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This is a refereed journal and all articles are professionally screened and reviewed **ORIGINAL ARTICLE**

Spray Modeling in Pulse Jet Engine and Surveying the Distribution and Fuel - Air Mixture in Combustion

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Kouros Nekoufar; Spray Modeling in Pulse Jet Engine and Surveying the Distribution and Fuel - Air Mixture in Combustion

ABSTRACT

The sudden fuel ignition produces the gases such as carbon dioxide, carbon monoxide and water vapor. These gases need more space than initial fuel - air mixture, and a sudden increase of pressure will occur within the pulse jet engine. High temperature due to the combustion causes to expansion of the produced gases that is also increases the pressure inside the pulse jet engine. Hot produced gases will exit from the end of pipe's engine with high speed and creates a thrust force. The present study is carried out in order to investigate the flow filed resulting the fuel injection inside the combustion of a pulse jet engine. In the study, some processes have been studied during the injection of fuel into the chamber including air entering the chamber, fuel position fuel after leaving the injector, the effects of fuel contact into the front walls, mass distribution of fuel and air and mean diameter of fuel droplets. For the reason, Fluent software is used to simulate the flow inside engine.

***Key words*:** pulse jet, fuel spray, injector, two phases flow, propane.

Introduction

First time, the pulse jet engine was used on V-1 missiles in World War II to bombard the cities of London and Manchester. The first wind tunnel tests for the engines took place by Mr. Smith in Germany in 1950, but its data results were reported missing during the war. Designing the pulse jet engines in order to produce maximum thrust force and lower fuel consumption was the main goal for engineers during 1940 -1960. After the end of World War II and the rise of the liquid fuel rocket engines; this engines did not use in flying systems as a propulsion force. But in 1985, scientists and engineers have once again found a tendency to use the jet pulse engine and a new generation of pulse jet engine s was emerged as x-jet and PDE. [1]

Cycling and Pulse Jet Engine Performance:

Today, many basic principles of pulse jet engine performance are specified, but ongoing investigations and experimental researches will done by engineers to precise understanding the details (figure 1). The sudden ignition of fuel produces the gases such as carbon dioxide, carbon monoxide and water vapor. These gases need more space than initial fuel - air mixture, and a sudden increase of pressure will occur within the pulse jet engine. High temperature due to the combustion causes to expansion of produced gases that is also increases the pressure inside the pulse jet engine. Hot produced gases will exit from the end of pipe's engine with high speed and creates a thrust force. Newton firstly described the phenomenon as action and reaction in which there is an equal and opposite reaction for every action. After leaving the combustion gases, there is a partial vacuum inside the engine and two points are noticeable: first, because of the reduced pressure inside the engine after discharging the combustion products, more pressure outside the engine may cause to open the inlet valves of engine and the pressure difference can move the air pressure from high pressure area into low pressure one. Second, a part of produced gases cannot exit the engine by reduction of pressure inside it and high pressure air outside the engine drives inside. In this case, there is a fresh air - fuel mixture at the beginning of engine in one hand, and gases did not leave the engine in other side. Cycling of engine is repeated again by creating a spark in the fresh air - fuel mixture and hot gases. In fact, sudden increase in pressure caused to close the inlet valve when sparking and the produced gases goes inevitably outside the engine and created a thrust force with striking the ambient molecules. The process occurs several times in a second in pulse jet engine and due to the alternative and periodic explosions, the pulse jet engine produces a special noise. [5]

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Fig. 1: Overview of Pulse Jet Engine.

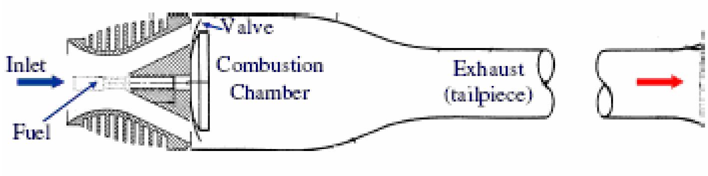

Fig. 2: Schematic view of Pulse Jet Engine.

Pulse Jet Engine Components:

Main components of pulse jet engine include:

- Air inlet duct
- Injector (fuel sprayer)
- Ignition (spark)
- Inlet Valve
- Combustion chamber
- Output nozzle

Simulating the Spray in Pulse Jet Engine Spray:

For quantitative analysis of fuel spray in combustion of pulse jet engine, it's prefer to use the experimental and laboratory methods but according to the high cost for doing these methods in one hand and lack of this kind of engine with desired performance in the country in other hand, numerical simulation can a best method for this case and the results of simulation is very effective in final design and lower manufacturing cost. Generally, the engines with power output more than 20 pounds are used the injection system rather than atomizing the fuel. In such a system, the fuel pressure is sprayed directly into the combustion. It improved the engine performance and can change the output power of engine by changing the amount of fuel being consumed. Of course, the limitation of this system is that fuel with high pressure should spray inside the engine as tiny droplets. It should be used the fuel pump or the fuel is under pressure inside the tank. This engine has 20 pounds of thrust and its fuel is also propane. Combustion of pulse jet engine includes an inlet valve (figure 3), injector plate (figure 4) and wall opposite the injector plate (figure 5). The wall can prevent the excessive deformation of the valve petal in one hand and help the better atomizing the fuel when hitting it.

