International Journal of Mechanical Engineering and Technology (IJMET)
Volume 9, Issue 3, March 2018, pp. 382–391 Article ID: IJMET_09_03_038
Available online at http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=3
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

EFFECT OF REYNOLDS NUMBER AND WEBER NUMBER ON THE ESTIMATION OF DROPLET SIZE FOR AN INJECTOR

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ABSTRACT

A numerical study has been conducted to assess the effect of Reynolds number and Weber number on the size of the droplets produced from an injector. With changing combustion chamber pressures, the non-dimensional parameters also vary, which in turn influences the Sauter mean diameter of the droplets. These two parameters become the deciding factors for an injector design. In this paper, the results are compared for two sets of oxidizer and fuel orifice number ratios. The most suitable injector design is selected based on its performance given out by the interaction of the non-dimensional parameters on the droplet size.

Keywords: Propellants, injector, SMD, mass flow rate, mixture ratio, Reynolds number, Weber number

Cite this Article: Adheena G J, Kalakanda Alfred Sunny, Aldin Justin and Nallapaneni Manoj Kumar, Effect of Reynolds Number and Weber Number on the Estimation of Droplet Size for an Injector, International Journal of Mechanical Engineering and Technology 9(3), 2018. pp. 382–391.
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1. INTRODUCTION

Over the period the satellites tend to decay due to various perturbations like the solar radiation pressure, Earth's gravitational pull, Luni-solar perturbations and the oblate shape of the Earth. Sometimes the debris in space can also distort the satellites from its orbit. Thus, to maintain the trajectory and attitude of satellites special propulsion requirements are needed. This aroused interest in the development and deployment of small thruster rocket engines. The thrusters are used as reaction control systems (RCS), which can provide small amounts of thrust in any required direction or combination of directions. The function of an injector is like that of a carburettor in an internal combustion engine. The injector introduces the propellant, atomized and mixed thoroughly into the combustion chamber. An ample amount of successful injector designs are now available [1], but there are still no inviolable rules to assure a successful design [2]. The ultimate challenge lies in understanding and predicting the chemical and physical processes that are encountered within the combustion chamber forming the initial design parameters for injector design [3]. The chemical reactions, mixing and the mechanism of droplet formation for a given propellant combination has been studied, for designing an injector. It is very important to keep the arrival order of fuel and oxidizer streams which depend on the propellant and its ignition characteristics during initiation. The propellant mass distribution and fuel-oxidizer mixture ratios influences the injector hole patterns, which in turn effects the combustion performance. Proper atomization and pressure drops of the propellant are taken into consideration during orifice designs [4,5].

2. MATERIALS AND METHODOLOGY

A. SELECTION OF PROPELLANTS

Propellant selection forms the basis of designing of a rocket engine. The characteristics and properties of the propellants in their unreacted conditions as well as post reaction is determined by its chemical nature. The selection of propellant combination is based on various factors like expense, specific impulse, effective exhaust velocity, specific fuel consumption and the physical properties of the propellants [6].

Table 1 Ranking of liquid bipropellants based on TEHF [6, 7]

Oxidizer	Fuel	TEHF	Notes
N_2O	Propane	0	Earth storable
O_2	Hydrogen	0	Semi-Cryogenic
O_2	Methane	0	Semi-Cryogenic
O_2	Propane	0	Semi-Cryogenic
N_2O	Ethanol 96%	0.03	Earth storable
N_2O	Kerosene	0.09	Earth storable
O_2	Ethanol 96%	0.15	Semi-Cryogenic
O_2	Kerosene	0.19	Semi-Cryogenic
O_2	NH_3	0.60	Semi-Cryogenic
O_2	N_2H_4	2.82	Semi-Cryogenic
O_2	AZ50	3.01	Semi-Cryogenic
O_2	UDMH	3.62	Semi-Cryogenic
H_2O_2 (95%)	Kerosene	4.58	Earth storable
H_2O_2 (95%)	Iso-Octane	4.61	Earth storable
H_2O_2 (95%)	Propane	4.65	Earth storable
H_2O_2 (95%)	Methane	4.66	Earth storable

Importance is given to the utilization of green propellants due to its reduced toxicity, pollution, launcher aspects, storability, availability and cost factor [7]. The propellant combination that satisfies the conditions has turned out to be the combination of Liquid Oxygen and Kerosene (Table 1). This combination rules out other fuel combinations in terms of a moderate balance with all the major factors: increased performance in terms of specific impulse, storability and low total volume for high total impulse missions, reduced overall life cycle cost and low TEHF (Toxic Environment and Hazards Factor).

