INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

IJARIIT

ISSN: 2454-132X
Impact Factor: 6.078
(Volume 8, Issue 4 - V8I4-1232)
Available online at: https://www.ijariit.com

Thrust vector control in rockets: Methods and effects

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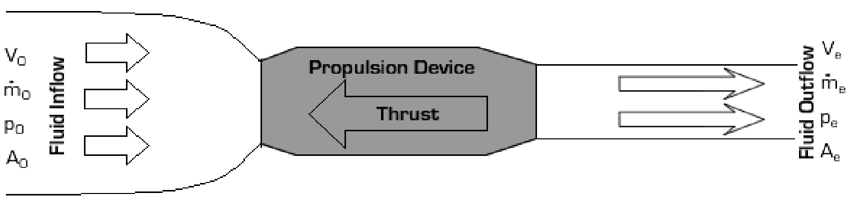
ABSTRACT

This paper discusses the basics of the design of a preliminary LITVC (Liquid Injection Thrust vector control) system in today's jet propulsion methods. In principle, several methods can be used, but because high-performance propellants produce very high temperatures and usually multiphase flow, thrust vector control methods that minimize contact between moving parts and propellant gasses are preferred. Also, the technique of obtaining thrust vector control by the injection of liquid into the supersonic region of a rocketnozzle has been studied. A basic model of fluid-injection thrust vector control is developed. The analysis is done to show the effects of injectant and propellant properties on the performance of the vehicle. Aero Thermochemical aspects are examined by predicting the performance of selected injections in combinationwith a hypothetical rocket propellant and nozzle. The idea of implying this method in the steering of terrestrial vehicles is also looked upon.

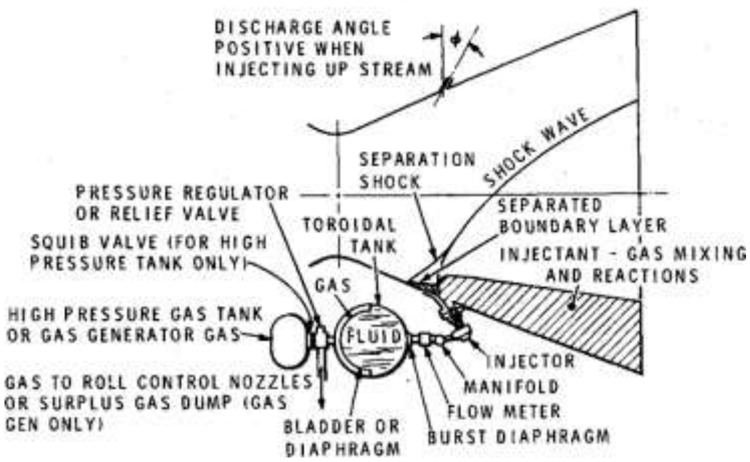
Keywords: *Liquid Injection Thrust Vector Control, Liquid Propellant Applied Research Motor, Bipropellant Injection Test, Solid Motor Injection Test, And Orifice.*

1. INTRODUCTION

In LITVC (Fig1), a vehicle is deflected for steering by injecting liquid into the side of the nozzle exit flow. The liquid is preferably both dense and exothermally reactive. The injection produces side thrust and added axial thrust mainly by pressures on the nozzle wall caused by shock waves and the addition of mass and energy to the flow.



Fig(1)Schematic of a propulsion device



(Fig2) LITVC system and its effects

LITVC adapts easily to rocket motor design. The components (servo-valves, piping, tanks, etc.) usually are located around the nozzle exterior and require only bracketry for attachment and lightweight insulation to protect them from exit-plume heat. The first step in design is to select a liquid injectant. The factors considered are specific impulse, density, storability, and toxicity. The injectant should have a high density to permit the use of small tanks, tubing, valves, and injectors. Reactive injectants have a greater specific impulse than inert liquids and should be used if possible. Problems of reactivity with materials, storability, and toxicity must be solved. Nitrogen tetroxide (N2O4), which gives the highest specific impulse of the operational injectants, is also the most toxic and reactive. It can be stored and used successfully if strict requirements for purity, container inertness, and safe handling are met. The amount of liquid needed depends upon the required vectoring.