Problem Description:

This paper is studied the simulated injector and pulse jet engine and spray droplets from the existing geometry. The problem is modeled in 3 states in which the results of each three state will explain below. Also the discussion of spray, droplet diameter, spray velocity and evaporation of droplets are more important that these issues have been studied.

Resolving the trend is one of the hardest problems in fluid mechanics, because the modeling along with phenomena such as fuel spray and oxidizer, following the liquid phase in the gas phase, evaporation of droplet and mixing the gases, is a hard action, costly and time consuming, while the above issue is unstable and should be considered as three-dimensional issue. Thus, the existing software should be used in this context according to the preferred need. It should be noted that the use of such software given the broad vision for the existing problems in the numerical analysis. Therefore, a well-known code in computational fluid dynamics (CFD) called FLUENT is used in the paper.

Geometries and Classification:

Engine geometry consists of three main parts: first, the entry is placed at the beginning of engine as a convergent - divergent nozzle but the nozzle's regime is subsonic, the second part includes a part where injector and its front plate are at the beginning the chamber. The third part consists of combustion and end tube or engine output. A quarter of engine is modeled due to the symmetry of 90 degrees of engine to reduce the number of elements. The block classification is performed according to the geometry engine and presence of injector in the middle part, thus the structured classification is used in the inlet area and output of the combustion, while unstructured classification is used in injector area (figure 6). Because there is impossible to use the structured classification given the geometry complexity and if the unstructured classification is used in all geometry so the number of elements will severely be increased and using such unstructured classification may cause to fine the classification in certain areas. Given the presence of injector, it is necessary to fine the classification around the injector as possible. Therefore, the size of classification is finer towards the injector due to the possibilities (figure 7). Totally, the number of elements is 162000. In fact, it is possible to avoid more elements by using the block classification.

Selecting the Model:

The continuity equation, momentum, energy, turbulence and discrete phase flow must be solved given the kind of issue. The model is used for turbulence. This model was chosen because of its performance in simple engineering and also the model is proper where special phenomena such as mass transfer from the wall or collision of boundary layers or very low Reynolds flow do not occur and the model is used in most engineering issues. The model of discrete phase is used for modeling the discrete phase flow in which the atomizer Pressure-swirl is selected due to the kind of existing injector.

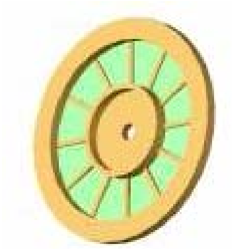

Fig. 3: Inlet valve.

Fig. 4: Injector's plate.

Fig. 5: Wall opposite the injector's plate.

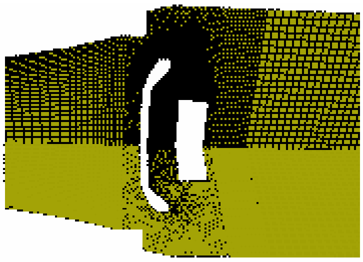

Fig. 6: View of classification.

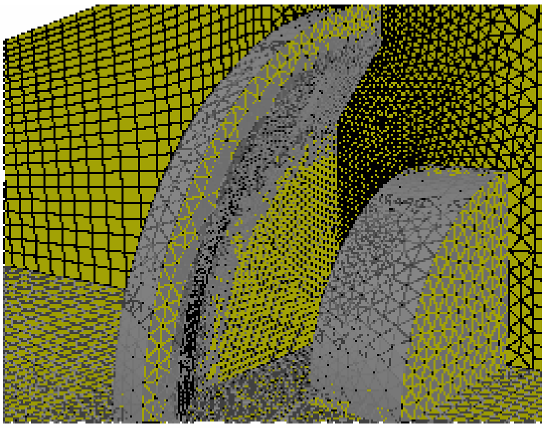

Fig. 7: Classification on the plate opposite the injectors.

Standard Model k – ε:

This model is a quasi-empirical model based on model of transport equations for turbulence kinetic energy (k) and the release rate (ε). Model of transport equation for *k* is derived by the real equations as this model for ε is obtained by the physical results. ***k – ε*** model is obtained by assuming the fully turbulent flow and despite the molecular viscosity. Thus, this model is only correct for fully turbulent flows.