B. PERFORMANCE PARAMETERS

The performance parameters of combustion chamber such as the combustion chamber pressure, mixture ratio, combustion chamber temperature, specific heat ratio and molecular weight were obtained from the charts and other parameters for instance, coefficient of discharge, density of propellant, surface tension and its viscosity were fixed [8].

C. ESTIMATION OF DROPLET SIZE

Droplet size estimation was done using isentropic equations to mathematically model the droplet size [9,10]. The two main parameters that influence the droplet size are changing diameter of the injector orifice with constant number of oxidizer and fuel orifices for different pressures and changing the number of injector orifices with constant injector orifice diameter again for varying pressures [11,12].

The calculations were done as follows [6]:

1. PRESSURE AT THE NOZZLE THROAT (P_t)

The pressure at the throat required for producing 2000N thrust is given as [6]:

$$P_t = P_c \left(1 + \frac{k-1}{2} \right)^{\frac{-k}{k-1}} \quad \textbf{(1)}$$

2. TEMPERATURE AT THE NOZZLE THROAT (T_t)

The respective temperature at the nozzle throat [6]:

$$T_t = \frac{T_c}{\left(1+\frac{k-1}{2}\right)} \quad \textbf{(2)}$$

3. EXIT PRESSURE (Pe)

The exit pressures which determine the type of expansions of the exit flow is calculated as [6]:

$$P_e = P_t \left(1 + \frac{k-1}{2} \; M^2 \right)^{\frac{-k}{k-1}} \quad \textbf{(3)}$$

4. EXIT MACH (M)

To obtain the exhaust velocity of the combustion products, the exit Mach is calculated [6].

$$M = \sqrt{\frac{2}{(k-1)} * \left(P_c^{\frac{k-1}{k}} - 1 \right)} \quad \textbf{(4)}$$

5. EXIT TEMPERATURE (Te)

The exit temperature is thus obtained from the isentropic relations as [6]:

$$T_e = T_t \left(1 + \frac{k-1}{2} \; M^2 \right)^{-1} \quad \textbf{(5)}$$

6. EXIT VELOCITY (Ve)

The mass flow rates of the propellants depend on the exhaust velocity [6].

$$V_e = M\sqrt{KRT_e} \tag{6}$$

D. SPECIFIC IMPULSE (ISP)

It is the change in momentum delivered per unit of propellant consumed. A propulsion system with a higher specific impulse uses the mass of propellant more effectively in gaining altitude, distance and velocity. This is because if an engine burns the propellants faster, the rocket has less mass for a longer period of time, which makes better use of total force times that was acquired from the propellant [6].

$$Isp = \frac{F}{\dot{m}} \ or \ Isp = \frac{V_e}{g} \tag{7}$$

E. MASS FLOW RATE ($\dot{m}$)

It is the mass of a substance which flows per unit of time [6]

$$\dot{m} = \frac{F}{Isp} \tag{8}$$

F. MASS FLOW RATE OF OXIDIZER ($\dot{m}_o$) AND FUEL ($\dot{m}_f$)

The mass flow rate of oxidizer and fuel are obtained from the total mass flow rate as calculated in the combustion chamber design. Individual mass flow rate is further divided with the number of orifices, so that the mass flow rate is uniformly divided into each orifice injector nozzle [6].

$$\dot{m}_o = \frac{\left(\frac{m_r * \dot{m}}{m_r + 1}\right)}{no.of\ oxidizer\ orifices} \tag{9}$$

$$\dot{m}_f = \frac{\left(\frac{\dot{m}}{(m_r + 1)}\right)}{no.of\ fuel\ orifices} \tag{10}$$

Where, m_r is the mixture ratio of the propellant.

