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Numerical Study of the Flow & Thrust Performancefor Angular Twin Inlet Pintle Nozzle

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ABSTRACT

A pintle nozzle valve is used to vary the throat area of a convergent divergent nozzle to vary thrust at the output in a solid rocket motor (SRM). The pintle is provided linear motion with an actuator, which moves it forward and backward according to the condition. A two-dimensional numerical model is developed to simulate the flow, inside the pintle nozzle valve for the different position of the pintle with respect to the throat of the convergent divergent nozzle. The k-ω SST turbulence model was selected to perform the simulation for unsteady flow since this model gives the least deviation (~2%) in results compared to the other turbulence models. The far field was not taken into account as the far field doesn't show much effect on the results. The analysis parameters are outlet velocity, chamber pressure distribution, temperature distribution, streamline and the velocity vector. To get uniform velocity at the exit is an important aspect of the study. The numerical model is compared with the analytical solution to validate the numerical results. Many flow related problems like flow reversals, flow recirculation and flow separation were rectified with the modification of the flow inlet and, the pintle shape and size. The shape and size of pintle play a crucial role in the thrust variation as the throat area mainly depends on the pintle shape and size.

KEYWORDS: Flow recirculation; Nozzle; Pintle; Streamlines; Thrust; Velocity.

Nomenclature

A_t	throat area (m^2)	T	net thrust (KN)
C^*	discharge coefficient (m/s)	g	acceleration due to gravity (m/s^2)
C_f	thrust coefficient	η_{nozzle}	nozzleefficiency
$\dot{m}$	mass flow rate in the throat (Kg/s)	t	throat
I_{sp}	specific impulse (sec)	sp	specific
P_c	chamber pressure (Bar)	c	chamber

1.INTRODUCTION

Solid rocket motors (SRM) are used in missile systems as well as boosters in space applications i.e. satellite launches since the ease and reliability of the solid rocket motors is its main characteristic over other propulsion systems. In a rocket engine thrust is produced by accelerating the combustion products by using a supersonic nozzle, basically convergent-divergent nozzle. The main constraint with solid rocket motor is the thrust variation as it's very hard to control the burning of the solid propellant inside the combustion chamber once the burning process is initiated. To overcome this problem the pintle nozzle valve is developed to vary the thrust in a solid rocket motor since the thrust produced in a solid rocket motor is directly related to the throat area in the convergent-divergent nozzle.

Many studies have been carried out in past decades on the pintle technology. It goes as long back as in 1950 NASA used the pintle in their Apollo mission to space though in this the pintle was used to control the fuel flow in an engine. Since then the research has been continuously going on the pintle technology with application in the field of the missile system as well as space missions. Pintle technology used in the emergency escape of the military aircraft provided fully controlled propulsion to help in the emergency scenario, see Rock et al. (1997). Airstream in a nozzle flow field under the restriction of pintle face and nozzle inside wall and real area with the position of the throat is changed by the pintle. So different shapes and sizes of the pintle will cause different flow fields in a nozzle, see Li et al. (2007). Hua et al. (2008) simulated the flow field of the varying thrust motor nozzle with pintle and gave optimized throat pintle contours. Wei et al (2009) to carry out experimental validation of variable thrust principle designed an experimental setup of non-coaxial pintle solid rocket motor to analyze the performance of variable thrust pintle. Tang et al. (2013) performed a study on non-coaxial pintle control thrust nozzle and gave a method for the calculation of the nozzle equivalent throat area.In a numerical simulation of pintle nozzle flow field, the *k-ω* turbulent model shows higher precision compared with other models,*Ruoyu Deng et al. (2015).* The far field did not affect the thrust, temperature, and velocity distribution, in a numerical simulation, Heo *et al. (2017).*

This paper helps to give a pintle nozzle valve characteristic under the given operating conditions in an unsteady state environment.

