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Modeling and Experimental Investigation of Injection Process in Micro motor Combustion Chamber of Liquid Fuel Missile

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ABSTRACT

Injection process and its modification in missile motor combustion chamber are one of the most important parameters in combustion process, stability of combustion and the value of propulsion that depend to some factors such as: the type of injector being used, injector arrangements in injector plate and the type of combustion chamber. Unbalanced and no uniform distribution of fuel and undesirable size and velocity of spray droplets which cause asymmetric spray and imperfect combustion that in critical state will cause fracture and explosion of combustion chamber [1].In this article, in order to exact investigation of injection in missile micrometer, initially some concepts including: injector, injector plate, jet break-up theory, atomization and atomized spray parameters are described. Then by designing and building of combustion chamber model, experimental and numerical injection parameters from viewpoint of macroscopically and microscopically are scrutinized. In this case, due to advantage and vast usage of centrifugal injectors and because of distribution and more desirable uniformly injection in circular injector plate which in previous researches are done, have been used. To validate the injection process and spray characteristics which are measured in Cold-Test and PDA laboratories, the results are compared with numerical modeling and previous researches.

Key words: Injection, Spray, Injector, Injector plate, Combustion chamber, liquid missile

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INTRODUCTON

The function of the liquid fuel missiles engines is very depended on injection characteristics that are produced by injectors. The method of fuel injection in to the combustion chambers in combustion process is very important. Because of the complexity and unknowing of the spray atomization, the most of researches have been done for experimental in this case. This process is very Obscurant and its mechanism is not so clear because some of droplets are break up and joint again. Therefore, the droplets with different sizes produce in this system that they are depended on the initial pressure and temperature of interior of the combustion and evaporating the droplets too [1, 2].

One of the important steps in fluid powdering or atomizing and presenting different break–up models is inspection of spraying process with experimental and analytical methods. Producing and providing fuel mixture that is including of oxidizer or Reducer affects

Accessories of laboratories models
The laboratories models that are used in this investigation includes: injector, injector plates and combustion chamber that are explained below.

Injector is a mechanism for converting the fluid into droplets and spraying them to the combustion chamber. The faster impinging the droplets, the faster evaporating the fluid atoms therefore the efficiency of combustion is higher and increases trust force [3, 4]. Figure (1) illustrates the using of the centrifugal injector two–pedestals blending. Combustion chamber model, experimental and numerical injection parameters from viewpoint of macroscopically and microscopically are scrutinized. In this case, due to advantage and vast usage of centrifugal injectors and because of distribution and more desirable uniformly injection in circular injector plate which in previous researches are done, have been used. To validate the injection process and spray characteristics which are measured in Cold-Test and PDA laboratories, the results are compared with numerical modeling and previous researches. Combustion chamber model, experimental and numerical injection parameters from viewpoint of macroscopically and microscopically are scrutinized. In this case, due to advantage and vast usage of centrifugal injectors and because of distribution and more desirable uniformly injection in circular injector plate which in previous researches are done, have been used. To validate the injection process and spray characteristics which are measured in Cold-Test and PDA laboratories, the results are compared with numerical modeling and previous researches [5, 6].

Fig.1 Centrifugal injector made of brass (includes: external injector, cap, internal injector and brazed injector)

The arrangement of injectors on the injector plate is very important. The manner of arrangement them on the injector plate in type conical of spraying and impinging jet fluids is effective. Figure (2) is the scheme of the circular injector plate that is used in this project (swirled atomizer).

Fig.2 Internal and external scheme of the circular injector plate

The model of missiles micro motor with liquid fuel that is made for this project is similar to actual motors RD–105 and RD–106. For computing of the combustion chamber cross section, the computations of injector plates are being used that are diameter of combustion chamber cross section. The value of injector plate or combustion chamber diameter is equal to 15 cm. Figure (3) shows micro mortar's dimensions.

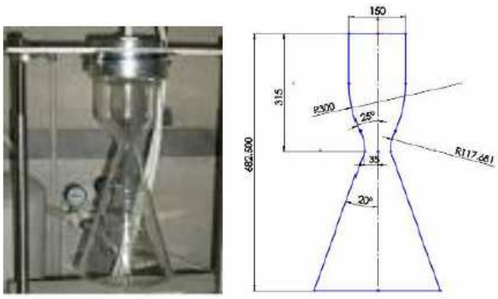

Fig.3 Laboratory combustion chamber dimensions

Laboratory experimental tests

These tests are accomplished in two cold – test and PDA laboratories. Cold – test mechanism includes: Under pressure fluid container, Nitrogen bottle 40–liter, 150–Atmosphere pressure, manometer and regulator for regulating associate pressure, pressure indicator for entering differential pressure on two sides of injector plate, camera with fast graphing (1000 frames on per second and 8-megapixel resolution), radial and sectional collectors for scrutinizing uniform injection and measuring distribution on two directions r–θ.