Some of the injectants considered here that are used to propel the system are Freon-12, perchloroethylene, Solid Motor, Bromine, Bipropellant, and water
Before using these injectants onto the rockets for steering, numerous experimental injectant tests are undertaken to ensure proper working characteristics, such as LPARM(Liquid Propellant Applied Research motor) and Solid Motor Injection test

2. LPARM TEST

The LPARM was operated with unsymmetrical dimethylhydrazine and inhibited red fuming nitric acid at the following nominal conditions.
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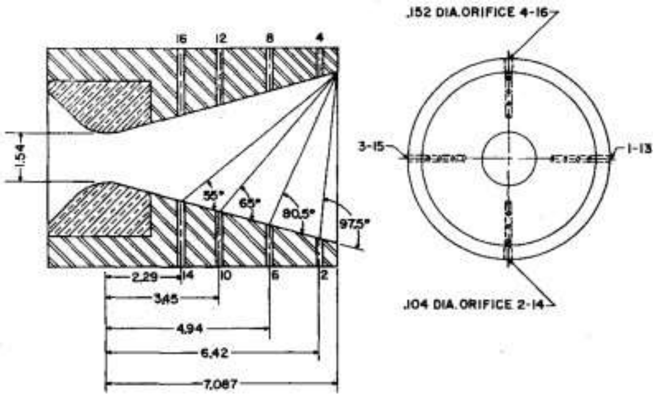
Table 1

CONDITION	RESULTS
Thrust	3500lb
Chamber Pressure	1200psi
Expansion Ratio	12:1
I_{SP}	200s

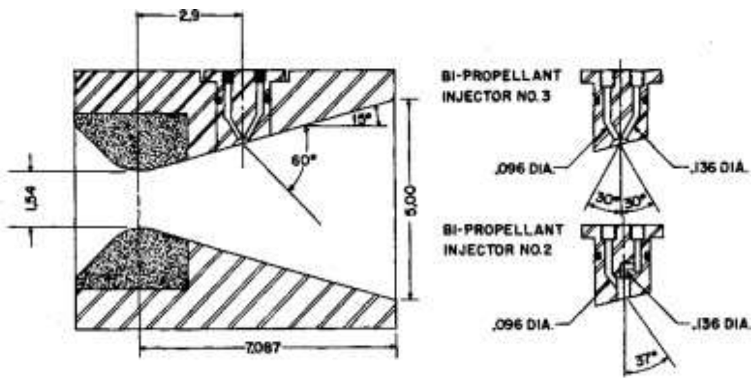
2.1 Procedure

The test nozzles(Fig3,4) were uncooled and used graphite throat inserts. These nozzles were adequate for tests of 3-4s duration. The 16-point nozzle(Fig3) was fabricated with four rows of 4 orifices 90 deg apart. Each row of orifices was drilled with a different diameter. This arrangement permitted the effect of the orifice area and axial location of the injection port to be studied. All orifices were round and were drilled perpendicular to the nozzle axis. During more tests, injection pressures and flow rates were varied through the use of a hydraulically controlled metering valve. For the bipropellant injection test, the basic nozzle body was modified to permit the insertion of bipropellant injectors(Fig4). Side force measurements were obtained through the use of a pivot mount, lever arm, and force transducers. The side force assembly was fastened in turn to a flexure mount to permit the measurement of axial thrust. All side force measurements reported are resolved to a point on the nozzle 6.42in from the throat.

Calibration of both side force and axial thrust was accomplished “in place” through the use of proving rings.