2. ANALYTICAL STUDY

The pintle nozzle mechanism is based upon the throat area of the nozzle, as the throat area increases the thrust output decreases and vice versa. To control the thrust as it's required in the solid propellant rockets, throat area is varied accordingly to get the desired results.

The relationship relating the throat area and chamber pressure is given as,

$$\dot{m} = P_c . A_t . C^* \quad (1)$$

Where $\dot{m}$ is the mass flow rate in the throat (Kg/s), $P_c$is the chamber pressure, A_t is the throat area, and C^* is the discharge coefficient. The propellant burn rate is being neglected and dry air has been used in the study conducted. Assuming no flow separation in the divergent nozzle the ideal thrust is calculated based on

$$T = A_t . P_c . C_f . \eta_{nozzle} \quad (2)$$

Where *T* is the net thrust, C_f is the thrust coefficient and $\eta_{nozzle}$is the nozzleefficiency. The value of the C_f is calculated using the below given equations.

$$I_{sp} = \frac{Total\ thrust}{Weight\ of\ propellant} \quad (3)$$

$$I_{sp} = \frac{C_f . C^*}{g} \quad (4)$$

$$C_f = \frac{I_{sp} . g}{C^*} \quad (5)$$

Where $I_{sp}$is the specific impulse in the nozzle which is dependent upon the *total thrust* attained by the nozzle with respect to the *weight of the propellant* used in the solid rocket motor and *g* is acceleration due to gravity. Using the equation (3), (4) and (5), the value of $C_f$is calculated to use for the net thrust estimation from equation (2).

3. NUMERICAL STUDY

To study the flow field of the pintle nozzle valve k-ω SST (Shear Stress Transport) turbulence model was selected for the simulation since it gives similarity with the experimental results.

3.1. Boundary conditions and computational domain

ANSYS FLUENT 16.2 is used to calculate the flow field of the pintle nozzle valve. To understand the flow velocity, streamlines and flow pattern the dynamic mesh motion was adopted with respect to the pintle movement. The simulation is done for the unsteady state in this paper. The working fluid has been adopted as an ideal gas. In terms of solution method, a fully implicit finite volume scheme of the compressible, Reynolds-Averaged, Navier-Stokes equation had been considered.The two-dimensional model has been built for the numerical results as shown in the fig. 1 for the 25% close condition. It has two angular inlets at the convergent part of the nozzle and an exit at the divergent end of the nozzle, with pintle at aligned at the centre in such that no leakage happens in the flow.

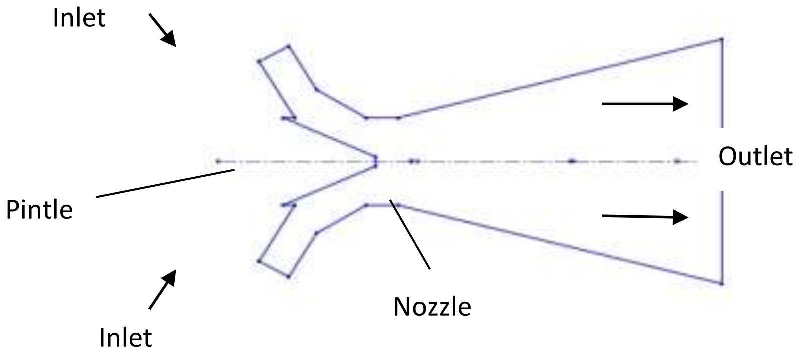

Fig. 1. Planar geometry of the pintle nozzle model

The boundary conditions are given below:

Inlet pressure: 4903.325 kPa Inlet temperature: 3000 K
Outlet pressure: 1013.325 kPa Outlet temperature: Atmospheric
Mesh independent study has been done with different grid to select the best grid for the above case. The mesh is composed of more than 0.023millions mapped elements without any external domain as it doesn't affect the flow field inside the nozzle.