The PDA laboratory is used for measuring the velocity and diameters of droplets that are sprayed, is shown in figure (4) on collection mechanism.

Fig.4 PDA measuring mechanism

The injector is usually tested by water in injection laboratory. The fluid specifications in the calculations is water specification should be used in laboratory environment temperature.

In general, the use of oxidizer or reducer for testing of the injector plate and injection process in high pressure is very dangerous and on the other hand is impossible often, these are self–flammable therefore test of injection and spraying is usually done with water fluid. The alternative fluid should be similar to thermo physic condition of real fuel.

The most effective parameter that affect on injection process is kinetic viscosity. For application of laboratory fluid with real fluid oxidizer or reducer the equation 1 is used [1], [7].

$$\dot{m}_{(f)or(O)} = \dot{m}_T \cdot \frac{\rho_{(f)or(O)}}{\rho_T} \qquad (1)$$

Where, T is fluid index that is tested.

MATERIALS AND METHODS

The experimental tests are used for investing of the injection parameters includes cold–test and PDA mechanisms. Results of cold–test injection include:

Flow-pressure test

This test is done for flow of the injectors on different high pressures. Flow–pressure rates in centrifugal injectors are shown on figure (5).

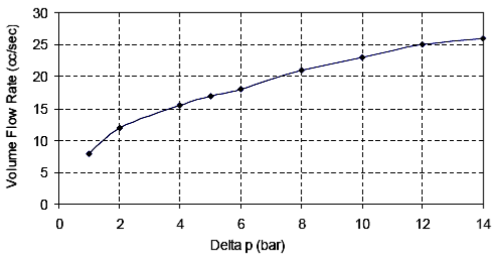

Fig.5 Changes of injector flow to differential pressure

Uniform injection test

The injectors were tested in uniform injection on 4 bars and l0 bars. And also, 6 bars and 8 bars nominal pressure. In paying attention with water volumes in collector's combustion the spray distribution diagram is plotted.

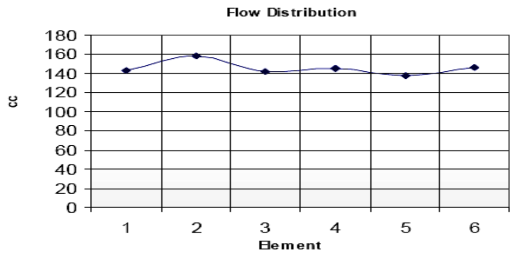

Fig.6 Distribution of injection flow on sample injector in θ direction

Angle of spray test

The goal of this test is scrutinizing the effect of differential pressure on two injector heads on properties of injection and break–up spray jet. One type of oxidizer injector and one type of reducer injector are being tested and angle of spraying in a conic shape is measured and scanned. This test is done for observation of introducing conic shape spraying from contact of injectors on injector plate. The angle of spray in internal and external is 80 and 70 degrees.

Fig.7 Angle of spray in internal (L) and External (R) injectors

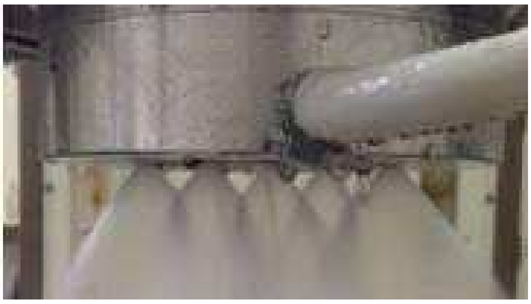

Fig.8 Tested injectors on injector plate in P_f = 10(bars), P_o =4 (bars)

Testing the flow distribution in collectors

This test is accomplished for output of injector plate pressure. The graph of flow–injector plate pressure is shown in figure 9.

