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A Technical Review on Effect of Spray Angles and Characteristics for a Pintle Injector

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ABSTRACT

The pintle injectors are one of the most important part also known as propellant injector is used in liquid rocket engines. This injector consists of movable pintle, annular nozzle, fuel injection port and a centre pintle nozzle. The spray phenomenon and flow characteristics resulting in formation of spray pattern shows out the effect of spray angles, droplet size and spray boundaries. Total momentum ratio (TMR) and spatial distribution of sprays plays a key role in order to influence the spray angles whereas opening distance, axial velocity and radial velocity is responsible for flow characteristics of injector. The review study of this paper is to show the influence of spray angles and characteristics such as flow as well as combustion on spray images, droplet size, momentum ratio, opening distance and SMD distributions which affect the injector geometry.

Keywords – Pintle injector, Pintle opening distance, Review, Sauter mean diameter (SMD), Spray angle.

1. INTRODUCTION

The injectors play a major role in directing the flow of fluids at high pressure. This system consists of no moving parts like calibrated orifices at the pintle tip and the injector body excluding the inlet valve and to be called as fluid dynamic pump. During which the pintle injector is one among the sort that is employed to inject cryogenic liquid propellants into the combustion chamber. Several experiments and test were been conducted to bring about a steady operation and lofty performance of liquid rocket engines. Here comes the parameter of the pintle injector alongside its advantages. The injector shows a greater throttling range than others by creating a self-stabilized stream pattern along with some rare acoustic ignition instabilities. The work flow of the pintle is that the bipropellant likes liquid methane, aerozine 50, hydrazine etc. From the fuel tank was allowed to flow into the combustion chamber were its metered propellant flow which is within the sort of stream lines. Here another propellant is been allowed to flow through the other orifice plate which is Directed to the toroidal chamber. Therefore, the mixing of the propellants takes place evenly before reaching the combustion chamber. Fuel is been injected radially and oxidizer axially therefore the collision of these two streams leads to great atomization. This review paper gives a brief content about different experimental setups, numerical analysis and even the comparison of the data along with Number of the major flow characteristics are been discussed here.

2. LITERATURE REVIEW

Son et.al (2015) has investigated the momentum ratio and weber number for determining the spray half angles on pintle injector. Form this experiment analysis we have come across the results for discharge coefficients value, spray images, spray pattern and its distribution which was stimulated in a way as the values of discharge coefficients results a lead up to a certain value around 0.75mm and decrease in values before it is presenting out the plots linearly. The value of discharge coefficient was found to be higher for lower pressure drops. The results for the spray images were founded as for lower value of pressure drops, a thin liquid sheet was made with the help of low liquid momentum. For estimation of spray pattern and distribution a tool or device named patternator was used which further results in capturing of spray images at certain point of values. At lower pressure drops, the cross-sectional area of spray increases for higher value of injected pressure responsible for decrement in opening distance [1].

Son et.al (2016) carried out study on pintle injector for verification of spray simulation over liquid engines. Similar experimental set up was taken as mentioned in M. Son et.al. The spray characteristic was studied using the simulant as water. The measurement of liquid in cylinder vessels was evaluated with the help of ultrasonic detector sensor. Four different injection runs were taken in consideration as decreasing the value for pressure drops to study the effect of weber number and momentum ratio. An unsteady based solver was also taken in account for analyzing first order implicit function and second order discretization. The numerical result was obtained as the formation of recirculation zones were initiated at the tip point of pintle as well as the streamlines of turbulent kinetic energies were different from those of spray geometries. The initial and final velocity obtained from the experiment was like those of the simulation results [2].

Sakaki et.al (2017) studied the combustion features of ethanol/liquid oxygen rocket engine combustor with planar pintle injector to survey total momentum ratio as well as the spray patterns. The characteristics exhaust velocity and an atomization characteristic was also taken in account regarding experimental analysis. The combustion effectiveness results were carried out in relations with features adeptness, flame structure as well as spray structures and total momentum ratio. The effect of TMR results in such a way that the value of O/F ratio was founded by varying the injected speed. The revision of propellant that was imposing on the combustion partition were done by optical instruments resulting in decrease of TMR value which adversely affect the characteristics efficiency to be increased. The injected velocity of propellant was also responsible for the penetration heights which states that it values decreases with the decrease in injected velocity. The characteristics efficiency was also responsible for better atomization performance [3].