4. RESULTS AND DISCUSSIONS

To validate the numerical study done using ANSYS FLUENT 16.0, the analytical solution results are used. The net thrust output values for various conditions of opening and closing with respect to the throat area are plotted on the graph along with the analytical solutions. The abscissa represents the percentage opening (%) of the throat area and the ordinate shows the thrust output in (KN).Numerical results show the similar trend with respect to the analytical results.

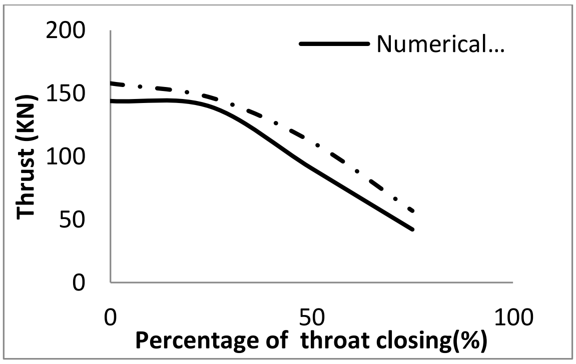

Fig. 2. Comparison of the thrust between numerical and analytical values

As shown in fig. 2, graph suggests that as the throat opening is decreased the thrust output tends to show a decrease in the output which is the aim of using the pintle to vary the thrust. This helps to use the solid propellant rocket (SRM) for the varying thrust applications like Divert and Attitude Control Systems (DACS) where variable thrust is a vital aspect of the rockets in manoeuvring the kill vehicle to destroy enemy missiles.

The *velocity distribution* contours for the different cases are shown below,

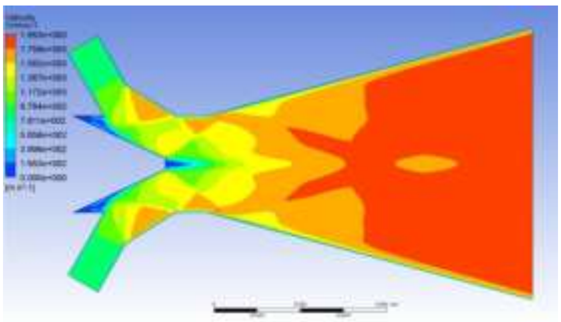

Fig. 3. (a). Full open Throat

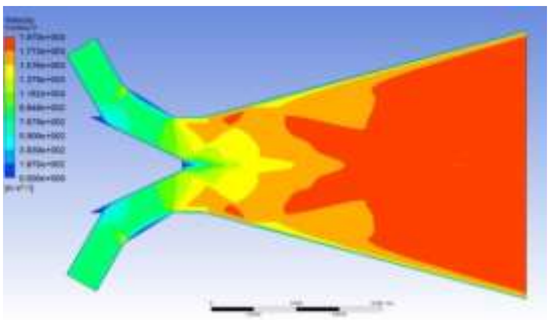

Fig. 3. (b) 25% close Throat

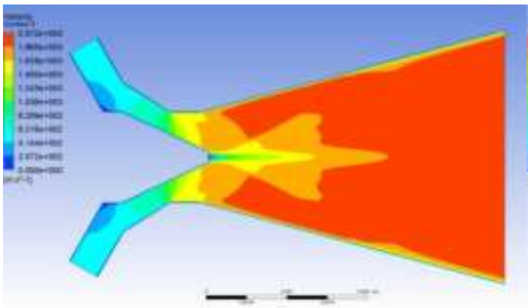 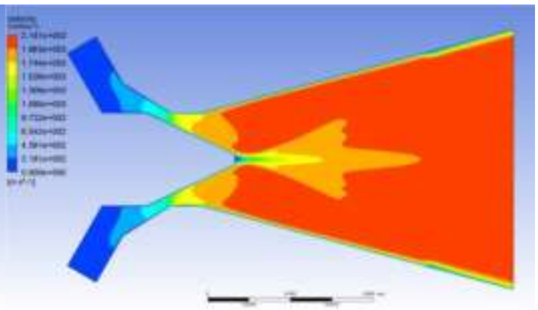

