*J*ournal of *A*pplied *F*luid *M*echanics, Vol. 9, No. 1, pp. 19-26, 2016.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.18869/acadpub.jafm.68.224.19388

Investigation and Comparison Effects of Fluid Injection Type in Thrust Vector Control

M. R. Heidari[1†] and A. R. Pouramir[2]

[1]*Islamic Azad University, Parand Branch, Iran*
[2]*Industrial Organization, Tehran, Iran*

†*Corresponding Author Email: heidarimr@piau.ac.ir*

(Received October 20, 2012; accepted November 25, 2014)

ABSTRACT

In this research, the effects of some liquid side injection from nozzle wall into exhaust gas of combustion chamber are studied. The side injection against main flow is as elliptical solid thing that change the symmetric of flow field on nozzle wall and causes some different pressure distribution on wall, and finally causes thrust vector deviation. Flows interaction causes some physical phenomena as bow shock wave in front of injection region. This paper explain the effects of this wave and variation velocity & pressure distribution at different cross sections of flow field and comparison results of air and other liquid fluid in thrust vector control system. The results are compared with experimental data and have well agreement with them. The results show that Freon is one of best injection liquid for this type of thrust vector control. Performance of Injection is optimum in relative position 35 to 40% nozzle divergence length.

Keywords: Thrust vector control (TVC); Side jet; Liquid injection; Bow shock wave.

NOMENCLATURE

Cp	specific heat capacity	$\dot{m}$	mass flow rate
F_t	total axial force	M_{inj}	injection mass flow rate
F_s	side force	M_{tot}	total nozzle mass flow rate
L	nozzle divergence length	X_{inj}	injection position

1. INTRODUCTION

From 1960 that Rich and Nuys Introduced a liquid injection thrust vector control system and compared with other thrust vector control methods, many studies has been accomplished. In 1962 shandor and walker developed a linear thrust vector control model. In 1963 Walker and *et al*. accomplished many experiments of gas injection into divergence nozzle section and measured its side force. Green and McCullough in 1963 with an experimental method, measured side force for liquid injection into nozzle at different positions and injection flow rate. Thielman analyzed injection temperature and injection fluid type in liquid injection thrust vector control. In Lawrence and Adelman investigations a method for thrust vector control for roll, pitch and yaw has been exhibited. In these investigations, they used from water, ammoniac, liquid Nitrogen and similar these. Fluid has been injected from 4 injectors (in minimum case) as motor performance was completed. Bankston shows in his investigations that was not evaporated all injection fluid and will be in exit flow. He also said that there is an optimum point for injection. Hausman shows a method for gas injection thrust vector control in 1966 that used some auxiliary nozzles around main nozzle. The control of thrust direction is done by a dual Reinforcement cycle. From helium and combustion, gases have been used. Pennington used some small hybrid motor for hot gas generation near the main nozzle. These small motor have solid propellant as fuel in motor case but its oxidant was liquid. Decrease total mass of motor is one of advantages of this method. Freon and N_2O_4 are general fluids for thrust vector control. Freon is an inactive gas but N_2O_4 is reacted. Burrows in 1968 has been studied atomization sequences, combination and activation of N_2O_4 and N_2H_4. McCullough in 1972 had proposed a liquid injection plane that made shock wave and new boundary layer for flow field, and causes a new virtual throat that has direction with nozzle axis. Thus exhaust gases has angle relative to nozzle axis. For virtual throat generation, two rows injectors are installed in nozzle wall, one row before throat and second row after throat. When liquid injected from before throat injectors and its adverse row at after throat, virtual throat is generated. Williams has been explained in his research paper in 1973 benefit and defects combustion chamber hot gas injection into divergence nozzle section. In NASA report, properties and subsystems have been explain and designed. Collier at 2001 has been investigated the benefits of thrust vector control methods for use in hybrid motor. Also, he has been presented a success thrust vector control properties and a design of nozzle. Jones *et al*. designed a hybrid injection thrust vector control system at 2002. The main motor could be liquid or solid propellant motor and this system can use for these two type motor. The results if this research shows that exhaust nozzle gas as injection gas has best side force value. Reaction liquid and inert gas are after it. Tsohas *et al* at 2007 experimented subsystems of a small hybrid motor (such propulsion system, fuel feed system, earth equipment, liquid injection thrust vector control, etc.) in LITVC system used N_2O_4 and calculated system parameters as force and total impulse. Glen in his paper presented a thrust vector control system for a hybrid rocket. He used N_2O_4 as oxidant. In this research, some mathematical equations have been presented. Injectors' structure has been designed base on a simple and fixed orifice. The used valve is a solenoid valve that can be replaced with a pneumatic valve.