Cheng et.al (2017) highlighted the study for spray angle for two corresponding fuel injectors. The analysis for the work was shown as the pintle injector chosen for the experiment has different slots and the liquid sheets are to be considered as axisymmetric because the radial sheet and liquid sheet imping out on each other to fully maintain the control surfaces. The numerical simulation was performed using Euler’s approach to study for the multiphase flows in addition with the RANS equation to validate the model. The computation analysis was made using pressure-based solver in ANSYS for two phase simulation flows. The boundary conditions were taken as inlet as velocity inlet, outlet is pressure outlet and walls to be stationary walls without any slip condition. The three different grid tests were performed considering three different zones [4].

Son et.al (2017) investigated the identical study for combustion behavior of injector subjected to center tip for rocket engine. This study was done on basis of steady and two-dimensional asymmetric conditions followed by Jones- Lindstedt model using eddy-dissipation analysis for turbulence kinetic reaction. The value for simulated pressure was observed to be lower than the targeted ones as role of combustion efficiency that was neglected. The streamline flow results in existence of recirculating flow at specific regions. The effect of mass flow rate results in such a manner that because of recirculation there is decrease in mass flow rate for low throttle condition. It was also observed that reduction in combustion efficiency results in reduction of flow rate for variable thrust condition. For recirculation zone, it was seen that poor performance exhibited by zone results in wider range of flame angles and causes instability problems [5].

Huang et.al (2019) investigated the pintle injector to study the rotating detonation wave in hollow chamber. The experimental set up consists of combustion chamber, gas supply system and control system. Pintle injector was inserted at different locations as 0, 5, 10, 15 mm respectively into combustion chamber. The increase in value for adding up length and shorten in diameter results in the formation of recirculation zone preventing the continuous rotating detonation (CRD). Another type of propagating mode saw tooth wave results in instability and have a limited value close to the deflagration. The intrinsic frequency was also calculated and compared with experimental results which show the error value less than 5%. The decreasing value in pintle injector results in varying conditions for CRD wave frequencies that is different from intrinsic frequencies [6].

Chen et.al (2019) formulated the specific spray behavior of pintle injector based on empirical approach. The experimental component that was used is like that of Huang et.al to detect the images for spray pattern, size of droplets and spray speed distributions. The interconnection between jet flows and the resemble film flows expresses characteristics of spray as well as the interaction of liquid with spray center representing to the flow behaviour of injector. The SMD curve for radial direction is found to be in “N” shape whereas for axial velocity as well as radial velocity a curve represents “V” shape. It was also observed that the spray density was relatively thin at outer boundary interacting among the droplets which results out to be weak [7].

Lee et.al (2019) studied the flow visualization of cryogenic spray from movable pintle injector. The experimental apparatus considered to perform experiment are- liquid simulant tank, gaseous simulant tank, reservoir, pressurized helium tank filled with liquid nitrogen and high-speed CCD Camera. The flow rate propellants are controlled by varying both supplying pressure and pintle opening distance. The result for propellant density variation was studied using camera trigger signal and data acquisition system. For visualized images, it was also found that value of TMR increases as the value for spray angles increases along with the change in pintle tip angle. There was also a formulation of an empirical correlation between spray angle and injected velocity for which the results obtained were found to be suitable for combustion experimental analysis [8].

Zhang et.al (2020) studied experimental and numerical alterations on flow field characteristics of pintle injector. Three different test conditions were performed using water as simulant any varying out the nitrogen momentum followed up by ANSYS software. The experimental set up was taken as- pintle, sleeve protective shield and two tight packings along with high speeding camera. The principal component analysis (PCA) as well as growing methods was also taken in account for calculation for fine spray angle. The critical momentum ratio was considered for further analysis for which atomization cone angle was neglected. The result was also seen for SMD distributions that are considered along radial and axial directions [9].

Son et.al (2020) studied the characteristics property for location and angles of GOX/GCH4 flames of annular type pintle injector. The visual study of flame characteristics was carried out with help of schlieren image processing technique. The two different flames shapes were obtained during study as- shear layer flame, which is positioned amid two added propellants and other as tip-involved flame that is located near pintle tip. It was also investigated that an upper density grade area exists near flame boundary. The shear layer flame was attached between oxygen and methane whereas for tip involved flame it started from pintle tip. The flame as well as spray angles are the important factors that are responsible for forming an association among angle and non-dimensional number. For limiting shear layer flame, the flame angles were measured with respect to momentum flow rate ratio. The characteristics of flame led to formation of correlation between pintle number, K_P with spray as well as flame angles [10].