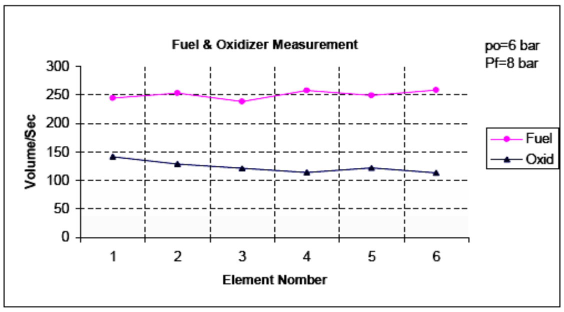

Fig.9 Distribution of flow in two sprays of injector plate

Investigation of injection parameters by PDA

After calibration and provision of the system, changes its displacement into two directions x, y from canter to radius of conic spray with defined steps. The average of 1500 points is calculated in each of steps. The system displaces in

17 stations on each test of injector on defined pressure. In other words the droplet compressibility in conic spray and density of injection are increased through the power of the laser ray because it is decreased by contacting and passing the droplets around the measuring area. To determine the spray diameter and its velocity are invested by this mechanism [8]. The results of this test is shown below for oxidizer on pressure range P_o= 4-6 bars and reducer P_f= 8-10 bars ranges.

Point	X(cm)	Y(cm)	U_{Mean}	D_{SMD}	D_{Mean}
1	1	0	12.203	117.984	125.737
2	1.5	0	11.123	117.02	123.493
3	2	0	8.79	116.896	122.818
4	2.2	0	7.843	116.622	122.657
5	2.4	0	7.284	115.573	121.467
6	2.6	0	6.473	114.338	119.566
7	2.8	0	5.674	113.433	118.382
8	3	0	5.497	112.449	117.055

Table. 1 Results of PDA test for P_o= 6 bars and P_f= 8bars

The results for mean diameter, Sutter diameter and velocity of atoms are shown below.

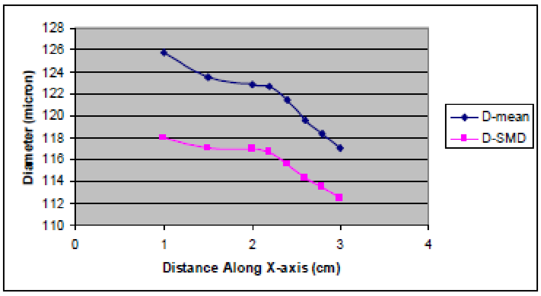

Fig.10 The mean diameter and particles SMD for P_o=6 bars and P_f=8bars

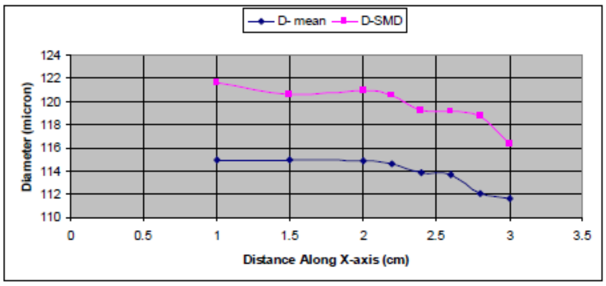

Fig.11 The mean diameter and particles SMD for P_o=4 bars and P_f=10 bars

Flow simulation

Flow simulation is accomplished by CFD that proper physical and Mathematical models and optimum strategy is required. GAMBIT software by means of under-order is used for simulation and analyzing [9].

- Geometrical modeling (by means of the GAMBIT software)
- Spreading of calculation range
- Determining of materials properties
- Determining of proper initial conditions
- Investigation and Analyzing the method (Methodological)
- Inspection the results
- Saving the results.

Geometric modeling and meshing the combustion chamber

Modeling and designing the combustion chamber is shown below.

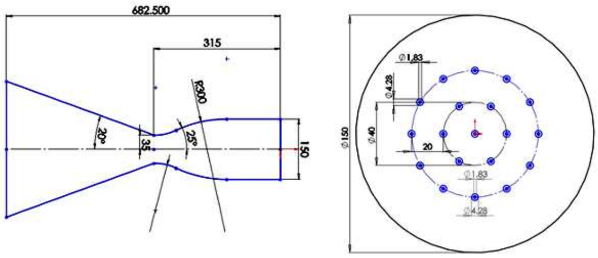

Fig.12 Circular injector plate and injectors arrangement (R), combustion chamber dimension model (L)

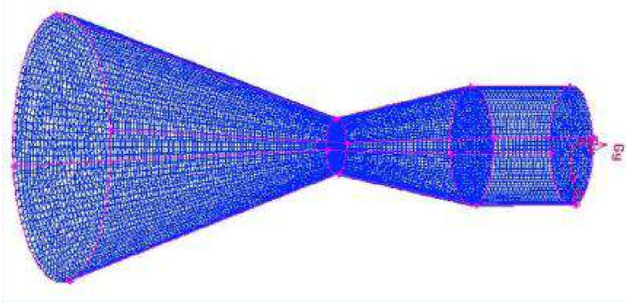

Fig.13 Meshing the combustion chamber with structural grid solver

Selection for flow solution

One of the numerical solution methods is selected by FLUENT software.