In this research, Freon 12, N_2O_4, water and air have been used. The main fluid of nozzle is same as solid rocket motors combustion gases. These gases don't react with injection fluids. Thus the results of N_2O_4 injection simulation are without reaction and have some error compare with exact values. Fluent numerical software has been used. Injection position, flow rate and angle investigated and presented some benefit curve and figure. that can be useful for design. The results of simulation have been validated with some experimental data. Figure 1 shows an example of he liquid thrust vector control system and its ohenomera can be observer.

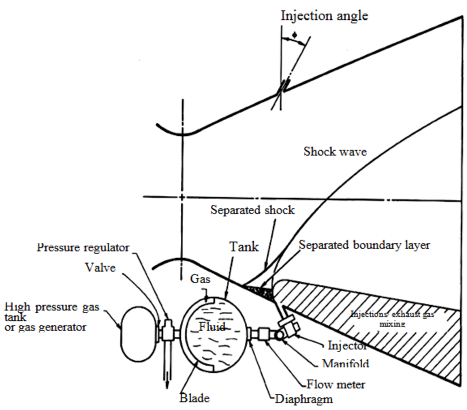

Fig. 1. Liquid thrust vector control system and its phenomena.

2. GEOMETRY AND FLUID CONDITION

Solution of flow field with injection in nozzle, is impossible with every mesh (structure or unstructured or combination of this two type). But, because in this simulation the accuracy calculation of velocity and pressure on the wall is important, using a structure grid could increase calculation accuracy on wall. There for, the grid which is used in this simulation is a partly structured grid that shown in Figure 2. This grid is more compressed in near the wall form inner region of nozzle. Really, the boundary layer grid generated in near the walls.

In this investigation, firstly grid study is down and lowest number of node for simulation determined. Increasing the number of nodes does not change results of simulation and these results are independent from grid. For grid optimization in any case of boundary condition and injection, the cells which are having more unbalanced mass are fined to give a better simulation. In this simulation, a turbulent flow with liquid injection is modeled. For this target the equations of momentum, energy, turbulence and the equations of discrete phase are used. Form k-ε model used for simulation of turbulence.

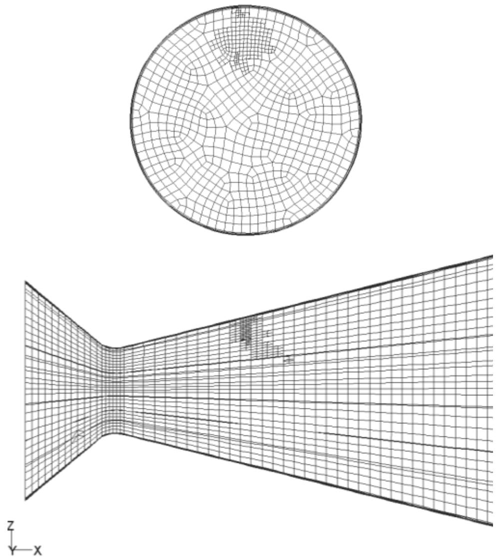

Fig. 2. Grid and adapted grid.

Figure 3 has shown the geometry parameters. Angle of injection is angle between axes of injection with vertical line on to axis of nozzle. X_{inj} is distance between injection points from nozzle throat that dimensionless with length of nozzle divergence section (L). In this simulation, chemical reaction is off.

Boundary condition which is defined is as below; for inlet boundary, mass flow rate is 7.93 kg/s and total temperature is 2400K. The outlet condition is define as sea level (T=300K & P=1atm). Boundary condition of wall is zero heat flux. Gas properties of nozzle flow are same as solid rocket motor's gas that main its properties are shown in Table 1. Also, the properties of three liquid injections that focus on those in this investigation are shown in Table 2.