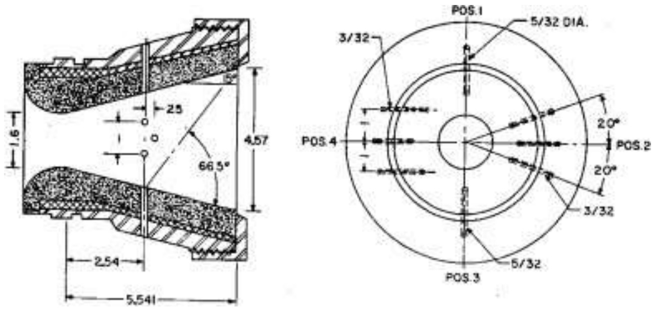
(Fig3) Sixteen-point nozzle



(Fig4) Bipropellant injection nozzle

3. SOLID MOTOR INJECTION TEST

This test was conducted primarily for purposes of data comparison. The effects of different motor performances and of the aluminized propellant were of particular interest. In addition, three different injection geometries were investigated. Fig(5) depicts the nozzle used in this test.



(Fig5) Solid motor test nozzle

The performance characteristics of this motor are as follows

Table 2

CONDITION	RESULTS
Thrust	3635-2835 lb
Chamber Pressure	1115-855psi
Expansion Ratio	8.15:1
Specific Impulse	237s
Burn time	35s

3.1 Procedure

Both freon-12 and nitrogen tetroxide were used as injectants. Nitrogen tetroxide was injected through a single orificeonly, and freon 12 was injected through both single and multiple orifice configurations.The fluids were injected in a cyclic fashion during the first 26 seconds of the 35-second motor burning time. Now, an attempt to vary the flow rate of each injectant by a “blow down” technique was only partially successful

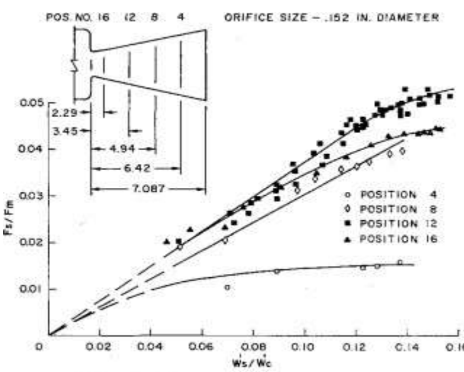
3.2 Results

- 7 Liquids including UDMH and IRFNA, were used as injectants in this experimental program.
- Fluids used were Freon-12, perchloroethylene, water, Bromine, and Nitrogen tetroxide.
- The nominal motor characteristics provided previously may be considered descriptive of the motor conditions under which the presented data were obtained.
- The detailed test data such as flow rate, injection pressure, thrust level, and ETC are provided in the tabulations Table(2).

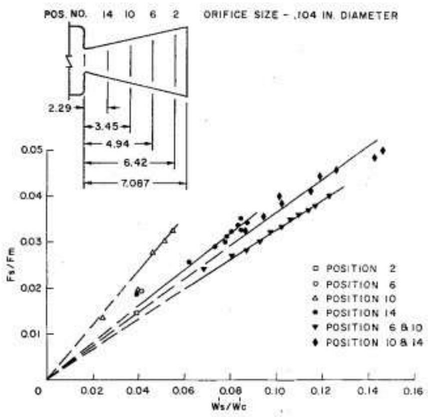
4. LPARM DATA

4.1 Freon 12 Injection

The family of curves shown in figure(Fig6) represents the results obtained by injecting freon 12 at 4 different axial locations through orifices 0.152in diameter. The effect of variation in axial locations is quite apparent. Fig(7) showsthe result of freon 12 injected through 0.104in diameter orifices at 4 different axial locations. Injection pressure for this case is considerably higher than for the 0.152in dia orifices.at similar weight flow ratios. The effect of axial location is consistent with the large dia orifices results. Comparing the results of positions 10 and 12,6, and 8, 2, and 4 (Identical axial locations), it may seem as if the smaller orifices provide better performance. This performance increase is greater than that to be expected from the contribution of a higher product of injectant mass flow rate and velocity. No improvement in performance is apparent in comparing the results from positions 14 and 12.