G. NON-DIMENSIONAL PARAMETERS

Reynolds number is the ratio of inertial force to viscous force, and Weber number is the ratio of inertial force to surface tension. The breakages of propellant particles are initiated by inertial forces which are countered by surface tension and viscosity of the propellant. Thus, higher the Reynolds and Weber number smaller droplet diameter [6, 13].

$$Re_o = \frac{V_e * D * \rho_o}{\mu_o} \tag{11}$$

$$Re_f = \frac{V_e * D * \rho_f}{\mu_f} \tag{12}$$

$$We_o = \frac{{V_e}^2 * D * \rho_o}{\sigma_o} \tag{13}$$

$$We_f = \frac{{V_e}^2 * D * \rho_f}{\sigma_o} \tag{14}$$

Where; Re_o and Re_f are Reynolds number for oxidizer and fuel respectively. We_o and We_f are Weber number for oxidizer and fuel respectively.

H. SAUTER MEAN DIAMETER (SMD)

Sauter Mean Diameter is the most widely used type of droplet size estimation, which is the average particle size in the atomized region. The volume to surface area ratio is same for these droplets [6, 14].

$$SMD_o = D * 82.23{C_d}^{0.64} * {We_o}^{-0.07} * {Re_o}^{-0.5} \quad \textbf{(15)}$$

$$SMD_f = D * 82.23{C_d}^{0.64} * {We_f}^{-0.07} * {Re_f}^{-0.5} \quad \textbf{(16)}$$

Where; SMD_o and SMD_f are the sauter mean diameter of oxidizer and fuel respectively. D is the diameter of the orifice. C_d is the coefficient of discharge.

3. RESULTS AND DISCUSSION

The Reynolds number and the Weber number tend to increase with increase in chamber pressure. The increases in the non-dimensional numbers are very minute compared to the increase in chamber pressure. Thus, the values of the non-dimensional numbers were selected for the chamber pressure of 75 atmospheres. The interpretation of the graphs converges to a common conclusion, wherein the SMD is the smallest for orifice diameter of 0.5mm. Both the non-dimensional numbers are also highest for 0.5mm diameter. This proves that the inertial forces, surface tension and viscosity of the fluid play a major role in atomization. For better atomization, the inertial forces must counter balance and be greater than the combined surface tension and viscous force. The Sauter Mean Diameter for both fuel and oxidizer seems to be more efficient for the 15:30 ratio of number of respective orifices.

REYNOLDS NUMBER VERSUS SAUTER MEAN DIAMETER OF LOX AND KEROSENE RESPECTIVELY FOR VARIOUS INJECTOR ORIFICE DIAMETER WITH VARYING NUMBER OF ORIFICES.

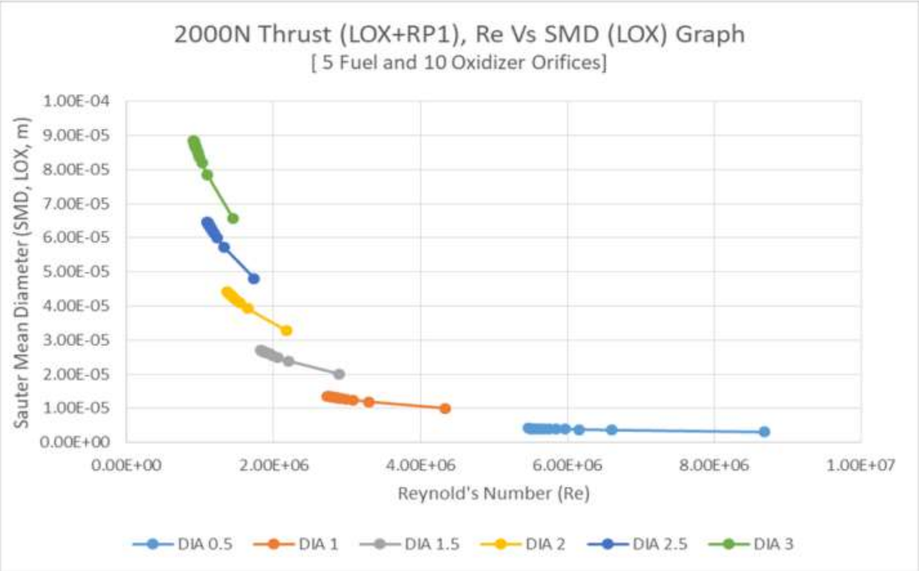

Figure 1 Reynolds Number Vs. Sauter Mean Diameter of LOX for 5:10 Ratio of Orifices