- Transfer equations for standard model

Turbulence kinetic energy (k) and the release rate (ε) are obtained by the following transfer equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad 1)$$

$$C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_i}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad 2)$$

In the equation, Gk represents the production of turbulence kinetic energy due to the mean velocity gradients; Gb represents the production of turbulence kinetic energy due to the floating and YM represents the expansion ratio of oscillation in compressible turbulence in total release rate. Also $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are constant values. σ_k and σ_ε are turbulence prattle values for k and ε, respectively . S_k and S_ε are known as source terms. [3]

Boundary Terms:

Mass flow inlet is used for input that its value is different in various states. The flow rate is equal to

292.4 g/s; 265 g/s and 87 g/s in first, second and third state, respectively. The airflow temperature is related to the height of engine operation that the ambient temperature is equal to 280 K in first state. In second and third state, the temperature is equal to 273 K and 280 K respectively. The ambient pressure is also equal to 87717 P (Pascale) in first and third states and it is equal to 77556 P in the second state that these values apply the operating condition.

The condition of pressure outlet with zero pressure difference than environment is considered for the outlet. Also, airflow is combined with the mass ratio of oxygen 0.23% and nitrogen 0.77%. For walls, the insulation condition is used for the heat and non-slip for velocity. One of the key points on the boundary terms is to determine their behavior towards the discrete phase. Specially, the walls opposite the discrete phase flow (spray droplets) have more effects on the behavior of discrete phase flow after hitting the walls; therefore, the condition "wall film" is used for the walls. In this condition, a fluid film is formed on the wall where the discrete phase flow has encountered it and different phenomena such as evaporation, spray and etc. (figure 8) are solved in the layer.

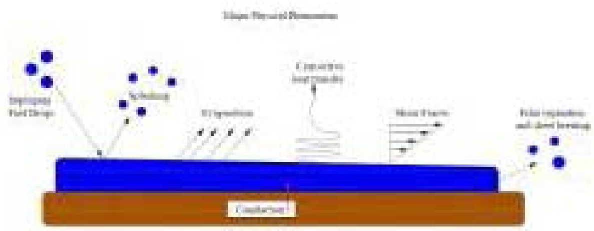

Fig. 8: Schematic for the wall film boundary.

Solution:

The solution was done steady and the coupled method has been used to solve the equations with Courant number 1 and the second-class discretization method is also applied. This model is used for spray modeling. Firstly, the unsteady solution of discrete phase is used with time step 0.00001 that it can studied the effects of velocity spray and droplet trajectory and then the steady solution of second phase is used to study the steady state o sprayed droplets. The solution was done in two steps, first the continuous phase is solved and then the continuous second phase is defined after reaching the convergence phase and is solved by the first phase as a couple.

Results:

Firstly, the simulation results are studied in the first state partially and then total results of second and third states are expressed too.

Flow Lines:

Figure 9 is presented the velocity contour. As we can be observed, the incoming air is pushed towards the corners given the injector plate is placed in the direction of flow, and as a result the velocity rises in inlet corners and therefore the velocity of inlet valves is obtained in 195 m/s as well as the velocity of outlet valve is obtained in 93 m/s because input flow can only be entered from the corners of plate opposite the injector, thus high velocity in inlet valve causes to rotate the flow inside chamber (figure 10). First, it should be noted that the flow rotation of velocity contour is obtained assuming that the inlet valve is always open. Figure 11 is shown the velocity vectors on the symmetric plate indicating the flow rotation in the corners of inlet valve. Also high velocity in inlet sucked up the around flow that it transferred the gases between the injector plate and its opposite plate towards the combustion (figure 12).

Temperature Contour:

Figure 13 is presented the temperature contour. As shown, the temperature between the injector plates and its opposite plate is equal to 220 Kelvin and it is 280 Kelvin in input area. Lower temperature of propane evaporation is a main reason for low temperature in an area where spray is done. Because the temperature of propane evaporation is 220 Kelvin and thus the temperature in the area is determined by propane gases of evaporation given that the inlet flow cannot be entered the area.

Spray:

The discussion of spray was solved as unsteady with time step 0/00001 second. In the first state, flow in each injector is 7 g/s and the pressure behind it is 8 atmospheres and the diameter of injector is equal to 625 micron. Injector was rotary swirl and its spray angle is equal to 13°. The diameter of spray droplets is shown in table 1. As we can be observed the mean diameter algebraically (D10) is 10/3 micron and its SMD (D32) is 17/2 micrometer. The mean diameter D_{jk} is defined as follows.