Fig. 3. (c) 50% close Throat Fig. 3. (d) 75% close Throat

The above contours in the Fig. 3. (a), (b), (c) and (d) show the variation of velocity with the throat area of the nozzle for the hot gases passing through the convergent section and exiting at the divergent section of the nozzle. The output velocity at the exit of the nozzle is nearly uniform throughout which is an advantage of the angular twin inlet pintle nozzle. In this particular nozzle, the obstruction due to pintle shows the minimum effect as the hot gases flow over the specifically designed pintle with minimum loss in the velocity, as this loss would have led to the loss in desired thrust output. Since the area decreases, the exit velocity increases subsequently at the exit at expense of the loss in the pressure of the hot gases.

The ***pressure distribution*** for the different cases are shown below,

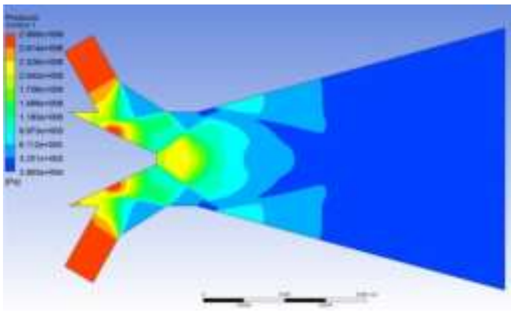 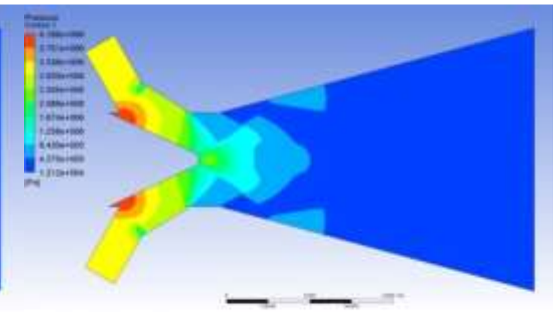

Fig. 4 (a) Full open Throat Fig. 4 (b) 25% close Throat

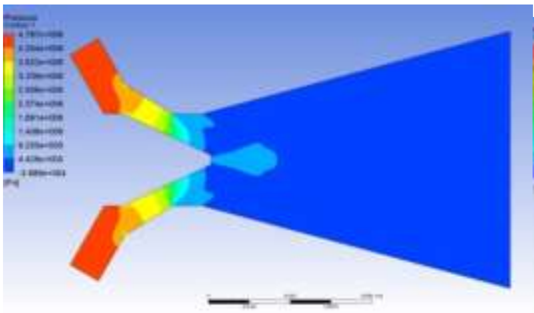 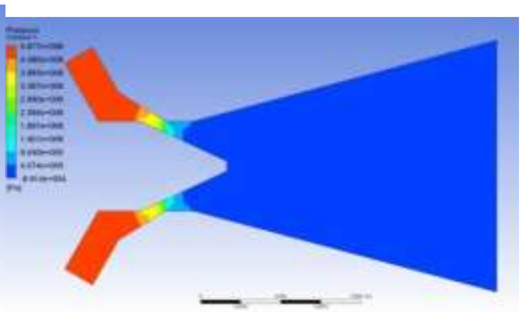

Fig. 4 (c) 50% close Throat Fig. 4 (d) 75% closeThroat

The pressure distribution contour of the nozzle as shown in the Fig. 4 (a), (b), (c) and (d) the hot gases enter with maximum pressure from the inlet of convergent section and tend to experience loss in the pressure as they move along the nozzle to the divergent section. During fully open condition near the throat pressure distribution seems to different when compared to the other cases, since in this condition the thrust produced is maximum and velocity is less in comparison but as the throat area opening decrease the pressure distribution in the divergent section of the nozzle tends to show uniform contour as result of this velocity also attains uniformity at exit.