- pressure–base solver
- Density-base solver

Generally the pressure–base solver is used for uncompressed flows while the density-base solver is used for compressed flows with high velocity. Both of these methods are reformulated and progressed for solving the flow conditions.

Control volume technique is being used for solving that includes:

- Division of solving range to independent control volume with calculated meshing.
- Integration from independent equations on control volume for algebraic equation with inconsequent independent variables. (I.e. velocities, pressure, temperature and conservation quantities)
- Linearizing discrete equations and solving linear equation system to gain new value for independent variables.

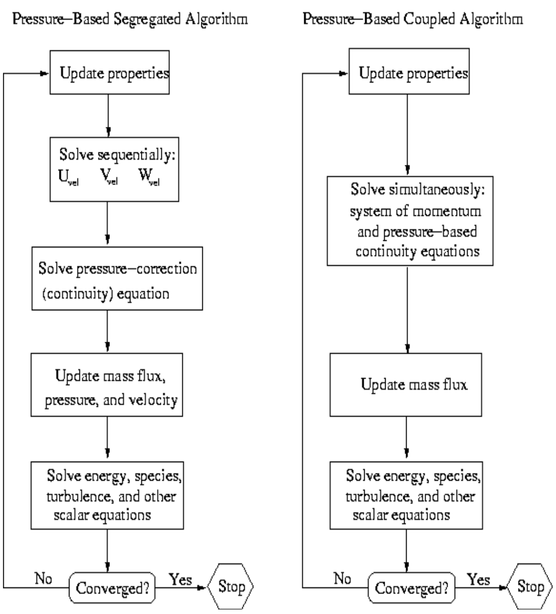

Fig.14 Pressure–base solver algorithm diagrams for two states, Independent and coupled

Here, the pressure–based solver couple algorithm is being used. This procedure is a usual method and forecasting the results. Velocity field is gained by solving the pressure equations (corrected pressure equations). The pressure equation is received from continuity and momentum equations, too. So that velocity is corrected by pressure equation and satisfies the continuity equation. Whereas these equations are non–linear and coupled, solving process is continuing until the converging is appeared [10].

Turbulence model selection

Improvement of k-ε models in different turbulence models is used for turbulence flows and improves below [11]:

- Realizable k-ε model includes new formulation for turbulent viscosity.
- A new transition equation for losing rate (ε) is used.
- This method has high accuracy in forecasting spray rates in planar and circular jets.
- Excellent operation in swirled flow, boundary layers under reversal pressure gradients, flow separation and circular flows.

Boundary layer conditions

Preplanning with different types of boundary conditions is accomplished by these theories [12]:

- Reflect boundary condition for walls, symmetrical flows and axial boundaries with reactionary coefficients.
- Escaped boundary condition for all of the flow bounds (i.e. boundaries with pressure or velocity inputs, output boundary condition in pressure …)
- Internal boundary conditions for internal boundaries (I. e. Radiators and porous spray).

Equations of motion

The fluent software solves conservation of mass equations and momentum for all of the flows. The conservation of energy equation is added to compress and conduction flows, too. The conservation of energy equations for chemical mixtures should be solved in a different manner. Transient turbulent equations are required for turbulent flows. In this article the conservation equations for laminar flows are determined in inertia reference [13].

- **Conservation of mass equation**

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \vec{v}) = S_m \qquad (2)$$

This equation is continuity equation in general form and properly for compressible and uncompressible flows. Source term(S_m) is added mass to continuity phase from the second non continuity phase (Because of evaporation of fluid droplets) and the other terms must be added by the user.

- **Conservation of momentum equation**

This equation in the inertia reference is:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \qquad (3)$$

P: static pressure, τ: tension tensor, $\rho \vec{g} + \vec{F}$: external forces (due to interaction with non-continuous phase) and body gravity. $\vec{F}$: Vector is dependent models (I. e. Porous environments and identified terms by user). The tension tensor is

$$\bar{\bar{\tau}} = \mu\left[(\nabla \vec{v} + \nabla \vec{v}^{T}) - \frac{2}{3}\nabla.\vec{v}I\right] \qquad (4)$$

μ: viscosity, I: unit tensor and the second term in R.H equation is thermal volume expansion.