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$$(D_{jk})^{j-k} \equiv \frac{\int_0^\infty D^j f(D)d(D)}{\int_0^\infty D^k f(D)d(D)}$$

3)

According to the above equation, D32 is the total volume of all droplets divided by the sum of all external surfaces for droplets divided by the number of droplets. The diameter of droplets is determined based on Weber and Reynolds number and in this case, the maximum diameter of the droplets is equal to 39 micrometer. Also the frequency amount of droplets based on their diameter is plotted in figure 1. As is known, the maximum frequency amount is between 8 to 18 and 20 to 90 micrometer. The spray droplets before hitting the opposite plate based on its diameter is also shown in figure 15. The velocity of spray droplets is plotted in figure 16.

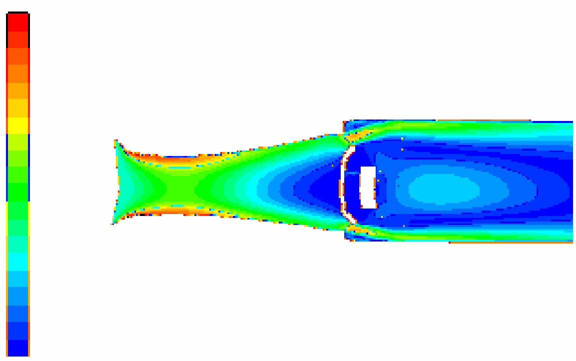


Fig. 9: Velocity contour on the symmetry plate for the first state.

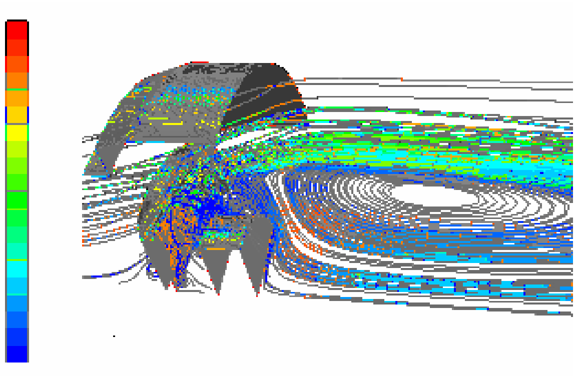


Fig 10: Flow lines in the spray area and chamber for the first state.

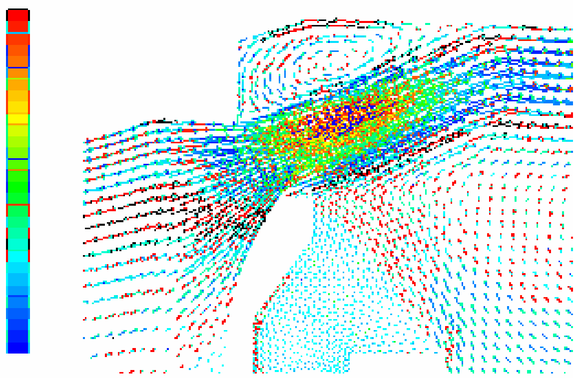


Fig. 11: Velocity vectors in inlet valve for the first state.

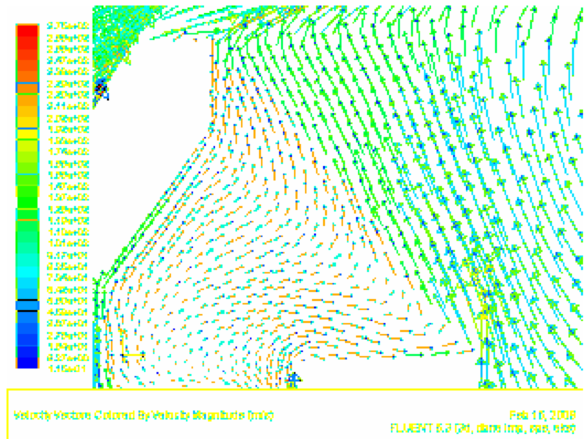


Fig. 12: Velocity vectors on the symmetry plate between the spray area and inlet valve for the first state.

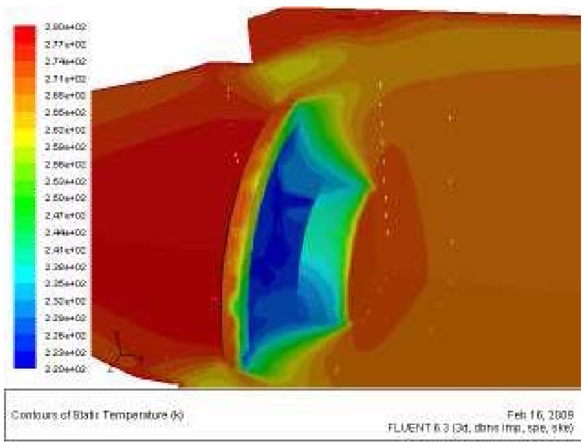


Fig. 13: Temperature contour in the spray area and inside the chamber for the first state.