Lee et.al (2021) investigated the skip distance on spray characteristics of pintle injector. The study was carried out in such a manner controlling out the throttle level representing as main component for pintle injector. The experimental set up were maintained as- pintle, gaseous methane, gaseous oxygen, liquid oxygen, digital camera, mass flow meter etc. The results obtained from this work occur as by change in skip distance the characteristics of spray changes as well for which the development of spray boundary occurs as well. It was also observed that by increasing skip distance, the skip length also increases which gradually increases the momentum loss rate for which spray angles becomes large. The calculations of average growth rate were also founded by analyzing between experimental data points for five different skip distances located out for alternating throttle level. The results of SMD represents that its value decreases with decrease in skip distance because of increase in value of aerodynamic forces and the approximate value obtained for spray angles was around 0.91. It was also noted that gas velocity distributions were analyzed numerically and was affected by ambient conditions [11].

3. DISCUSSION

3.1 Discharge Coefficient

As the injector has a variable area at different opening pintle distances. Few parameters that must be considered for the calculation of discharge coefficient values: a) the distance representing the gap near pintle center denoted by L_{cg}, b) the measuring length from halfway of pintle tip in particular parallel direction denoted by L_{open}. Once the pintle moves away from its initial position (i.e., zero) to some instant, the mass flow rate of injector increases. For recirculation zone, the value for mass flow rate is higher as of the fewer gaps that were assumed to be taken. The results were obtained as for opening distance of 0.75 mm, the discharge coefficients values were decreasing in linear manner and after while it shows an increase which results in low values of pressure drop [1].

3.2 Spray Images

The spray images were obtained using shadow technique method for which the value for opening distance followed by series from 0.2 mm to till 0.8 mm and from 0.1 bar to 1.0 bars and 0.01 bar to 0.2 bars for liquid and gas pressurized liquid, respectively. For low pressure drop, a thin film liquid sheet was formed on overall region. It was also observed that pressure drop affects the breakup performance and shows that high pressure drops values result in higher breakup performance. The half angle was measured at a particular distance away from tip portion resulting in half spray angles to represent its increment when the value of pressure drop was at 0.1 bars [1].

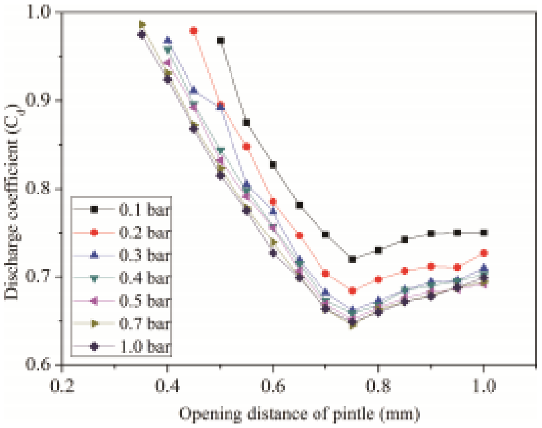


Fig.1 Discharge coefficients for pressure drops and opening distance [1]

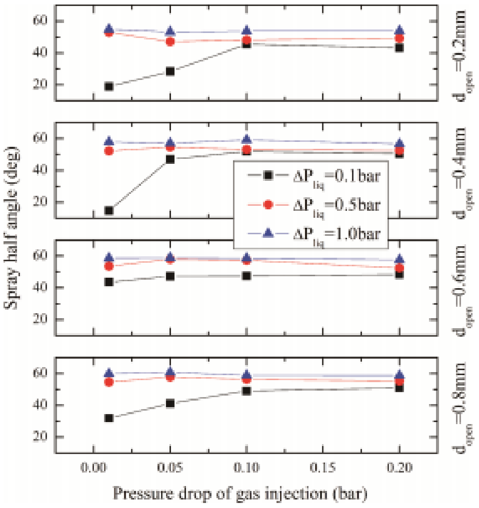


Fig.2 Spray half angles at different opening distances for pressure drops [1]

From this graph it is clearly stated that for pressure drops at 0.1 bars for opening distance of 0.2 mm the values increase with increase in spray half angles and at a particular angle i.e., around 40° the curve becomes linear and after while slightly tends to decrease because of low opening distance at pintle tip and lower pressure drops. Similarly, such plots were shown for theoretical opening distance that were taken for which the spray half angle value is around 42° for 0.4 mm, 43° for 0.6 mm and 45° for 0.8 mm at 0.1 bar. At 0.5 bars, it is seen that for 0.2 mm the curve decreases till at an angle of 40° after while it becomes linear. The curves plotted for different opening distances shows the spray angles as 50°, 52° and 55° respectively. The overall conclusion made from these plots are for lower opening distance we have less value of half spray angles and further resulting in lower pressure drops.