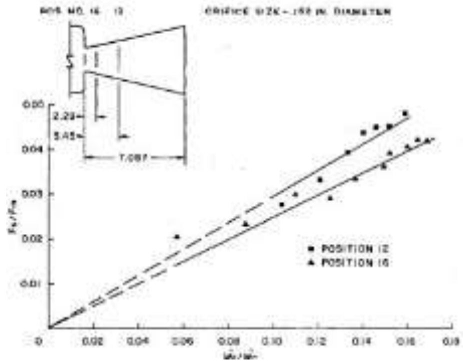
(Fig6)Freon-12 injection data for 0.152 dia



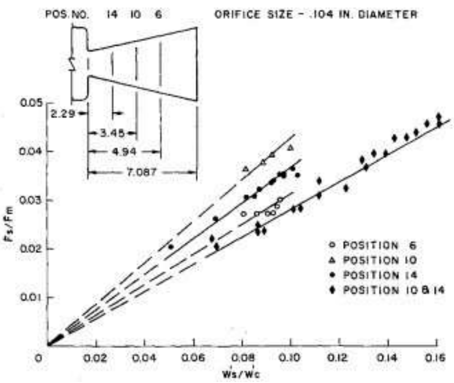
(Fig7) Freon-12 injection data for 0.104 dia

4.2 Perchloroethylene injection

Fig(8 and 9) shows the results obtained by injecting perchloroethylene through 0.152 and 0.104in dia orifices at various axial locations. The effect of axial location and injection pressure is consistent with the freon 12 data in all cases. The double orifice injection (Fig 9 positions 10 and 14) gave results lower than a single orifice of 1-half theeffective area and gave results approximately equivalent to a single orifice with an equivalent total area.



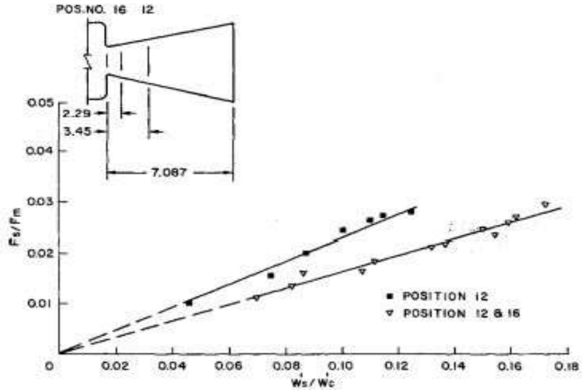
Fig(8)



Fig(9)

4.3 Water injection

Double orifice injection again shows a reduction in performance when compared to the single circular orifice of 1-half the effective area. Refer to Fig(10)

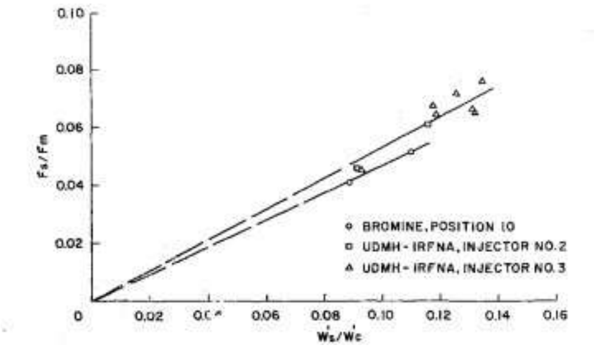


Fig(10)

4.4 Bipropellant injection

Fig(11) shows the results obtained from the simultaneous injections of UDMH and IRFNA. The objective of the test was to determine the effects of any exothermic reactions of the injectant within the expansion cone. To inject a design we use for these tests(Fig 4); both designs yielded approximately the same results. Bipropellant injection provided the highest performance ratio obtained in this test series. Secondary O/F ratio and injector design had no apparent effect on performance. The secondary O/F ratio varied between 0.875 and 3.8.