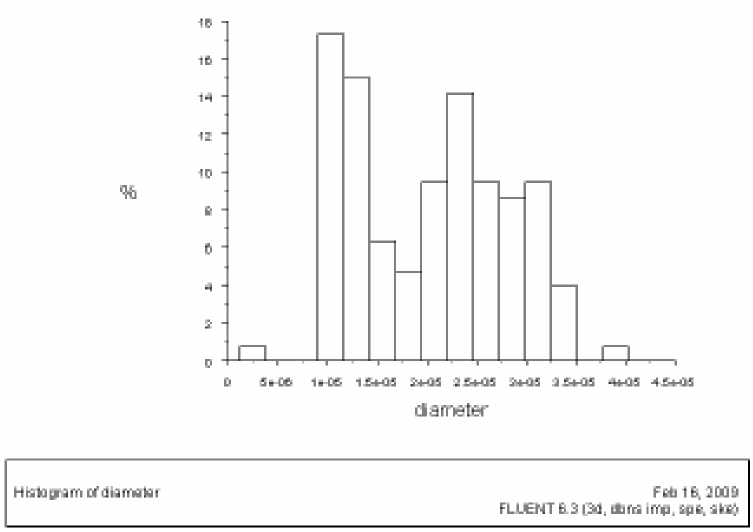
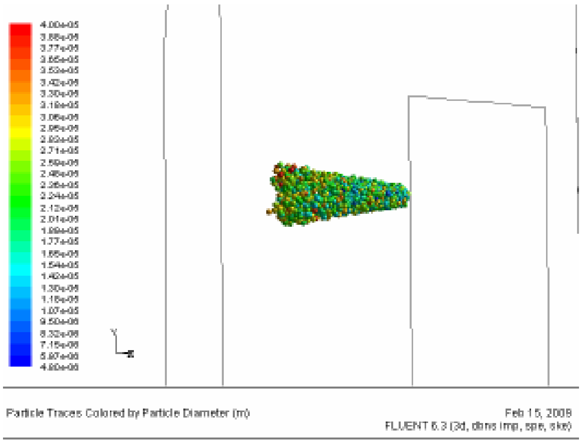


Fig. 14: Frequency diagram of droplets for the first state.



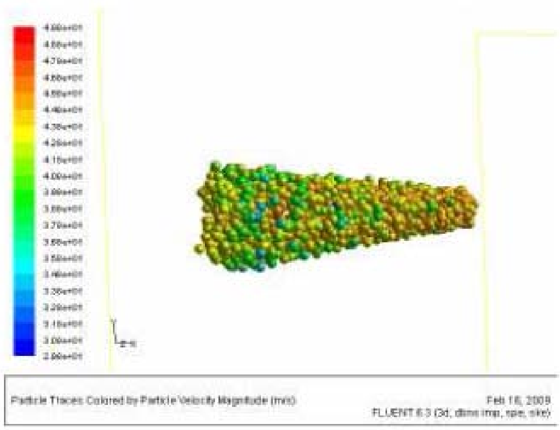


Fig. 15: The droplets formed by spray based on the diameter for the first state.

Fig. 16: The droplets formed by spray based on the velocity of droplets for the first state.

Table 1: The diameter of spray droplets

j	k	Order j + k	Name
1	0	1	Mean diameter, D_{10}
2	0	2	Mean surface diameter, D_{20}
3	0	3	Mean volume diameter, D_{30}
2	1	3	Overall surface diameter, D_{21}
3	1	4	Overall volume diameter, D_{31}
3	2	5	Sauter mean diameter, D_{32}
4	3	7	De Brouckere diameter, D_{43}

It is shown that the velocity of spray droplets from the injector nozzle is 45 m/s; and greater the distance from the injector will decreases the velocity.

Droplets are moving on the wall tangentially upon collision with the wall. In fact, a film of propane fluid is formed on the wall after hitting the jet droplets on the wall. Spray droplets on its opposite plate is shown in figure 17. As it is shown the droplets are directed tangentially to the side edges and finally they are sprayed from the side edges to the around.

As we can be observed, the droplets are evaporated largely but the droplets with high diameter are not completely evaporated. In essence, all spray droplets should be evaporated inside the chamber that the vapor of droplets' evaporation participated in the combustion. But the temperature inside the chamber will not increase because the spark and combustion has not been modeled in the simulation and as a result the temperature potential required for whole evaporation of droplets is not created.