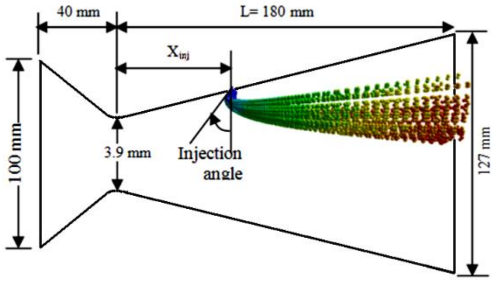

Fig. 3. Nozzle and injector geometricalparameters.

Table 1 Nozzle main flow properties

Parameter	Value	Unit
Cp	1800	J/kg-K
MW	24	kg/kmole

Table 2 Injection liquid properties

Fluid	MW (kg/Kmole)	Cp (J/kg-K)	Density (kg/m^3)
Freon 12 (CCl_2F_2)	120.92	978.1	1518.9
N_2O_4	92.011	Cp(T)	1628
Water (H_2O)	18.015	2014	1027

3. ANALYSIS OF INJECTION LOCATION FOR TWO TYPES OF LIQUID FLUID

To investigate the suitable location (maximum Ft/Fs) for injecting the liquid into the nozzle flow field in thrust vector control, eight different locations in the diverging part of the nozzle were selected. This was done to see the effect of injection location on the nozzle flow while other parameters kept fixed.

After simulation of this 8 point, 2 other point choices for better determine maximum point. There for the results of this 10 point are shown in Figure 4. For more study of injection location, this simulation for three injection mass flow 0.4, 0.566 and 0.793 kg/s that are equal to 5, 7 and 10 percent of total mass flow rate of motor repeated and results shown in figure curves.

The results have shown that suitable and optimum point for side injection fluid (Freon) is about 35 to 40% nozzle divergence length. Note that Fs is side force and Ft is total axial force and ratio Ft/Fs is equal to tangent of thrust deviation angle. Except this main result, it seems that when injection is in 15% from divergence section, the curves are very close together. Note that although the results are very close together nonetheless in all positions increasing mass flow (from 0.4 to 7.93) make increase thrust vector deviation. This different increase when the position of injection went to maximum point of curves.

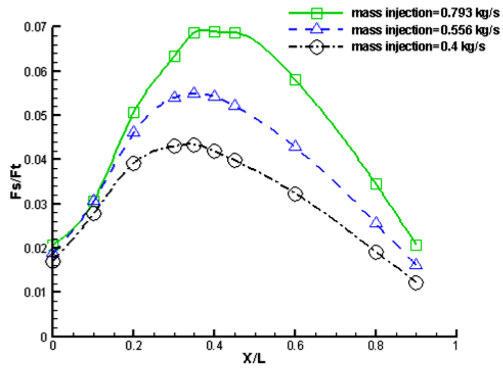

Fig. 4. Injection position effect for Freon (injection angle=30 degree).

Domain of this differential (difference value of side force and axial force) at maximum point of three curves (X/L=35%) is equal to 0.028 that this is equal to 1.1 degree thrust deviation angle (70% increases). As can see injection from those position near the exit section of nozzle, the difference between curves decreased but are more than 15% that was in primary positions of nozzle. Range of Variations of side force to axial force ratio for three injection flow rate 0.4, 0.556 and 0.793 kg/s is respect 0.031, 0.036 and 0.048, which is equal to thrust deviation angle 1.8, 2.1 and 2.8 degree.

Relative position of maximum point went to exit section of nozzle when injection mass flow rate increased (approximately from 35% to 40%). The effect of injection in nozzle throat is equal to injection in position 0.8. The results of simulation for injection position investigation for injection fluid Nitrogen tetra oxide are shown in Figure 5. Trend of curves is similar to Freon. Approximation results of three curves at near throat location and increasing differential between them at points beyond throat and accruing maximum thrust deviation angle at relative position between 35 to 40% are represent in this Figure . The different of curves of Figure 4 and 5 is in thrust vector deviation that Freon is more than N2O4.

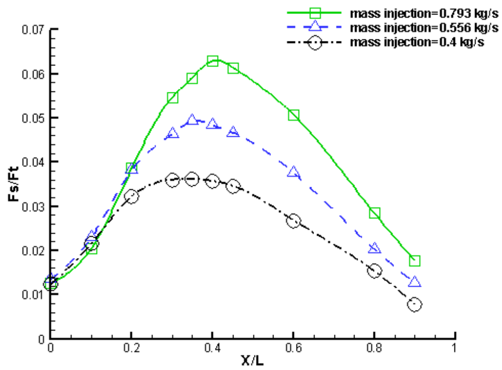

Fig. 5. Injection position effect for N_2O_4 (injection angle=30 degree).