4.5 Bromine Injection:

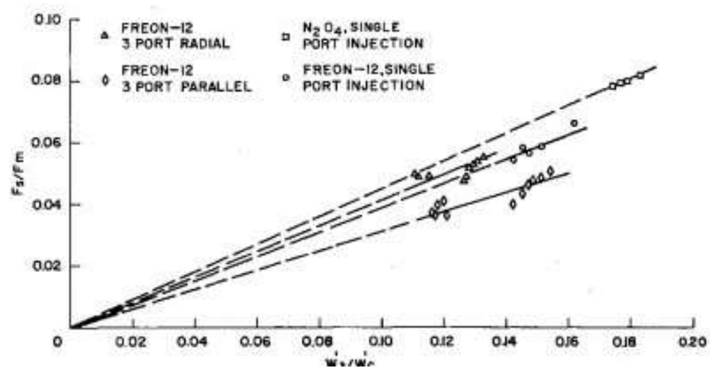


Fig(11)

Only 2 data points were obtained for bromine, these points are presented in the figure with bipropellant injection data. Refer to Fig(11)

5. SOLID MOTOR INJECTION DATA

Table represents the data obtained from the tests with a solid propellant motor both freon 12 and nitrogen tetroxide were used as injectants for these tests. Nitrogen tetroxide was injected through a single orifice only and freon 12 was injected through both single and multiple orifice configurations.



Fig(12)

NOTE: *The propellant-specific impulse was assumed to remain constant over the test duration*

The various factors affecting the injectant flow rate were studied and tabulated in Table 3

Table 3

FACTORS	EFFECTS
Side thrust	Variation of side thrust with secondary flow rate was found tobe linear essentially for near optimum axial locations. The slope of the line describing the data was termed as the performance ratio If injectant flow rates were varied via a variable area orifice a non-linear relation would be expected.
Axial Location	The LPARM data indicates that injectant performance increases for secondary flow rates of 5%-15% through a 0.152in diameter orifice. As the injection port is moved upstream to a point 3.5 in from the throat the secondary flowrate increases by 13% and the performance ratio of Freon-12tends to decrease. This is caused by extreme radial dispersion of the pressure field causing side-force or reflection of the shockwave off thewall opposite to the injection port.

Orifice Area/Injection Pressure	Orifice area tends to increase the injection pressure. Consequently, it was postulated that the rate of change of injectant momentum had influenced the degree of penetrationof the exhaust stream by the injectant fluid, thereby influencing injectant vaporizing and mixing. This increases the injection flow rate of the secondary and primary streams.
Injectant Characteristics	A 1- Dimensional model of the fluid interaction with the expansion cone of the rocket nozzle was analyzed and the results indicated that the injection should provide as large an obstruction as possible to mainstream flow and should react ordecompose with the release of heat or, in the case of an inert fluid vaporize or dissociate with a minimum amount of heat absorption. Some of the desirable injectant characteristics are Low specific heat (Liquid and vaporphases) Low boiling point Low heat of vaporization Low molecular heat of products ofcombustion High density.

Side-thrust performance thrust deflection angle is plotted for several injectants in Fig(12). The values represent performance in a nozzle having a half-angle α, of 16 °. α is defined as the half-angle of the exit cone determined bya straight line from the injector opening to the exit lip. If the nozzle has an a/ larger than 16°, the values from Fig(12) should be corrected by the following formula:

Isp (corrected) = Isp (cosα//cos16°)

The total amount of liquid required is estimated as follows:

1) The liquid needed during each vectoring interval is found by dividing the required side force by the specific impulse (from Fig12, corrected if necessary) to get the flow rate and then multiplying this by the time duration.
2) The amounts of liquid needed for all of the vectoring intervals are summed to obtain the total weight of usable liquid required.
3) The amount of additional liquid required for ullage, filling of piping, etc., can be calculated from internal geometries.

Storage

Liquid injectant usually is stored in stainless steel or titanium tanks. If hot gas provides pressure, a diaphragm or bladder is needed to keep it from heating and reacting with the injectant.The gas usually comes from a compressed-gas bottle or a propellant-burning gas generator. Pressure should be sufficient to give the liquid
momentum to produce the required shocks and mix in the nozzle. The pressure provided in existing systems usually is equal to or greater than the motor chamber pressure.

Injection location

Flight-weight LITVC hardware (tanks, gas source, piping, injectors, and brackets) in existing systems weighs 84 to 100% of liquid weight for booster rockets and 70 to 88% for upper stages. The optimum injection location is a compromise between too far upstream, where injection effects crossover and degrade performance, and too far downstream, where not enough wall area can be acted upon. This optimum axial position can be estimated using the table below.