The ***temperature distribution for*** the different cases are shown below,

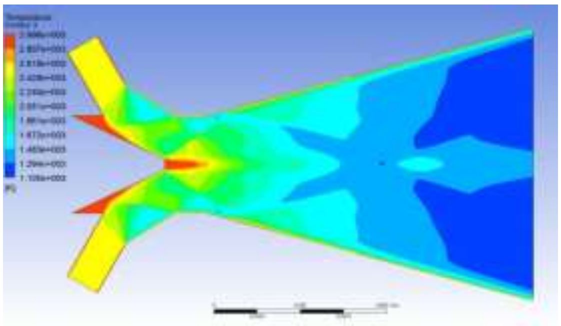

Fig. 5. (a) Full open Throat

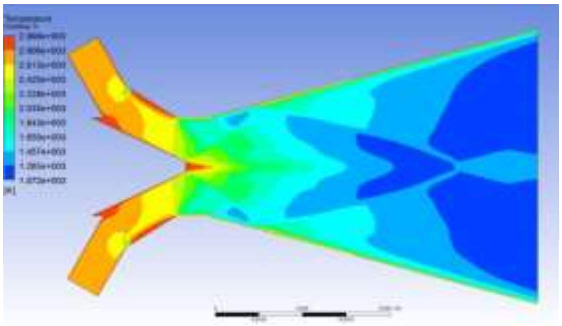

Fig. 5. (b) 25% close Throat

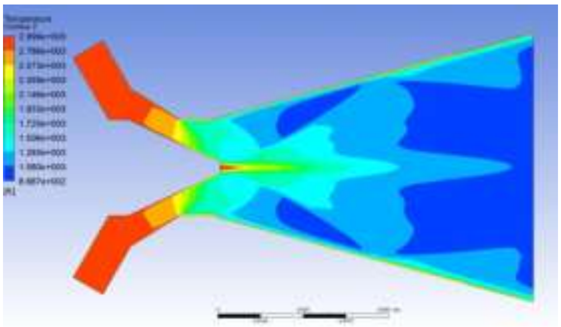

Fig. 5. (c) 50% close Throat

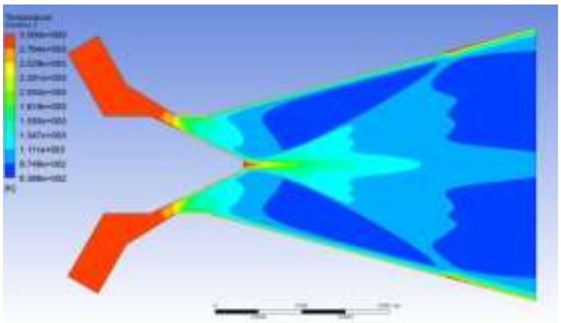

Fig. 5. (d) 75% close Throat

The temperature distribution contours are significant criteria of consideration, as in the nozzle temperature should not reach a level which might damage the pintle or nozzle walls. Though proper insulation is done for the nozzle wall and pintle to withstand high operating temperatures due to hot gases. Since the temperature tends to decrease as shown in the Fig. 5. (a), (b), (c) and (d) as the gases flow in the nozzle with maximum at the inlet, tends to decrease as the gases move along in the nozzle and minimum at the outlet of the nozzle, which is sufficient condition for the safety of the nozzle and pintle. The maximum temperature is faced by the walls of the pintle and the nozzle.