4. INVESTIGATION OF INJECTION FLOW RATE RATIO FOR TWO TYPES OF LIQUID

Mass flow injection is one of most important thrust vector control system parameters. Amount of injection at any point of nozzle divergence section could increase until do not affect nozzle total operation. In this study, three position of nozzle 0.036, 0.072 and 0.126 m that respect to 20, 40 and 70% nozzle divergence length simulation was done and the results was obtained. In Figure 6, the results of Freon injection are shown. The most considerable result of this analysis in three curves is that there is a maximum point that in it more deviation in thrust angle accrued. This maximum point for injection location 0.036m is relative mass flow 7.5% and value of side force to axial force ratio is 0.037 (equal to 2.12 degree deviation in thrust vector). For injection location 0.072m, maximum point happened in flow rate ratio 11% and value off side force to axial force is 0.053 (it is equal to 3.03 degree deviation in vector of thrust). At last, in injection location 0.126m, optimum injection flow rate ratio is 22% that this value is equal to side force to axial force 0.0776 (equipollent 4.48 degree thrust deviation angle).

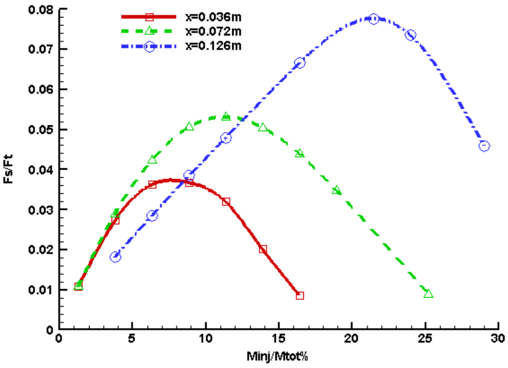

Fig. 6. Injection flow rate effect for Freon (injection angle=30 degree).

As the injection point gets off the throat, the optimized injection ratio increases. The reason for it is by getting off the throat, the area of the nozzle which is in contact with high pressure injecting liquid will be reduced and so to compensate this effect, more pressure should be applied on this surface. This could be done with increasing injection rate and create a strong shock.

The other point can be seen on this Figure is except injection in far from throat, results for injection rate under 2% in different location is almost same. This can be observed by notice on primary parts of two curves x=0.036 and x=0.072. At last must be note that with high increasing in injection rate at each these three points, efficiency of system decreased and tend to fail. In Table 3, these parameters and efficiency are shown. Performance efficiency is thrust deviation angle to injection rate ratio that could be show the optimization value of injection rate and position. Performance of positions1 and 2 is near together and point 3 has a low performance.

The other note that can be seen in curve of Figure 6 is that the gradient of curve x= 0.072m is more than two other curves. It mean that for less injection rate, more side force obtained and this demonstrated that the injection point is optimum. This motif is shown in Figure 4 too and is agreeable with that.

Table 3 Maximum point properties in injection rate investigation curves

*	Injection position (m)	Flow rate ratio	Deviation	Performance %
1	0.036	7.5	0.037	0.493
2	0.072	11	0.053	0.481
3	0.126	22	0.0776	0.35

In Figure 7, thrust vector variation for different injection flow rate in three position of nozzle divergence section for injection fluid N_2O_4 is demonstrated. Maximum point of curves in two Figures 6 and 7 are different and occurred in different relative injection flow rate. The major deference is that optimum injection position for Freon relative to N_2O_4 occurred far from throat and in near the throat has less performance.

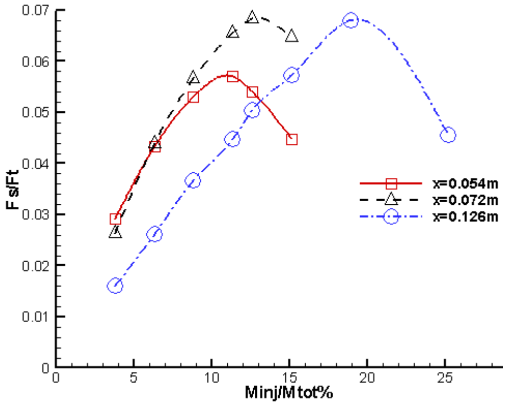

Fig. 7. Thrust vector variation for different injection flow rate for N_2O_4 (Injection angle =30 degree).