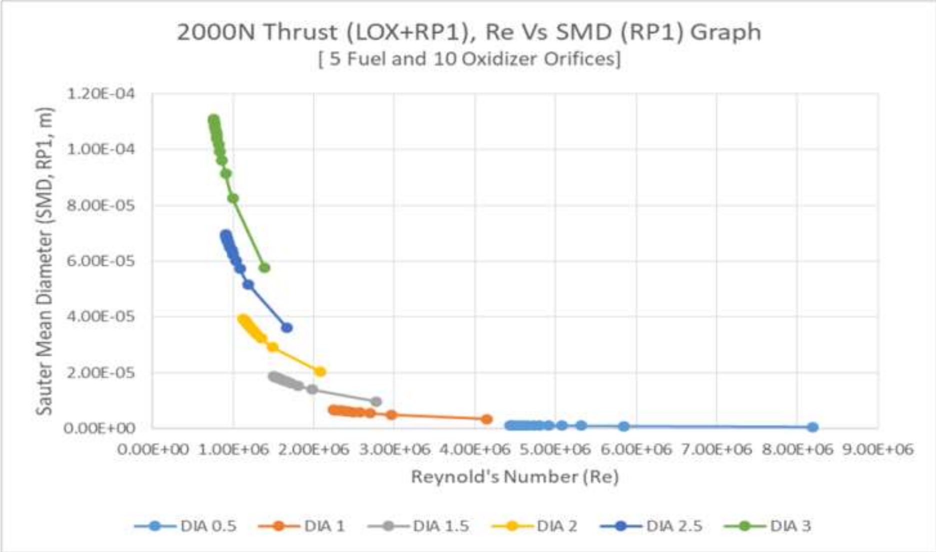

Figure 2 Reynolds Number Vs. Sauter Mean Diameter of RP1 for 5:10 Ratio of Orifices

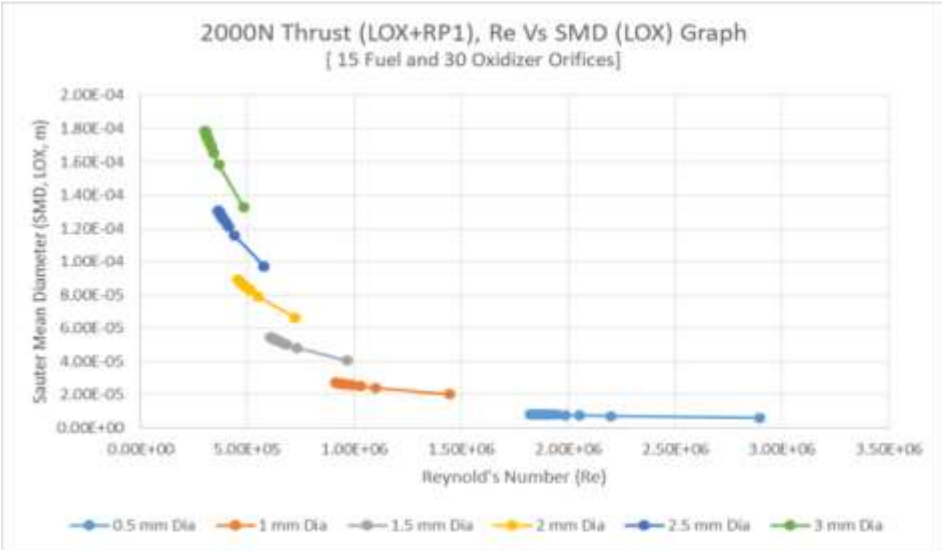

Figure 3 Reynolds Number Vs. Sauter Mean Diameter of LOX for 15:30 Ratio of Orifice