- **Energy equation**

The general form of energy equation is:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\vec{v}(\rho E + p)) = \nabla.(k_{eff}\nabla T - \sum_j h_j \vec{J}_j + (\bar{\bar{\tau}}_{eff}.\vec{v})) + S_h \qquad (5)$$

K_{eff}: effective conduction coefficient (k+ k_t is based on turbulence model that k_t is turbulent conduction thermal coefficient.) and $\vec{J}_j$: is flux influence of materials. Three terms of right sight of the equation are energy transition for conduction, influence and viscosity losses, respectively. S_h: includes chemical thermal and each thermal resource.

- **Transition equations in Multi–Phase of different chemical flows**

Multi–phase flows are used in transition equations solving conservation equations in multi–phase flows, forecasting Convection–Diffusion equation for k-term and each local mass(Y_i^k). The general equation and extended conservative chemical types is:

$$\frac{\partial}{\partial t}(\rho^q\alpha^q Y_i^q)+\nabla.(\rho^q\alpha^q\vec{v}^q Y_i^q)=-\nabla\alpha^q\vec{j}_i^q+\alpha^q R_i^q+\alpha^q S_i^q+\sum_{p=1}^{n}(\dot{m}_{p^iq^j}-\dot{m}_{q^jp^i})+R \qquad (6)$$

R_i^q is net producing rate for sympathetic types by chemical reaction q–phase, $\dot{m}_{q^jp^i}$ is the source of mass transition between i and j for q to p phase and R is incongruous reaction rate. α^q: is volume fraction for q- phase and S_i^q producing rate by no continuity phase with each other resources defined by the user.

Conclusion of numerical modeling

After modeling the injector plate and arrangement of oxidizer and reducer injectors with solid work software, designing and meshing the combustion chamber are recalling by Gambit and Fluent software. Flow simulation with desired solver, boundary conditions fluid properties, turbulence model, checking mesh and …, is iterated with convergence criterion ($\varepsilon=10^{-4}$). Amounts of flow of injectors, differential pressure on two sides of injector and angles of spraying are entry values in this simulation. At first, the flow simulation is done for one injector and the gained results compared with experimental amounts and previous investigations then after trusting on outputs, simulate for all of the injectors.

The below selected figures illustrate the simulation process from geometrical production to gained results:

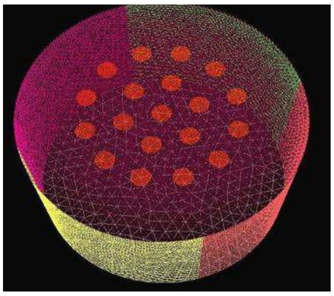

Fig.15 Arrangement and meshing Injectors in combustion chamber model

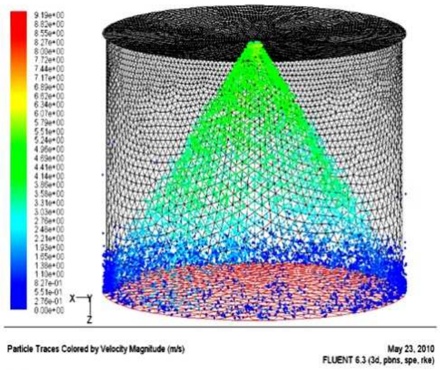

Fig.16 The velocity and spraying Profiles in the middle injector

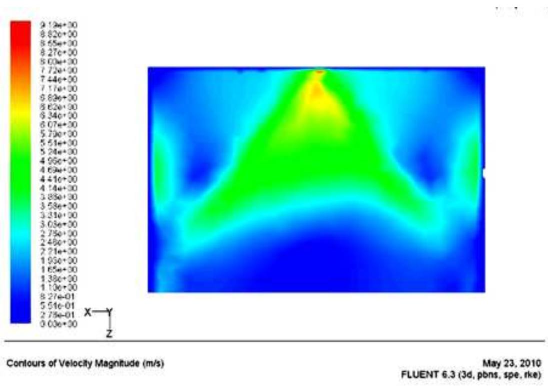

Fig.17 Counter of velocity magnitude for spraying on one injector

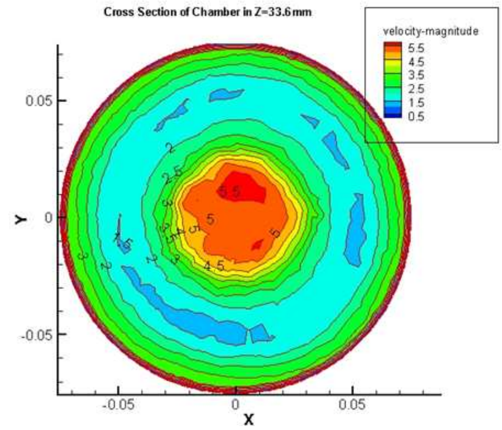

Fig.18 Counter of velocity for spraying on top of the injector

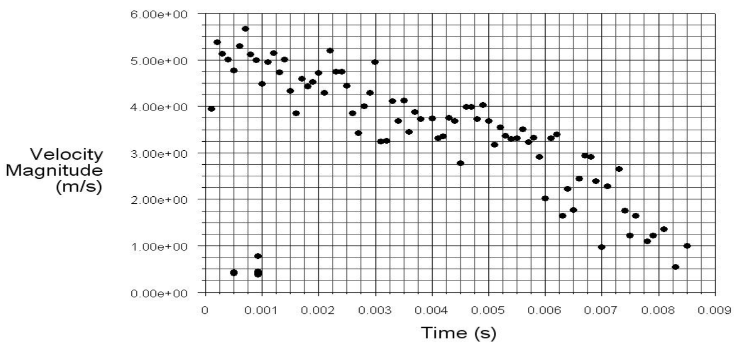

Fig.19 Changing droplets velocity on the time

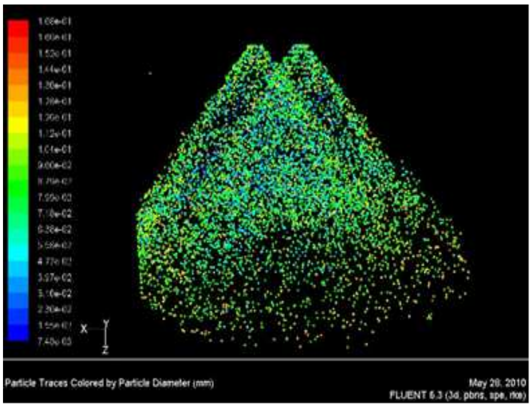

Fig.20 The spraying profile resulting contact of two sprays

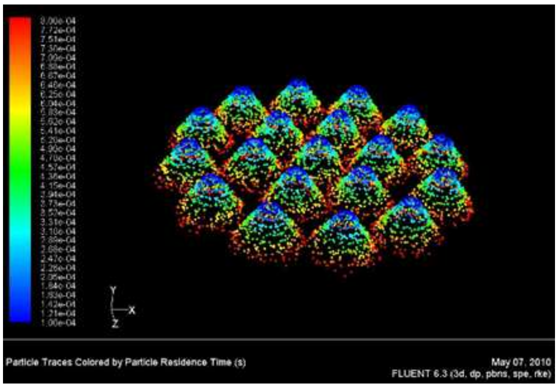

Fig.21 All of the sprays profile before the sprays contacts

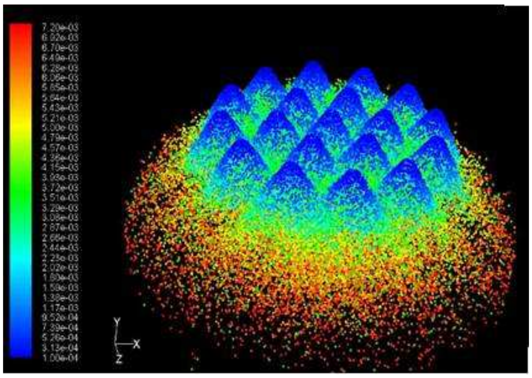

Fig.22 The spray contact profile after complete convergence

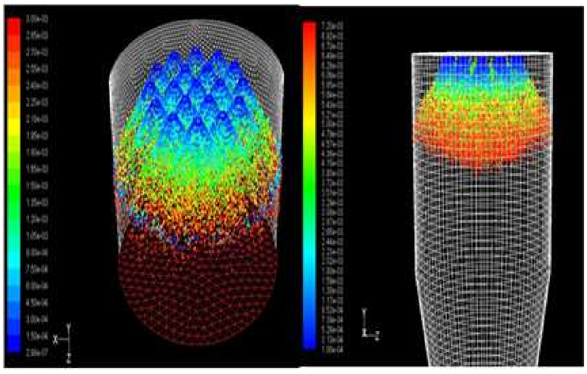