5. INVESTIGATION OF INJECTION ANGLE FOR TWO TYPES OF INJECTION LIQUID

Another important parameter in side injection thrust vector control is injection angle. This parameter is more important when combustion occurred. For investigation the effect of angle injection, position x=0.054m that is equal to 30% nozzle divergence length has been selected. The choice of this point is based on past results and is accordant with references (this point is optimum position for injection).

As can see in Figure 8, this investigation is for three injection flow rate (0.3, 0.5 and 0.7kg/s that respect equal to 3.8, 6.3 and 8.8% total nozzle flow rate) to investigate and compare the effect of variation of injection angle.

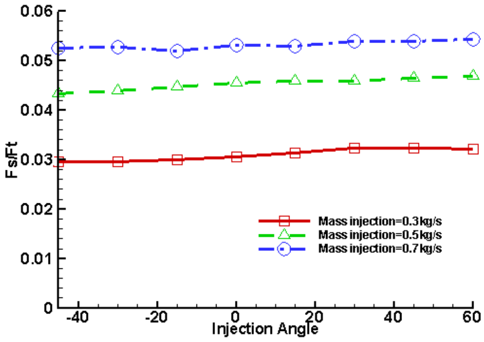

Fig. 8. Injection angle effect at vary injection flow rate on thrust vector deviation for Freon (X_{inj} = 30% Nozzle divergence length).

The Main result of this simulation is that in Freon injection (without chemical reaction) injection angle has not considerable effect on control system performance and very little changes happened.

Another note that can see from these curves is that variation of thrust deviation angle is not linear with injection flow rate. With a same increase in injection rate from 0.3 to 0.5 and then to 0.7 kg/s, average value of side force to axial force ratio changes from 0.031 to 0.044 and then to 0.053. In fact at first with 0.2kg/s increase in injection rate, Fs/Fa has a jump equal to 0.013 (equal to 0.75 degree deviation in thrust vector) but with a further increase injection rate (0.2kg/s), the jump is equal to 0.009 (0.5 degree deviation in thrust vector).

Relative increasing could be seen in thrust deviation angle for each flow rate from injection angle -45 to 60 degree (although this is very negligible). With a more accurate observation on curve 0.3 kg/s, could be seen that until 30 degree angle, Fs/Fa increased and then this curve has an inconsiderable decline. For better consideration injection angle results, curve 0.3kg/s is highlighted in Figure 9. These results don't show a Specified optimum injection angle.

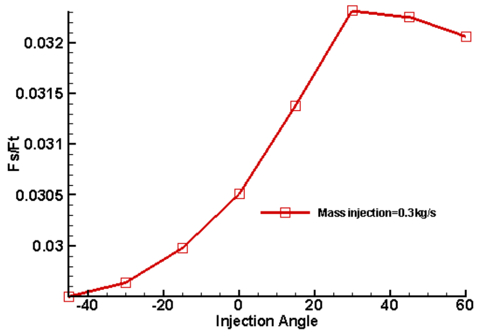

Fig. 9. Injection angle effect on thrust vector deviation for Freon (X_{inj} = 30% Nozzle divergence length).

Figure 10 has a different aspect from injection angle effect. Simulation is done for injection rate 0.5 kg/s in three position on nozzle wall (X_{inj}=0.018 m, X_{inj}=0.054 m and X_{inj}=0.126 m that are equal to 0.1, 0.3 and 0.7 nozzle divergence angle). The curves of figure 10 show that optimum injection angle is depending on injection position. At positions near the nozzle throat, increasing in angle injection resulted decreasing in thrust deviation angle and then decreasing thrust vector control system performance. The curve of injection position X=0.018 m (that is equal to 10% of nozzle divergence length) shows this fact. At this position, from injection angle -45 to 60, the value of relative thrust deviation vector varies from 0.0267 to 0.0202 (decreasing 0.4 degree in deviation thrust vector) that is 0.25% of maximum deviation of this curve. This trend in injection point X=0.054 m (30% nozzle divergence length) is different. At this location, that in position investigation discuss as an optimum point, injection angle variation has not considerable effect.