A fluid film is formed in a place where droplets colliding the plate opposite the injector. Figure 18 is shown the thickness contour for fluid film on the wall. More thickness is equal to 0.8 mm, in fact due to the boundary condition “film wall” that was selected for the walls, the droplets is formed a thin layer of fluid on the wall where they have hit the walls in which layer thickness varies depending on its location. The formed layer thickness depends on the diameter of droplets, the velocity of droplets' collision and number of droplets (discrete phase flow). Evaporation contour of droplets on the wall is shown in figure 18. Given the small difference between the temperature of material and the temperature of propane vaporization, in practice, a small amount of propane will evaporate in which more evaporation rate is located on the corners of the plate opposite the injector where droplets is entered the airflow. Contour of chemical components of propane and oxygen is plotted in figures 19 and 20. In all areas except an area where spraying occurs, there is an airflow (with mass ratio of oxygen 0/23 and nitrogen 0/77) but because the airflow cannot entered the spray area therefore the area is filled by gases arising the vaporization of droplets, and the propane mass ratio is equal to per unit in the area but its value is reduced to 0/04 while combining. In the case the inlet airflow is 292 g/s and given that the propane vapor inside the engine results of evaporating the droplets, so the exact amount of the evaporated droplets can be calculated. In fact, this ratio is 0/0457 if all droplets were evaporated inside the chamber that it's obtained by dividing 14 g of propane to 306 g (sum of propane and air). Therefore it can say that from 14 g of propane inside the chamber, only 12/25 g will be evaporated. If the calculation is studied through the evaporation of droplets in steady state, the following result is obtained: table 2 shows that from 3/5 g of propane in a fourth engine, just 3/14 g will be evaporated during the entire engine. It means 12/52 g from 14 g. therefore it can say that 12/25 g of the evaporated amount inside the chamber can be a correct amount.

Now the results of spray are examined in the problem of second state. In this case, the inlet airflow is 265 g/s with 273 kelvin. The diameter of injectors is 526 micron and the pressure behind the injector is equal to 4 atmospheres. The spray angle is also 13°. The process of solving the problem in the first state is similar to the second state.

The velocity contour on the symmetric plates is plotted in figure 21. As shown, the velocity in inlet valve is 185 m/s and the output velocity is 75 m/s. Table 3 represents different mean diameters at the beginning the spray. What is remarkable as the injector properties is the mean diameter before starting the evaporation. In this case as represented in table 4, the diameter of obtained droplets is equal to 51/6 micrometer at the beginning of spray therefore it becomes 23/1 micrometer if we calculated the same diameter when droplets are evaporating. But the above injector property is initial mean diameter; meaning that the injector produces the droplets with mean diameter 51/6 micrometer.

The spray droplets based on their diameter is shown in figure 22. As we can be observed, the maximum and minimum diameter is 106 and 14/4 micrometer, respectively. It is considered that the injector produces the droplets with higher diameter than the injector in first state, there are two reasons for it, first, it reduces the spray flow and thus reduces the Reynolds number and second, it reduces the pressure loss behind the injector than the first state. This makes that the formed droplets have more diameter. It expected that the spray velocity has been reduced in this state than before. In figure 23, the spray droplets are plotted based on their velocity. As shown, the spray velocity in injector nozzle is 23 m/s and the greater the distance from the nozzle, the velocity slower. The velocity of droplets is reduced to 27 m/s before hitting the wall as depicted in figure 23. The spray droplets is equal to 45 m/s in first state, and low spray flow as well as low pressure behind the injector may reduce the velocity of spray droplets. Figure 24 shows the droplets spread on the plate opposite the injector. The behavior of droplets in this state is similar to the behavior of spray droplets in first state. The blue droplets where they hit the wall indicate that many droplets were evaporated in the area. Therefore, the droplets have very less diameter in the area.

In the third state, the injector characteristic is similar to the second state. In this case, the inlet airflow and ambient conditions have been only changed. The inlet airflow, ambient pressure and temperature are equal to 87 g/s; 87717 P; 280 K; respectively. As table 4 represents, the mean diameter of droplets bases on pre-state is 52 micron. The spray droplets are plotted in figure 25 and 26 according to their velocity. There is no little difference in terms of spraying between the second and third state but it expected that the velocity in valves will decrease because of reduction of inlet airflow.

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Table 2: The evaporated mass from the droplets in steady state.

(*)- Mass Transfer Summary -(*)

Fate	Mass Flow (kg/s) Initial	Final	Change
Evaporated	3.133e-003	0.000e+000	-3.133e-003
Escaped - Zone 15	3.675e-004	1.827e-005	-3.492e-004

Table 3: The mean diameter of droplets at the beginning of spray.