Fig.23 The spraying profile in the combustion chamber after complete convergence

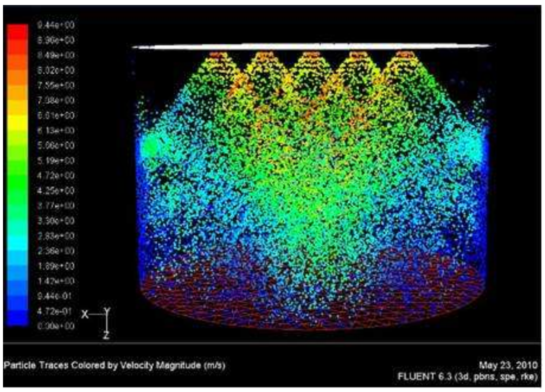

Fig.24 The counter of velocity for the linear injectors on the injector plate

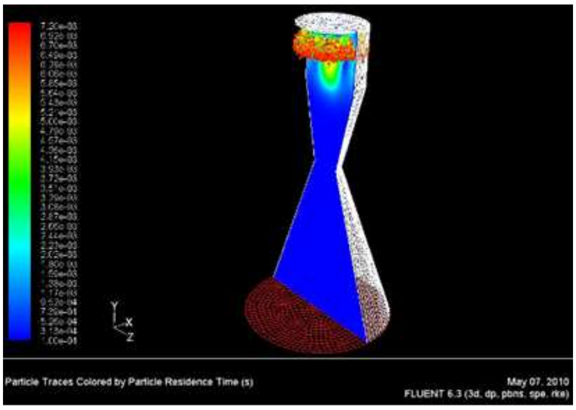

Fig.25 The complete expanded of the sprays in combustion chamber

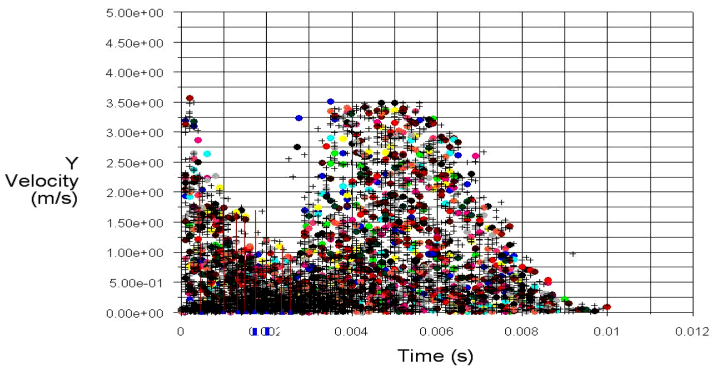

Fig.26 Graph of changing velocity on y-axis (V_{mean})

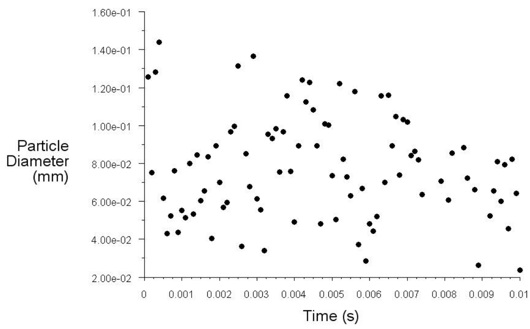

Fig.27 Graph of changing particle diameter by time

Investigation and comparing the experimental and simulation results

In this section, the numerical results are compared with experimental results. Also, confirming the recent results and revolving accuracy are compared with previous investigations, Amount of droplets velocity is compared on two states ({p_f = 10 bars , p_o = 4 bars } , { p_f = 8 bars , p_o = 6bars}) are shown in figure 28 and 29.