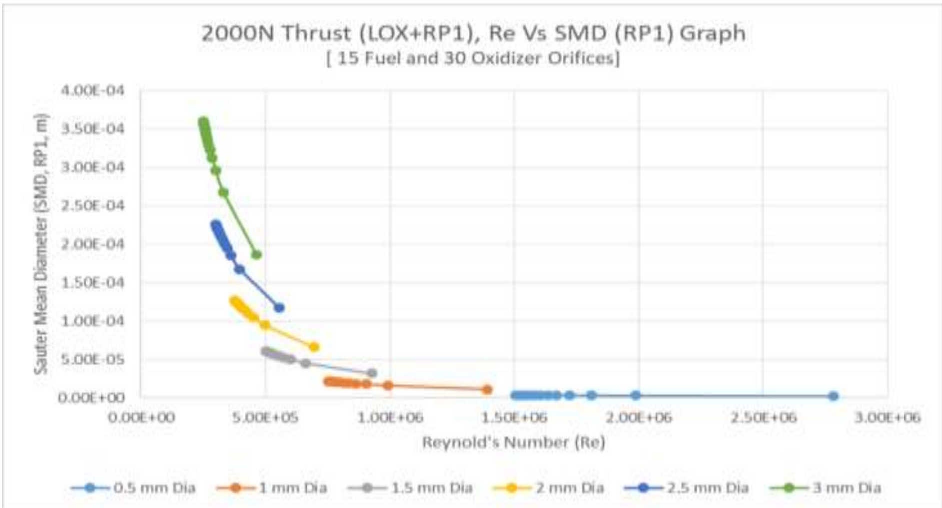

Figure 4 Reynolds Number Vs. Sauter Mean Diameter of RP1 for 15:30 Ratio of Orifice.

The Reynolds number is compared with the Sauter mean diameter of the propellant. Reynolds number being the ratio of inertial force to viscous force, higher Reynolds number indicates that the flow is having stronger inertial force than fluid viscosity. The atomization is mainly dependent on the inertial forces for break up, meanwhile the viscous force resists the breaking of the liquid film.

Figures (1) and (2), gives the comparison of droplet size (SMD) with Reynolds number for 5 fuel orifices and 10 oxidizer orifices. The graphs show that the SMD is exponentially raising with increase in Reynolds number. This is because the Reynolds number is inversely proportional to viscosity of fluid. The bonds between the particles are stronger for viscous fluid, the inertial force present will be small compared to viscous force. Lower Reynolds number means higher viscous force this hinders the atomization of the propellant.

The graphs also show that, smaller the orifice diameter greater is the Reynolds number and smaller the SMD. The SMD of LOX is smaller than kerosene owing that viscosity of kerosene is more than that of LOX. The subsequent figures (3) and (4), also gives out the comparison of Reynolds number with SMD for 15:30, number of fuel and oxidizer orifices respectively. The only difference in all the graphs is that the SMD increases with the increase in number of orifices. The possible reason can be that with the increase in number of orifices the net energy required for breakage is lost in terms of higher pressure loss through the orifices.

It is also observed from the above graphical analysis that the droplet size is quite smaller for the orifice diameter of 0.5mm. Considering the average results, it is suggested that a ratio of 15:30 fuel and oxidizer orifice numbers would be more apt with hole diameter of 0.5mm.

WEBER NUMBER VERSUS SAUTER MEAN DIAMETER OF LOX AND KEROSENE RESPECTIVELY FOR VARIOUS INJECTOR ORIFICE DIAMETER WITH VARYING NUMBER OF ORIFICES.

Figure 5: Weber Number Vs. Sauter Mean Diameter of LOX for 5:10 Ratio of Orifice.

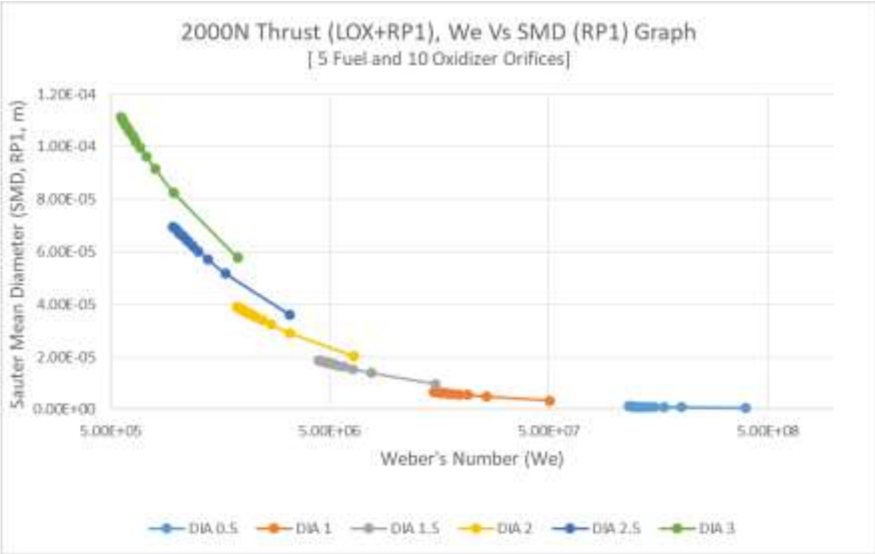

Figure 6 Weber Number Vs. Sauter Mean Diameter of RP1 for 5:10 Ratio of Orifice.