Overall RR diameter	(D_RR):	6.441103e-005	(m)
Overall mean diameter	(D_10):	3.461994e-005	(m)
Overall mean surface area	(D_20):	3.877295e-005	(m)
Overall mean volume	(D_30):	4.266635e-005	(m)
Overall surface diameter	(D_21):	4.342815e-005	(m)
Overall volume diameter	(D_31):	4.736584e-005	(m)
Overall Sauter diameter	(D_32):	5.166532e-005	(m)
Overall De Brouckere diameter	(D_43):	5.864547e-005	(m)

Table 4: Diameter of droplets at the beginning of spray in third state.

Overall RR diameter	(D_RR):	6.546421e-005	(m)
Overall mean diameter	(D_10):	3.545137e-005	(m)
Overall mean surface area	(D_20):	3.970287e-005	(m)
Overall mean volume	(D_30):	4.366379e-005	(m)
Overall surface diameter	(D_21):	4.446424e-005	(m)
Overall volume diameter	(D_31):	4.845805e-005	(m)
Overall Sauter diameter	(D_32):	5.281058e-005	(m)
Overall De Brouckere diameter	(D_43):	5.978407e-005	(m)

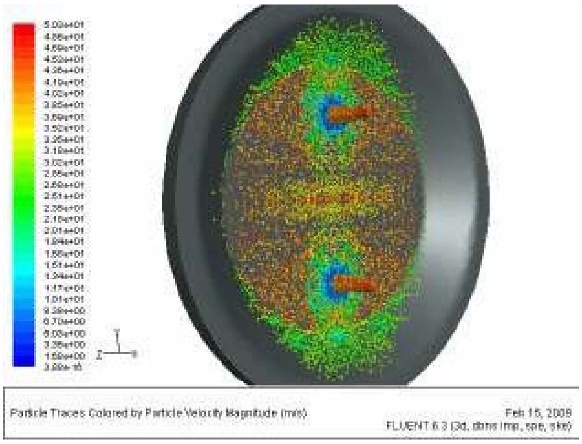

Fig. 17: Full view of droplets during the tangential motion on the front plate for the first state.

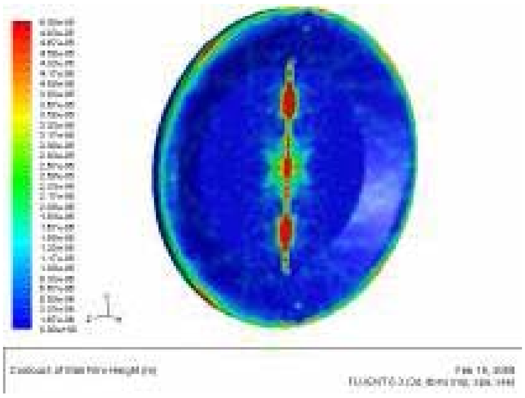

Fig. 18: Contour of fluid film formed on the wall for the first state.

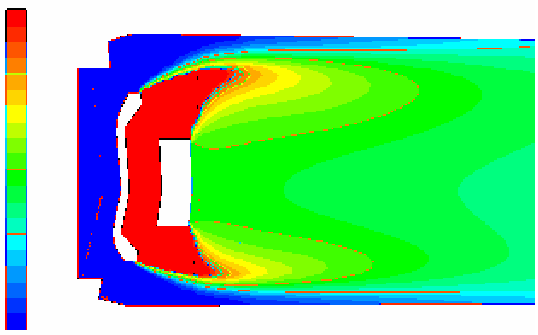

Fig. 19: Contour of propane vapor mass ratio on the symmetry plates for the first state.

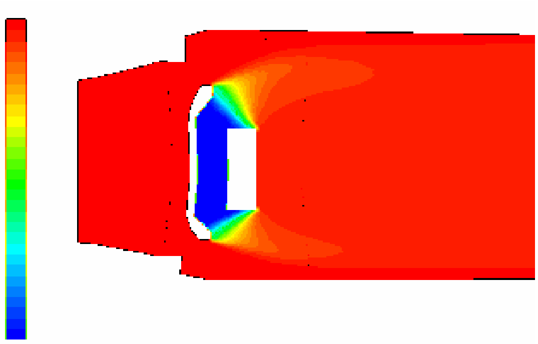

Fig. 20: Cantor of oxygen mass ratio on the symmetry plates for the first state.