3.3 Spray Pattern and Distribution

At low pressure drop of liquid, the sectional area for spray images increases as due to accumulation of gas particles altogether. The spray area decreases for decrease in gas pressure drop when injected pressure for liquid is high. It is also seen that for spray angles of liquid pressure drop at 0.1 bar increases as gas pressure drop increases and decreases for higher pressure drop of liquid. Thus, the results obtained for spray pattern were in dispersed form from that of spray images [1]. The spray pattern gets increases as it goes under an expansion process which results in increment of momentum ratio and for which the area region at center of spray becomes more dense [7]. The plot for spray pattern is shown below-

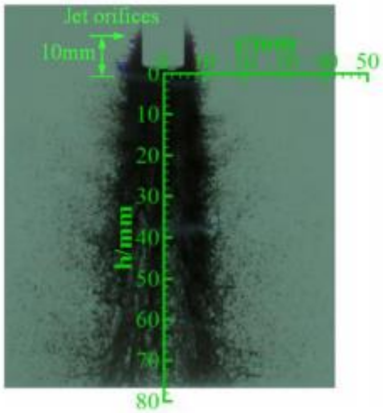


Fig. 3 Spray pattern variation at different heights [7]

The spray boundaries are calculated using the concept of volume rate measuring for every single definite point. The pattern for injector is valid for only half space tip portion. From above shown spray pattern it is stated out that with increase in spray boundaries the volume rate also increases. The maximum value for volume rate obtained as 9mm was seen at boundary spray of 75 mm.

3.4 Effect of Total Momentum Ratio (TMR)

*3.4.1 Effect on Characteristics efficiency C**

The relation between the TMR and C* represents a linear plot which for which it is been found that the value of TMR decreases with increase in characteristics efficiency. For fuel-centered portion, the effect on efficiency is not clarified as that of oxidizer center because the imping nature of propellants striking at combustor walls were not affected by the TMR which further results to decrease in efficiency. The effect of impingement of propellants affects the performance of c* efficiency as it was obtained that the results for fuel centered portion are less affected than that of oxidizer fuel portion because of the variant in compositions of oxidizer and fuel rates as well as injected velocity. As of this, the atomizing property, and the time magnitude of propellant drops for the vaporized area region also reduce. The improvement in atomization features results in increase for the response of propellants used in process [3].

3.4.2 Effect on Spray Patterns

The effect of momentum ratio on spray pattern shows that with increase in momentum ratio, the region for boundary layer also expands for which spray angles also rises. It was observed that the images of spray intersect for which the estimation of density is obtained on account of outer boundary layer. The productivity shows that the consequence of momentum ratio on jet expansion is ignored [7].

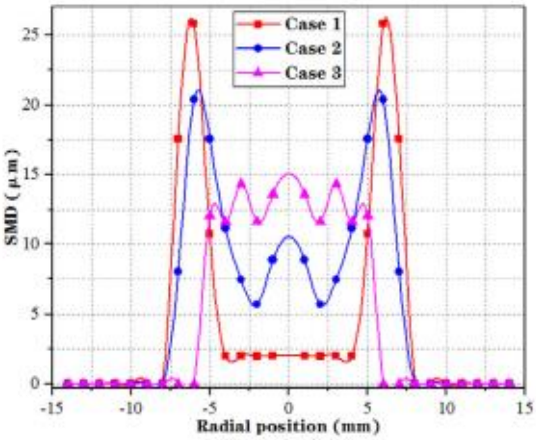
3.5 Sauter Mean Diameter (SMD)

The evaluation of SMD is done using a curve equation followed by-

$$SMD = 185.5d_{open} + 65.1 \qquad (1)$$

Where, d_{open} is the opening distance of injector.