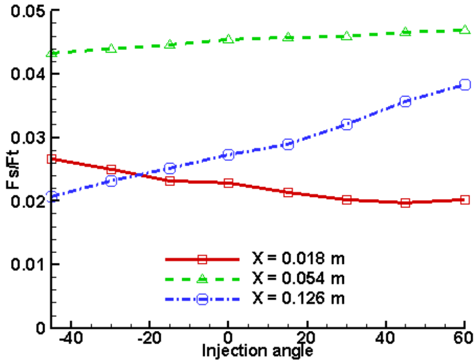

Fig. 10. Injection angle effect in different injection position for Freon (m_{inj}=0.5 kg/s).

At region near exit section of nozzle, system trend has basically changes relative to injection angle. Trend of curve X=0.126 m (70% nozzle divergence length) in opposite of X= 0.018 m (10% nozzle divergence length). This curve shows that increasing injection angle increased side force to axial force ratio. This accretion from minor angle to major angle is continued and side force to axial force is varied from 0.0206 to 0.0383 that means 46% maximum deviation value (equivalent 1.015 degree accretion thrust vector deviation) that is a considerable value. Thus optimum injection angle depend on position injection must be define. Investigation of injection angle effect for injection liquid N_2O_4, same as previous Figures, are shown in Figures 11 and 12. With comparison Figures 8 and 11 it can be finding that trends are same. All curves have addition trend (although very little). Except difference in value, difference trend in curves of these Figures is not observable.

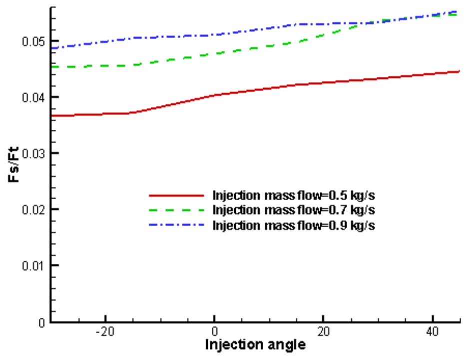

Fig. 11. Injection angle effect for three injection rate atX_{inj}=0.054 m for N_2O_4.

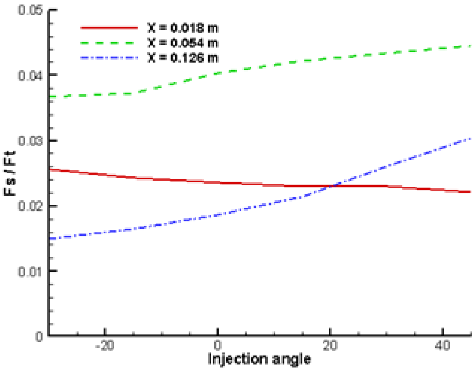

Fig. 12. Injection angle effect for three injection position, for N_2O_4 fluid and m_{inj}=0.5 kg/s.

With comparison Figures 10 and 12, differences and similarity of Freon and Nitrogen tetra oxide can be seen. The trends of two Figures are very similar. At region near nozzle throat increasing injection angle cause decreasing thrust deviation angle and at region near exit nozzle cause increasing and at middle region has not considerable effect. Differences of value of two complex curves, as hoped, could be seen.

6. MAIN FLOW RATE EFFECT FOR TWO LIQUID INJECTION FLUIDS

Previous investigation was for a nozzle that its flow rate was 7.93 kg/s. In this section, total flow rate variations effect investigated. Three constant injection flow rate (0.3, 0.5 and 0.9 kg/s) selected and main flow rate varied and flow field simulated. In Table 4, the values of total flow rate and performance parameters for every three injection flow rate have been shown. In this simulation the injection angle was 30 degree and injection point was x=0.054m (30% nozzle divergence length). In this analysis, total flow rate varies from values less than 7.93 kg/s to more times that. This shows curves trend before and after of this value. The results are shown in Figure 13. These curves shows sensible change in thrust deviation angle compare with curve of Figure 6 (notwithstanding in every two simulations the injection rate to total flow rate ratio is constant). Thus, total flow rate effect of system performance and in design must be considered.