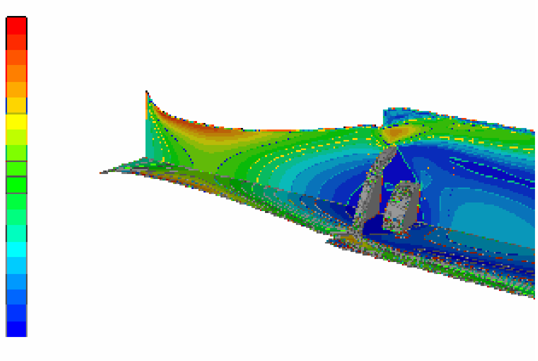

Fig. 21: Velocity contour on the symmetry plate for the second state.

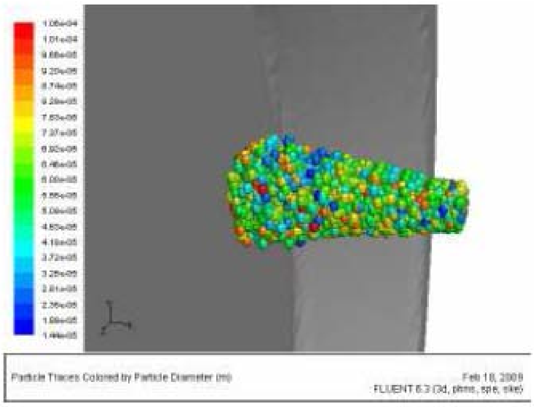

Fig. 22: The droplets formed by spray based on the droplets' diameter at the beginning of spray for the second state.

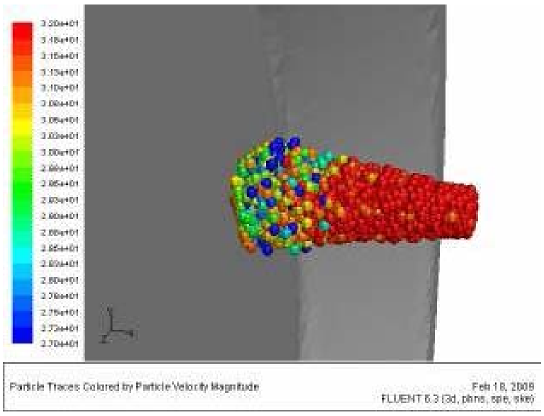

Fig. 23: The droplets formed by spray based on the droplets' velocity at the beginning of spray for the second state.

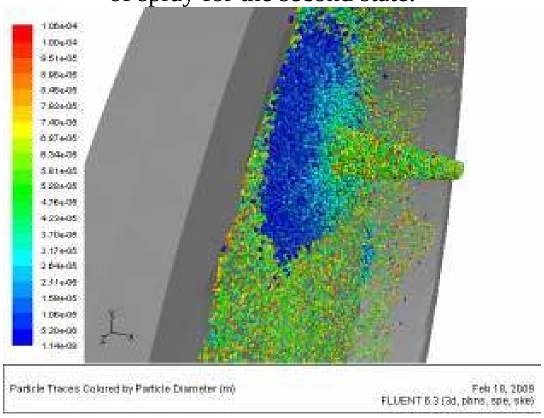

Fig. 24: The droplets formed by spray based on the droplets' diameter after hitting the wall opposite the injector for the second state.

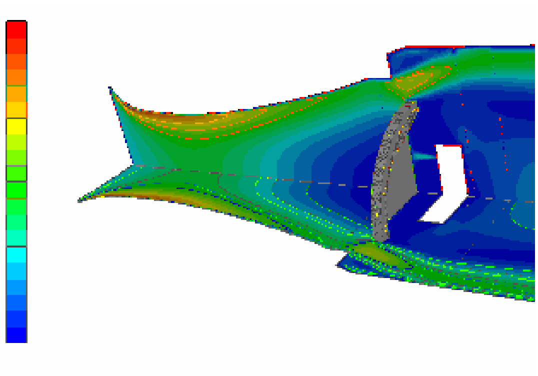

Fig. 25: Velocity contour on the symmetry plate for the third state.

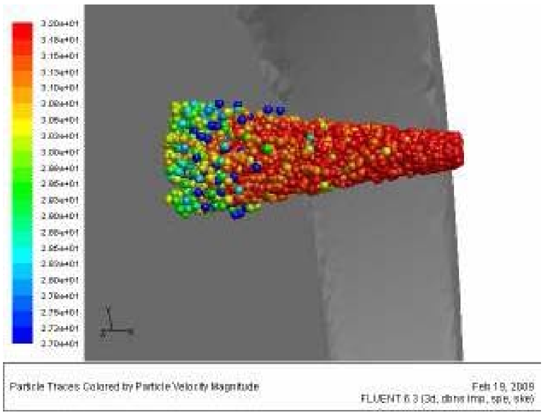

Fig. 26: The droplets formed by spray based on the droplets' velocity for the third state.

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