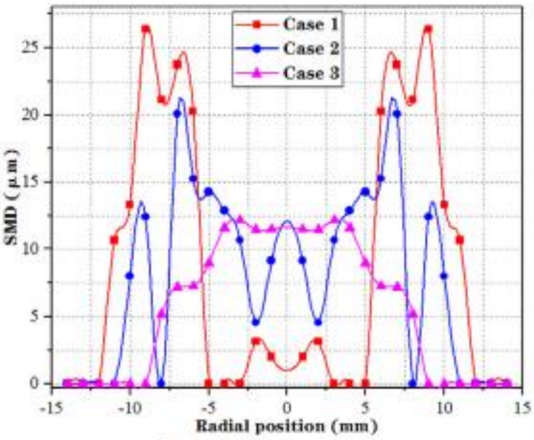
The determination of SMD is based upon two important parameters- opening distance, size of droplet. It was observed that the deviation in flow field fallouts to the larger extent which encounters that the SMD is affected by several parameters such as momentum ratio, weber number, positons etc. The relation among these parameters is in a manner describing as with increase in rate of weber number the axial location for SMD decreases due to higher formation of jets and the uniform distribution of droplets [9]. The three different case runs were performed to study the variation of SMD at different positions that are shown below-



(a) Axial position x=8mm

Fig. 4 SMD distribution at axial position x=8 mm [9]

From Fig. 4 it can be found that at position lying between 0-5 mm the curve for case 1 shows the linear variation whereas for case 2 and case 3 the results are found to be little different that are varying in a frequent manner. It was concluded from plots that the SMD distribution has major influence on droplet size as well as the mixing area which further parallels to the uniform field distribution.



(b) Axial position x=40mm

Fig. 5 SMD distribution at axial position x= 40 mm [9]

A similar plot was generated for the axial position of 40 mm (Fig. 5) which shows that for case 1 and case 2 there is a rapid decrement that can be seen for positions lying between -5 to 5 mm where negative sign basically represents the downstream position for jets located at that specific position in linear manner whereas for case 3 it was observed a little linearity in the curve.

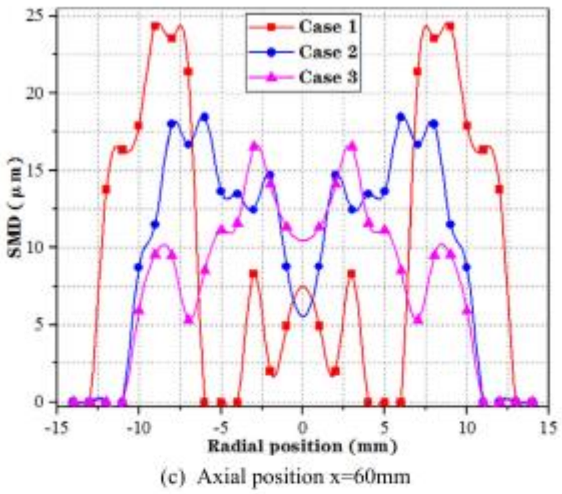


Fig. 6 SMD distribution at axial position x=60 mm [9]

For Fig. 6, it is clearly visible that the results for case 1 were found to be like that of case 2 at SMD angle of 7° at x =0 mm. A similar result was also found when results for case 2 and case 3 coincidence for downstream position i.e., x =-3 mm at an angle of 13° as well as at x = 11 mm for an angle at 3°. The maximum values for SMD from all these three different conditions were obtained as- 26 μm, 27 μm and 28 μm correspondingly.

3.6 Spray angle (θ)

The detailed data is been observed with the help of all visualized images. In the liquid- liquid mixture the interaction between the wall surfaces is also considered. Using the data processing method, the spray angles are been imaged and even the heights are obtained for each single point along with which the SMD besides the mean axial rate is arithmetically managed using all the models, 50%, 20%, 100% sequentially. These images give the details about the expansion of spray from which the spray angle can be calculated. From the previous study the spray angle is depended on TMR which is calculated from the equation for liquid-liquid mixture that too typical based on the momentum conservation in the axial way. From Cheng et al the spray half angle θ' is been predicted using

$$\text{Cos}\,\theta = 1 / 1 + \text{TMR} \qquad (2)$$

For the radial orifices the TMR is been replaced by LMR. Many models are been experimented in which they have noted that considering LMR the radial channel was by LMR considering the radial channel is formed as isolated orifices than continuous gap. The image explains different spray angles obtained at different operating conditions; radial distances change according to the working ranges.