Two trends region in curves (for 0.3, 0.5 and 0.9 kg/s) of Figure 13 are observable. These regions are before and after maximum point (approximately before flow rate ratio 11%). In first region that thrust deviation angle increased, the differences of three curves are low. The difference is about 8-12%. But at other region (after flow rate ratio 11%), differences are raised and each curve have a unique maximum point. This trend is shown and discussed in figure 6. At the end of this region, much injection rate cause disorder motor performance and failure.

Maximum value for curves 0.3, 0.5 and 0.9 kg/s are occurred at 20, 16.7 and 9% and it is respect 0.067, 0.06 and 0.054 that the corresponding value of total flow rate is 1.5, 3 and 10 kg/s. Accordingly decreasing of side to axial force ratio is rational when injection flow rate increased (from 0.3 to 0.9) because the injection to total flow rate is determinant and cannot predict result with injection rate only. Chart of Figure 14 is obtained for N_2O_4 and shows the effect of nozzle total flow rate for constant injection rate. The trends of curve are same as for Freon. The value of relative injection flow rate at maximum point is more than Freon for each case.

Table 4 Effect of total main flow rate on LITVC.

M_{Inj} = 0.9 kg/s			M_{Inj} = 0.3 kg/s		
M_{tot}	M_{inj}/M_{tot}	F_s/F_t	M_{tot}	M_{inj}/M_{tot}	F_s/F_t
5	0.18	0.045	1	0.30	0.064
6	0.15	0.052	1.5	0.20	0.067
7	0.129	0.053	2	0.15	0.063
7.93	0.113	0.053	3	0.100	0.052
10	0.09	0.054	4	0.075	0.046
15	0.06	0.048	5	0.06	0.041
20	0.045	0.043	6	0.05	0.037
30	0.03	0.035	7.93	0.038	0.032
			10	0.03	0.028
			15	0.02	0.022
			20	0.015	0.018

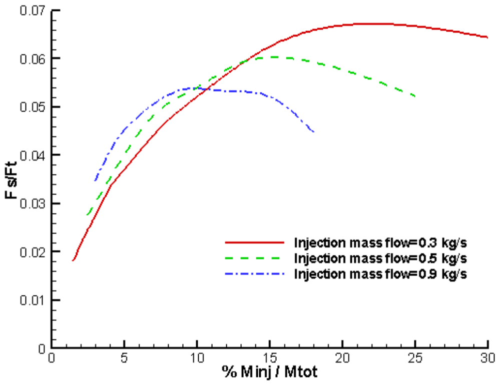

Fig. 13. effect of total flow rate of main flow on thrust vector deviation for Freon.

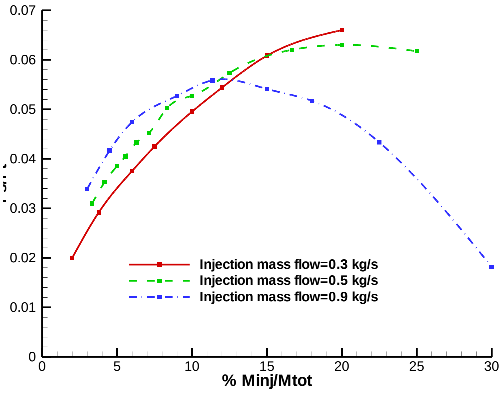

Fig. 14. Effect of total flow rate of main flow on thrust vector deviation forN_2O_4.

7. SUMMARIZED AND COMPARISON EFFECTS OF FOUR DIFFERENT INJECTION FLUID

Table 5 has the data of four different injection fluids (air, water, Freon and N_2O_4). This Table shows value of thrust deviation angle for some different injections to total flow rate. For simulation of air, a tube was attached to nozzle wall and air coming to nozzle from this channel. The data of this Table is shown as curve in Figure 15. Value of flow rate ratio limit is different because of injection rate could be raised until don't affect 100% on motor performance. As shown in Figure 15 increasing in injection rate causes thrust deviation angle increased. This trend continued until rate ratio 0.1. More injection rate cause nozzle performance and thrust deviation angle decreased. Maximum point of these fluids is in rate ratio 0.1 to 0.12. Freon because of low latent evaporate heat and high molecular weight and water because of high latent evaporate heat and low molecular weight, respect have more and less effect on liquid injection thrust vector control performance. Note that in this simulation chemical reaction is not simulated.