Figure 7 Weber Number Vs. Sauter Mean Diameter Of LOX for 15:30 Ratio of Orifice

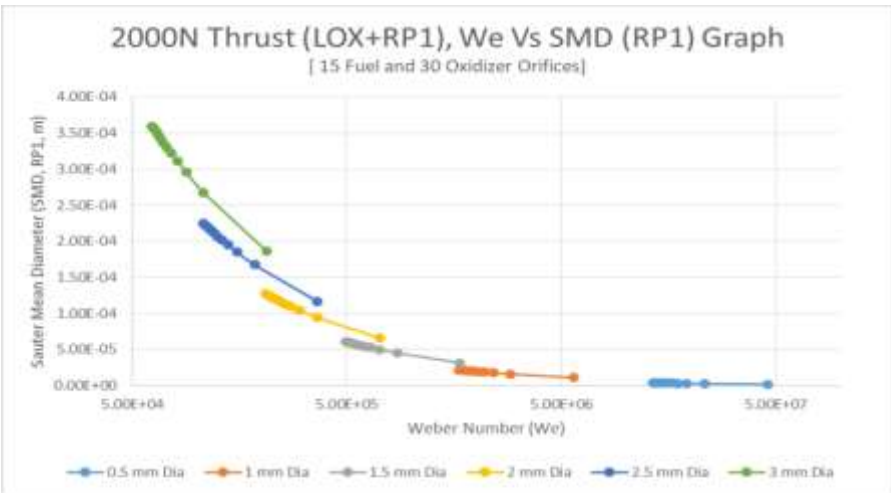

Figure 8 Weber Number Vs. Sauter Mean Diameter Of RP1 for 15:30 Ratio of Orifice.

Weber Number and SMD is compared with changing orifice diameter. Weber number is the ratio of inertial forces to surface tension. Surface tension, like, viscous force, resists the breakage of liquid film. Thus, with increase in weber number, the surface tension of the fluid particles reduces when the inertial forces rise.

Figure (5) and (6), shows how the Sauter mean diameter varies with increasing Weber number for oxidizer and fuel with the number of orifices being in the ratio of 5:10 respectively for fuel and oxidizer. The general observation is that the SMD seems to increase with the increase in Weber number as the surface tension tends to vary inversely with Weber Number. The graphs also depict that the for a certain orifice diameter, the effect of increase in weber is limited, i.e. after a certain value, further increase in Weber number has no effect in the atomization.

Similar inferences are made from the other graphs (figures 7 and 8). The analysis is carried out for 15:30 ratio of fuel to oxidizer orifice numbers. Like with the graphs of Reynolds number above, the fuel SMD is slightly higher than the SMD of oxidizer since kerosene is more viscous. It is also observed that in all the cases the orifice diameter of 0.5mm gives the smallest SMD value and the greatest Weber number, for both fuel and oxidizer.

4. CONCLUSIONS AND FUTURE WORK

Mathematical modelling of an injector design for a 2000N thruster rocket engine has been carried out. The variations of SMD with the non-dimensional numbers were graphically analyzed, since these numbers have a greater impact on the atomization size. Even though injector pressures influence atomization, the phenomena also depend mostly on the physical and chemical properties of the propellant combination. Considering the most efficient atomization and mixing, studies have concluded that impinging type injectors prove to be a better option, especially, when the thrust required is instantaneous for trajectory and attitude correction of satellites. Thus, the future course of work will be about considering an oxygen rich propellant mixture, being impinged for optimal mixing. Analysis can be made for changing impingement angle along with the other parameters to identify the best suitable injector design.

ACKNOWLEDGMENT

Authors were immensely indebted to Dr. Pradeep Kumar S, professor of Karunya Institute of Technology and Sciences, retired scientist and ex-group director of ADTG, Vikram Sarabhai Space center, and Dr. A N Subash, consultant and retired scientist of VSSC, whose expertise were of great help in shaping this work.

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