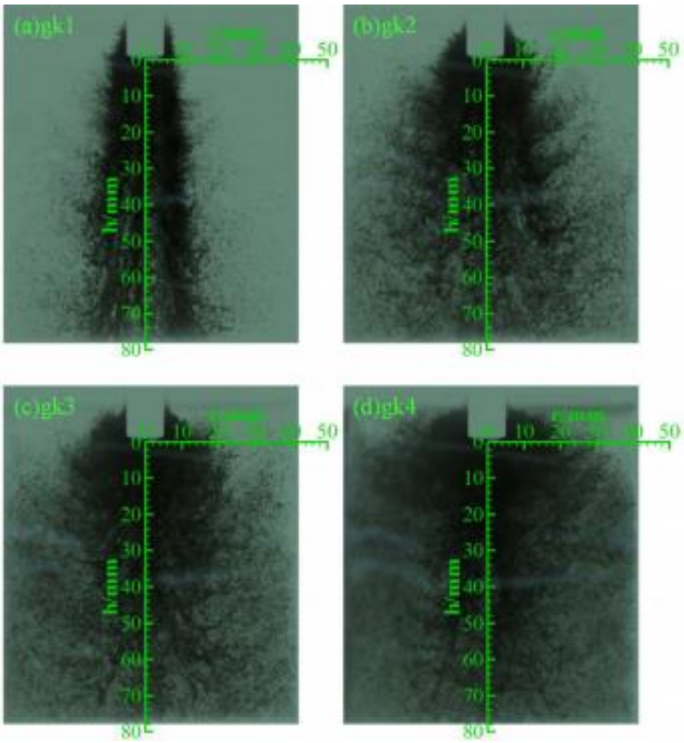


Fig. 7 Spray patterns under different working conditions

Lee et.al have explained clearly the relation between the bunch angle, skip distance and regulating level. The images indicate the raw data of the spray angle denoted by red line. They have made use of Otsu's method to find the relation; it indicates the average standard deviation of the angles was ±8.33◦.

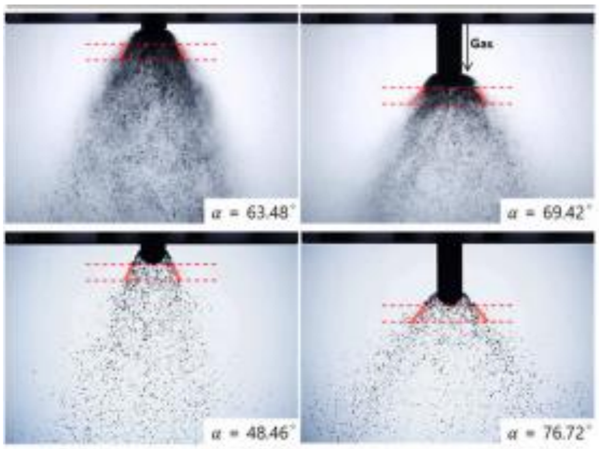


Fig. 8 Spray angles under different skip distances

The figure 8 explains between the skip distance and throttling level from which the angle is influenced. For the skip distance 0.25 and 0.91 the spray angle is been increased gradually, here when the skip distance increases the spray angle also improved gradually but the throttling is been reduced. It is concluded that spray angles are been influenced by the skip distance and not by the throttling level. This is because the affinity of the gas to expand before collision of the liquid. Initially with the change there will be a gradual increase in the angle but cause of the momentum loss percentage of the gas due to expansion which primes to the friction produced on the pintle exterior which tremendously increases the spray angle further [11].

5. CONCLUSION

The phenomenon of spray and the factors influencing the spray angles like opening distance, axial and radial velocity along with the flow characteristics of the pintle injector includes droplet size, spray pattern, spray boundaries, SMD, TMR, weber number and the factors resulting in affecting the injector geometry with detailed explanation is been reviewed in this paper. Discharge coefficient is been related with the pressure drop and concluded that discharge coefficient increases in a linear manner laterally with the low values of the pressure drop. Spray images for certain opening distances are observed, the outcomes explains that pressure drop affects the breakup performances sideways for low opening distance lower values of half spray angles. Then comes the spray patterns expresses the relation of TMR and C* in linear plot, if TMR increases laterally with the characteristic's efficiency. Concluding that the improvements in atomization structures results in the increased response of the propellants used. Thus, the SMD and TMR are all observed and explained in this paper.

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