Table 5 Data of effect of different fluid on thrust vector deviation

Freon		Air		N_2O_4	
Minj/ Mtot	Fs/Ft	Minj/ Mtot	Fs/Ft	Minj/ Mtot	Fs/Ft
0.038	0.031	0.013	0.012	0.038	0.028
0.063	0.045	0.038	0.029	0.063	0.042
0.088	0.053	0.050	0.036	0.088	0.050
0.113	0.054	0.088	0.045	0.113	0.052
0.139	0.051	0.126	0.046	0.126	0.051
0.164	0.016	0.151	0.042	0.164	0.035
		0.177	0.038	0.189	0.016
		0.214	0.029		
		0.252	0.022		

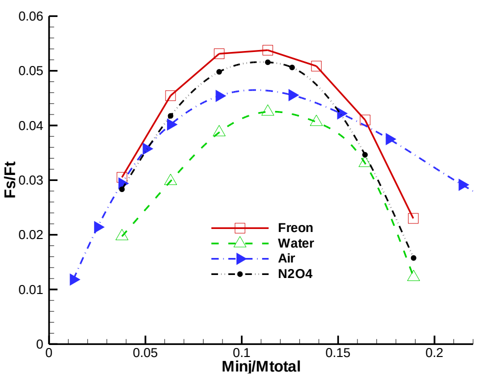

Fig. 15. Comparison effect of different fluid on thrust vector deviation.

Much number contour is shown in Figure 16 for air and Freon. This Figure shows for air and Freon, flow field is very different. Air simulation is as single phase and air enter to flow field from a tube that attached to nozzle's wall. At this simulation because of injection fluid and main fluid is similar, injection model is off. Elliptical zone at every two Figures is observable. The effect of Freon is more than air.

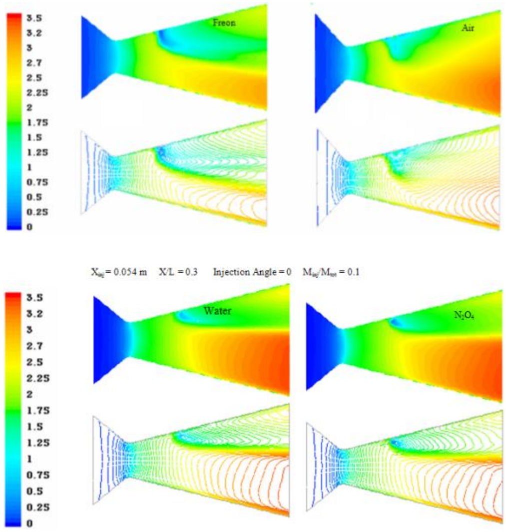

Fig. 16. Much contour for Freon, air, water and N_2O_4.

For validation, experimental data has been used. Experimental condition of this reference was not completely available but more important condition is in Table 6. Comparison of simulation and experimental data has been shown in Figure 17. Nevertheless, some simplification, the results have good agreement with together (10% error).

Table 6 Experimental boundary condition for TVC

Parameter	Unit	Value
Main flow rate	kg/s	7.93
Input main flow total temperature	K	2400
Input main flow total pressure	atm	85
Injection temperature	K	232
Injection angle	Degree	30

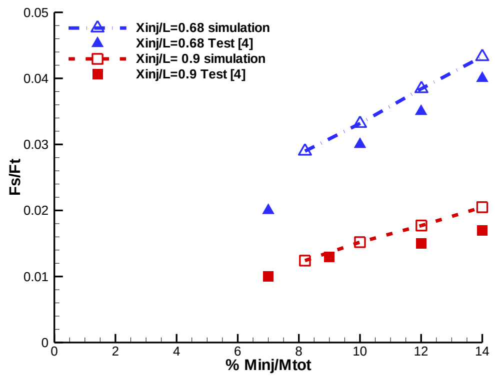

Fig. 17. Simulation validation for Freon injection.

8. CONCLUSIONS

Side to axial force ratio curves and charts for different injection rate, position and injection angle are good tools for liquid thrust vector control system design. Values of error for these simulations are very low and acceptable and this means that this software is a suitable tool for simulation. The results show that different injection fluids have a similar quality trend although has different value. Freon is a better fluid to injection from than other liquid injection such as N_2O_4 and water and also air. Injection parameters have optimum value and for design a thrust vector control system with liquid injection; these optimum parameter could be used.

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