The ***streamlines*** for the different cases are shown below,

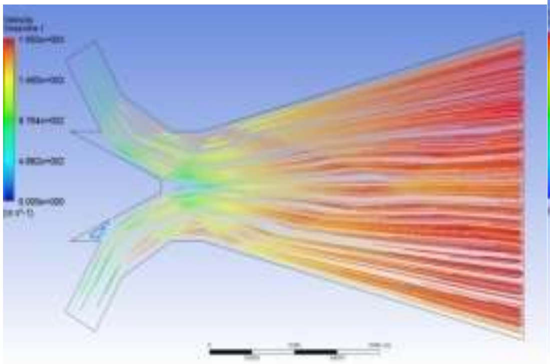

Fig. 6. (a) Full open Throat

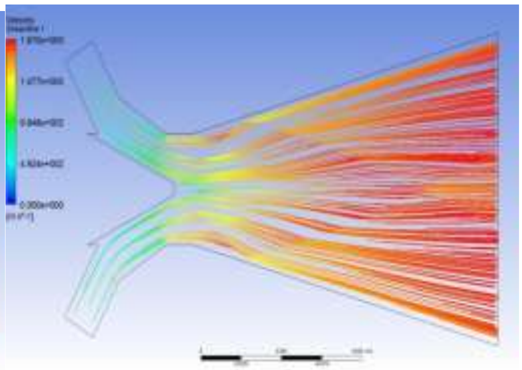

Fig. 6. (b) 25% close Throat

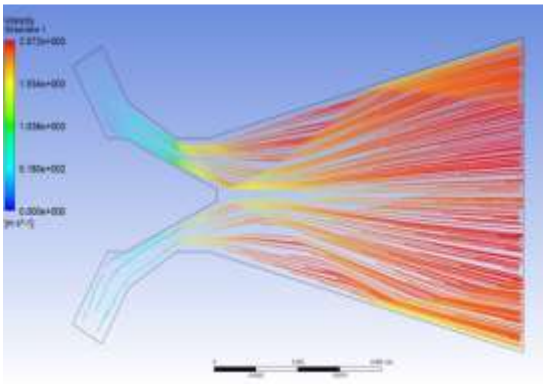

Fig. 6. (c) 50% close Throat

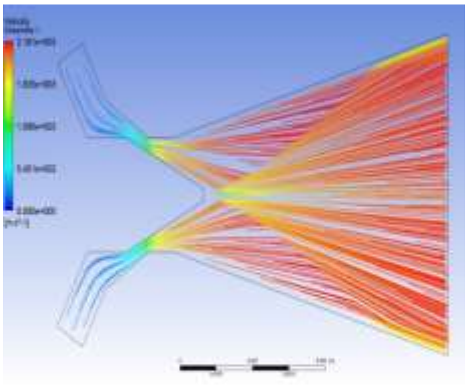

Fig. 6. (d) 75% close

The streamlines as shown in the Fig. 6. (a), (b), (c) and (d) for different cases of observation shows no flow recirculation or flow reversal, which is a problem in while using the single vertical inlet for the nozzle due to obstruction of flow by the pintle. This obstruction can result in significant loss in the thrust output. The above streamline is achieved with the help of angular twin inlet, which allows the hot gases to flow smoothly over the pintle with least obstruction. The streamlines suggest that the flow is not obstructed by pintle to a greater extent as the gradually the uniform velocity is achieved.

CONCLUSION

This study conducted a numerical simulation with the twin inlet to pintle nozzle with the use of ANSYS FLUENT 16. The flow is simulated with k-ω SST turbulent model to get high precision results. The numerical results are compared with the analytical results, shows similar thrust trends for the different cases and are quite a good match to analytical results. The angular twin inlet helps to provide uniform thrust output for the different openings of the throat area using the pintle nozzle for the thrust variation. The throat area is the main factor upon which the thrust variation can be achieved for the desired conditions but there is a limit up to which the throat area can be decreased. Effective throat area is being considered while calculating for the analytical solution which is an important point to be taken care while the calculation is done. In this case, it’s found to be 77-76% of the original throat area that can be decreased, as on further decrease in the throat are flow separation or flow reversal occurs due to low pressure. The shape of the pintle is quite crucial when the flow analysis is being conducted and ensures removal of the flow related problems like flow recirculation or flow reversal throughout the nozzle. While conducting the unsteady study, for the particular cases it is observed that the thrust takes 1-2sec to get the constant output thrust and its value tends to increase for few seconds in the start. A lag between the thrust and pintle movement is being noticed.

5. References

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