated with higher pressures as in Figure 6(e), the magnitude reaches levels of 10 times the final value, which is 0.0013368 microns/h.

### 4.3 Needle lift

Figures 6(a) and (b) shows a lift changing effect (comparison between the 1/4 % plus and 1/4 %, respectively, here is possible to observe that with other conditions maintained the total pressure do not have any expressive difference. A good comparison of indicators is surface erosion which although appears in Figures 6(e) and (f), the respective scales have very large orders of magnitude, showing that the restricted flow has an enormous influence on the geometric cavitation. Table 1 shows the interaction of the experiments. This table is based on the initial conditions, of this form, experiments #9, shows an experiment with half the initial pressure of 100 MPa, and opening needle 1/4 % larger than reference. The spray development is somewhat similar, but the values involved differ. In experiment 13, with high pressure and high temperature and higher rise of needle, we have a more gas phase and decelerated in the final parts of the injected plume

When analyzed the data obtained by the numerical experiments, high pressures and greater leakage have great influence on the injection and especially on cavitation. The higher velocities involved aid in the effect of pressure drop in the injection hole, added to the geometric effect of the flow failure between the SAC and the channel, resulting in an environment conducive to cavitation due to a marked pressure drop. This tendency to cavitation develops other problems, such as the lower energy efficiency of the system, since the mixture of air-fuel is impaired when it does not reach an ideal penetration and a compatible jet aperture. As a result of these effects, the pollutants at the combustion outlet are expected

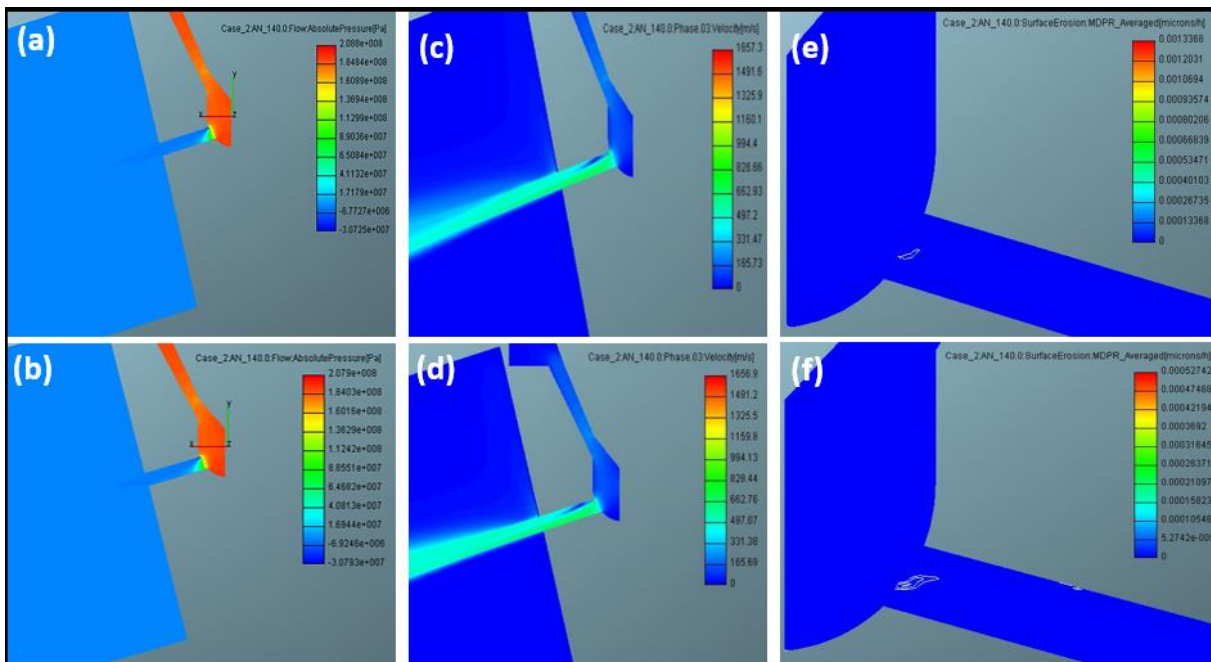


Figure 6. Needle lift influence: (a) Total pressure at 1/4 % plus of lifting , (b) Total pressure at 1/4 % less lifting. (c) Vapor velocity of experiment #13. (d) Vapor velocity of experiment #14. (e) Mean depth of penetration rate of surface erosion (MDPR) at experiment #15. (f) Mean depth of penetration rate of surface erosion (MDPR) at experiment #14.

to be higher than under normal operating conditions. The characteristics of fuel results in higher emissions of pollutants, particularly the formation of soot.

## 5. CONCLUSION

The objective of this study was to understand how initial parameters influence the fuel injection phenomenon, how the effects were affected and how they behaved in terms of cavitation. When analyzed the data obtained by the numerical experiments, high pressures and greater leakage have great influence on the injection and especially on cavitation. The higher velocities involved aid in the effect of pressure drop in the injection hole, added to the geometric effect of the flow failure between the SAC and the channel, resulting in an environment conducive to cavitation due to a marked pressure drop.

This tendency to cavitation develops other problems, such as the lower energy efficiency of the system, since the mixture of air-fuel is impaired when it does not reach an ideal penetration and a compatible jet aperture. As a result of these effects, the pollutants at the combustion outlet are expected to be higher than under normal operating conditions. The characteristics of fuel results in higher emissions of pollutants, particularly the formation of soot.

It is possible to notice that the manufacturers adopt the posture of increasing the injection pressure, reducing the amount of fuel injection and in more injections phases, tending to eliminate the effects of the failure of the mixture, but increasing the tendency to cavitation and erosion of the system. The balance between temperature and pressure is delicate in diesel engines, for that reason understand phenomena such as cavitation, which can alter the geometry of the nozzle and thus damage all the fuel injection, is of extreme importance for the industry in general, aiming reducing pollutants and increasing efficiency. Understanding the mechanisms involved in the combustion phenomenon is important, given its great use, especially in the road transport part. Means that help us reduce pollutants and improve the environmental condition for all are increasingly exploited and valued.

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