Optimum axial position of injectors:

Table 4: Optimum X/L

Half-angle α,(degrees)	**Small thrust deflection(abt1°)**	**Large thrust deflection(abt6°)**
17.5	0.3	0.4
25.7	0.2	0.3

Note: X=distance (measured along nozzle axis) from throat to injection point; L= distance from throat to nozzle exit plane.
X/L = Axial position of the injector.

Procedure

The injectors usually discharge perpendicular to the nozzle center line. However, if the motor configuration requires the injectors to be closer to the exit than is optimum, the injectors should be aimed upstream to compensate. Most operational injectors control flow by central pintles, but other valve-gate arrangements should work well provided

that at both high and low flows they deliver full pressure to the orifices to make high-momentum jets. Injection through a large number of small orifices generally increases efficiency because the small jets cause the shocks, mixing, and reaction to occur close to the nozzle wall, where they produce side thrust most effectively. The optimum number of orifices is found by a tradeoff against system weight.1 Current upper-stage motors with low thrust deflection requirements, usually less than 4°, usually have four injectors giving simple pitch-yaw control. Each injector usually has three orifices, for a total of 12 orifices. First-stage motors require larger thrust deflections and therefore more injection orifices; the largest number in operational use is 24.

6. DESIGN CALCULATION-LITVC

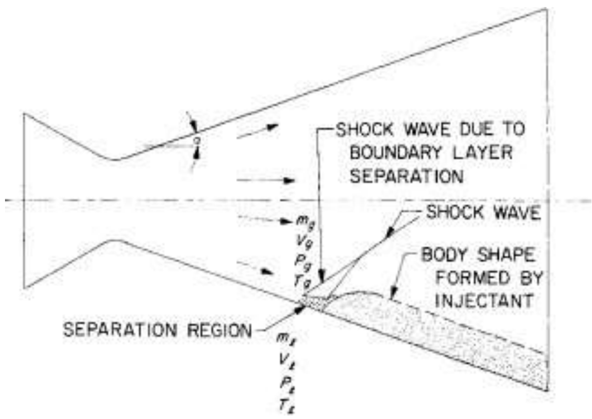
- **Motor Characteristics:** The motor is of medium size, a second stage, having thrust/= 28,000 Ibf, pressure Pc = 800 psi, burn time = 50 sec.
- **Nozzle Characteristics:** Throat diameter Dt = 5 in., expansion ratio = 20, nozzle length (throat to exit) L=22 in., nozzle half-angle a = 22°, and injector-to-exit-lip half-angle a, = 18.5°.
- **Flight thrust:** The flight thrust deflection requirements are Θ=2° for 1 sec and Θ=0.5° for 49 sec. The required side forces Fs =FtanΘ=978 and 244 Ibf for 2° and 0.5°, respectively. We adopt the conventional upper stage arrangement of four injectors 90° apart with three orifices each. The required jet deflections under the worst conditions will be midway between the pitch and yaw planes so that two adjacent injectors each 45° from the desired force direction must provide components of the required force. Thus, the side force due to each injector is F5/=F5/(2 sin45°) = 691 and 173 Ibf, and the local deflection angles are 1.41° and 0.35°, respectively, for motor thrust deflections of 2° and 0.5 °.
- **Injectant characteristics:** N_2O_4 is selected as the injectant; therefore, the Isp (uncorrected) is 305 and 325
  Ibf sec/lbm for Θ= 1.41° and 0.35°, respectively. Using the α correction equation, these become 301 and 321 Ibf sec/lbm. Flow rates for the two injectors are $M_i = 2F_{sj}/I_{sp}$ = 4.59 and 1.08 lbm/sec. The useful fluid required is found by multiplying the flow rates by the vectoring times of 1 and 49 sec, giving 4.59 and
  52.92 Ibm, respectively, or a total of 57.5 Ibm. The allowance for ullage and system filling estimated at 10% is 5.8 Ibm. This brings the total liquid required to 63.3 Ibm. The maximum flow rate per injector is needed for sizing injectors. Based on the maximum 2° deflection, the Isp and corrected for α is 276 Ibf sec/lbm. The maximum flow rate is 978 lbf/276 Ibf sec/lbm = 3.54 Ibm/sec. The optimum injector location X is estimated using Table X/L= 0.275 by interpolation for α = 22° and Θmax=2°. For L =22in, the axial distance from the throat to the injector is X=6.1in.
- **Weight:** The preliminary estimate of the weight of this LITVC system is as follows: liquid (N2O4)
  required, 63.3 Ibm; hardware (based on hardware-to-liquid weight ratios for upper-stage systems), 44.3 to
  55.7 Ibm; estimated total system weight, 108 to 119 Ibm. 57.5 Ibm of this total is the usable liquid that may be considered as propellant if full consumption of injectant is programmed. (As liquid becomes surplus during flight, it is released from all injectors.) Isp (axial) = (321 Ibf sec/lbm) x tan 18.5 ° = 107 Ibf sec/lbm.
- Further developments in this preliminary design procedure can be worked upon in the future