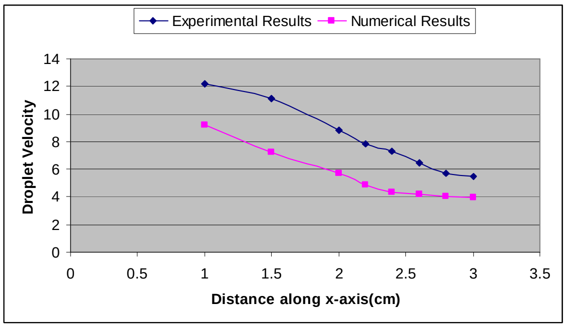

Fig.28 Comparing PDA results with numeric results for { p_f = 8 bars , p_o = 6bars}

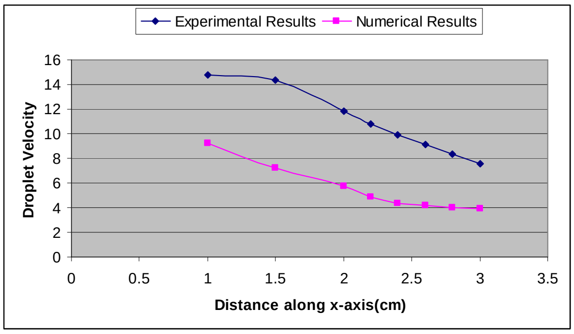

Fig.29 Comparing PDA results with numeric results for {p_f = 10 bars, p_o = 4 bars}

Table (2) shows amounts of the mean diameter, Sutter diameter and droplet velocity are gaining from experimental and numerical methods.

Table 2 Comparing velocity and diameter in experimental and numerical solutions

$D_{Mean}(\mu m)$		$D_{SMD}(\mu m)$	
Experimental	**Numerical**	**Experimental**	**Numerical**
113	80	115	205

Umean Experimental(m/s)	Umean Numerical(m/s)	X(cm)	Time(s)
12.203	9.19	1	5×10^{-4}
11.123	5.5	1.5	10×10^{-4}
8.79	4.7	2	14×10^{-4}
7.84	4.5	2.2	16×10^{-4}
7.284	4.4	2.4	18×10^{-4}
6.473	4.75	2.6	20×10^{-4}
5.674	4.3	2.8	24×10^{-4}
5.497	3.9	3	26×10^{-4}

In this research, authenticating and confirming the results are compared with Vessalo p. and Ashgriz N.([14] and [15]) results that, They use laser measuring instruments (PDA), which is accomplished by Atlantic researching Institute for (22–N) trust in real missile engine is done.

Also, in their research, water is operating fluid in these tests (oxidizer and reducer). The centrifugal injector is used in this test. This figure shows comparing velocity contour with the recent results.

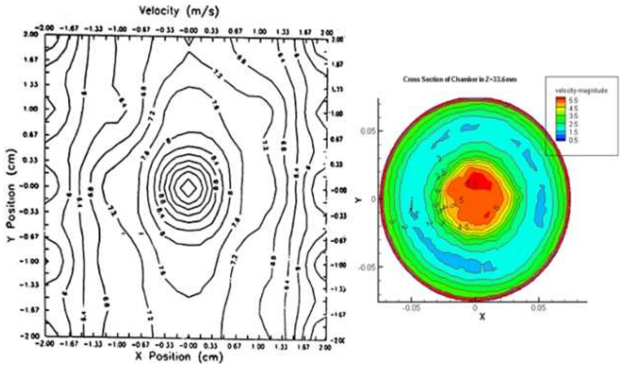

Fig.30 Compared velocity counter for an injector with Vessalo . p. results

RESULTS AND CONCLUSION

By means of gained tables and figures, we can find out:

✓ The gained numerical results from internal and external injector velocity by the time were graphed in figure 16 to 20. As you see, the droplets velocity with experimental results decreased by the time while the distance of injector increases and misses the initial momentum droplets.

✓ Figure 22 to figure 26 illustrate distribution and contact of spray to all of the injectors on the injector plates in combustion chamber. These figure show injectors spray from the beginning to convergence results.

✓ Figure 26 shows droplets velocity in injection spray. At first step as the droplets velocity decreases while decreasing momentum, then increases suddenly after contacting with injection spray to the other spraying injectors and this procedure repeat as decreasing.

✓ Figure 20 and 27 droplets diameter counter and graph are shown for one injector the farther injector nozzle, more decreasing particles diameters.

✓ Figure 28, 29 and table (2) indicates droplets velocity, mean diameter and Sutter diameter illustrated in two injection pressure ranges (({p_f=10 bars, p_o=4bars}, { p_f = 8 bars , p_o = 6bars}). These results are scrutinized and similar to decreased droplets velocity and droplets mean diameter.

✓ Figure 30 shows comparing Vessalo and Ashgriz results that the distribution of injector spray is symmetric and velocity profile is gained perfectly, The farther nozzle in axis direction, the more decreasing droplets velocity.

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