7. ANALYTICAL MODEL-LITVC

The practical aspects of changing the thrust direction of a rocket motor by liquid injection into the supersonic streamof the rocket exhaust are well established by numerous experimental data; however, the complex interaction between the secondary injectant and the primary flow is not well understood and is not readily amenable to theoretical analysis. Many approximate analytical solutions for predicting the induced side force have been generated, and a complete review is available. Most of the published work ignores the factors affecting the fuel injection like atomization, evaporation, jet penetration, and mixing because they are difficult to analyze. Moreover, a liquid with ahigh vapor pressure (relative to exhaust stream pressure), such as Freon 12, will flash and vaporize. Recognizing these problems, an improved analytical model has been developed. A general schematic of secondary fluid injection into the rocket nozzle exhaust is shown in Fig(13). The injectant liquid creates a disturbance, and the pressure field created on the wall causes the side force. The resultant total side force can be expressed as

$$F_t = F_1 + F_2 + F_3$$

where FI, F2, and F3 are the side-force contributions owing to the momentum of the liquid, the separated region ahead of the injector, and the pressure disturbance downstream of the injector, respectively. The injectant liquid considered in this study, Freon 113, is one that has a low vapor pressure relative to the pressure it encounters during the injection process, thus eliminating the phenomenon of flash evaporation.



Fig(13)Schematic of secondary fluid injection

Some of the other ambient factors are

8. ATOMIZATION

It refers to the process of breaking the mass of liquid injected into small droplets when the liquid jet encounters the high-velocity gas stream. A successful analysis should result in an expression describing the size distribution of drops as a function of liquid physical properties, the geometry of the system, and operating conditions.

9. EVAPORATION

For liquid injection thrust vector control, liquid vaporization is of significant importance in maintaining excess pressure downstream of the injector. Once the initial mean droplet diameter is known the next quantity to be determined is the rate of droplet vaporization. The droplet mass and volume should be continuously diminishing as it travels downstream to the nozzle owing to evaporation

10. DROPLET DRAG COEFFICIENT

In order to determine the body shape or the trajectory of a droplet, the drag coefficient of the droplet at any time t must be known. :

$$C_{D_{x,y}} = \frac{C_{D0_{x,y}}}{K_{M}^{2}} f(M) \times$$

$$\begin{cases} f(M) = 1 & \text{for} \quad 0 < M < 0.5 \\ f(M) = 0.689(M + 0.952) & \text{for} \quad 0.5 < M < 2 \end{cases}$$

where M is the relative Mach number. The values of $\mathbf{C_{D0(x,y)}}$ can be determined by using Stokes' law

$$C_{D0_{x,y}} = 24/Re \qquad \text{for} \qquad 0 < Re < 0.1$$

Why is this method not preferred for terrestrial vehicles?

- Firstly, the injectant used produces a large amount of side force and heat which does not make it feasible for regular passenger vehicles to adopt this method.
- Traffic issues and other ergonomic factors do not go in conjunction with this method.
- Using this method can create various kinds of pollution and safety issues

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