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A Computational Study on the Thrust Performance of a Supersonic Pintle Nozzle

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ABSTRACT

Typical solid rocket motors (SRM) have advantage of their inherent simplicity and reliability, but they do not have the capability to change thrust profile like other propulsion system. Pintle technology is one of the means to achieve variable and programmable thrust. This paper describes a study of the static and dynamic characteristics of a pintle nozzle under the constant mass flow rate. The mass flow rate is fixed in 1.744kg/sec and pintle stoke is adjusted in range from 0mm to 60mm . An analytical model has been created for comparison. A two-dimensional axisymmetric numerical simulation has been carried for thrust performance during the pintle moving process. To validate the ability of the numerical model, numerical results were compared with the analytical and experimental results. They show quite good match in different pintle strokes. Aiming to optimum dynamic performance, different pintle speeds should be researched. Chamber pressure goes up dramatically due to pintle movement. The pressure evolution is not unique in the process of the pintle movement but shows the delay effect. By adjusting the pintle speed, chamber pressure and thrust histories with time would be calculated based on CFD models. The dynamic characteristics of the pintle nozzle largely depend on the mass flow rate through the throat. It also depends on the pintle activation because mass flow rate through the throat varies with the pintle stroke in the dynamic process. The result will provide the reference to the further development.

INTRODUCTION

Solid rocket engines are used on air-to-air and air-to-ground missiles, on model rockets, and as boosters for satellite launchers. Solid rocket motor has dominated the tactical missile field owing to its inherent simplicity and reliability without significant design compromises. However, it is difficult to change the designed thrust profile with a conventional solid propellant motor because the solid propellant is continuously or unstoppably burned until all the propellant is consumed after ignition. Pintle technology, to achieve the variable thrust for the mission, is basically similar to that of the flow control employed for the globe valve, of which the cross-sectional area of the flow passage is changed by the pintle. Detailed flow features concerned with pintle section play the key role in thrust manage system.

Many studies were carried out in the last four decades to research the pintle technology. Pintle technology used in escape system of military aircraft was searched, this system provided fully controllable propulsion to suit the circumstances of each emergency, see Rock et al.(1997). Dual-thrust technology was to control the burning surface of the solid propellant by designing the grain shape, and pulse motor technology divides solid propellant into two or three sections using an insulation technique. It was developed to increase mission range and end-game maneuverability, see Harold et al. (1996). The effects of several important parameters were studied in pintle technology, the important relationship between pintle geometry, pintle position and throat area can be determined and used for design decisions, see Ostrander et al. (2000). Various pintle nozzle exit cone contours were investigated using analytical model, it provided the optimizing pintle nozzle contour which produces the highest specific impulse, see Randall et al. (1995). Steady and unsteady characteristics of a pintle conical nozzle were studied numerically based on Spalart-Allmaras one equation turbulence model. Also, performance variations were examined in terms of the pintle speed and pintle geometies, see Lee et al. (2013). Although many researches on developing optimal strategies of pintle nozzle were done during past years, there was few numerical study based on two-equations turbulent model.

A computational fluid dynamics (CFD)-based study has been conducted for studying the steady and unsteady phenomenon. The purpose of the present study has been to explore the actual throat variation with the pintle stokes in steady and unsteady process. Analytical and numerical models have been established to study the thrust variation. Numerical results have been compared with analytical and experimental results. The pressure distribution of divergent nozzle in different pintle strokes has been studied in the steady condition. The parameter that affect thrust performance, such as pintle speed, has been studied in unsteady process.

ANALYTICAL STUDY

The pintle technology is one kind of approaches which control the nozzle thrust directly, see Burroughs (2001) and John et al. (2003). This approach is to introduce a mechanism that can control the nozzle throat area. This mechanism is typically a tapered plug, called a pintle. When the pintle inserts into the throat, the throat area and thrust can be changed, see Christina et al. (2003). The schematic of pintle nozzle is shown as Fig.1.

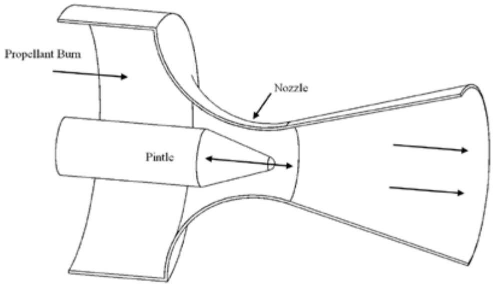


Figure 1. Schematic of pintle nozzle

The variation of throat area produces the large change of throat mass flow rate. Also, chamber pressure will be changed with the variation of throat area. The propellant burn rate is a function of chamber pressure. The relationship of some important parameters in pintle system is shown as follow equations.

$$\dot{m} = P_c \cdot A_t \cdot C^* \tag{1}$$

Where m is the mass flow rate in the throat, P_c is the chamber pressure, A_t is the throat area, and C^* is the discharge coefficient. The effect of propellant burn rate is neglected and the cold dry air has been used in this study. It is supposed that mass flow rate is constant as 1.744 kg/s. The ideal thrust of pintle nozzle is prdicted based on isentropic process. It assumed that no flow separation occurs in the divergent nozzle.

The area ratio with various stroke is known based on the geometry. The Mach number in nozzle exit can be obtained by equation (2) with the isentorpic hypothesis.

$$\frac{A_e}{A_t} = \frac{1}{M_e} \cdot \left[\frac{2 + (\gamma - 1) \cdot M_e^2}{\gamma + 1} \right]^{\frac{1}{2} \cdot \frac{\gamma+1}{\gamma-1}} \tag{2}$$

Where A_e and A_t represent the area of nozzle exit and throat, M_e represents the Mach number in nozzle exit, γ represents the gas specific heat ratio.

The pressure ratio of chamber and nozzle exit is calculated by equation (3).

$$\frac{P_c}{P_e} = \left(1 + \frac{\gamma - 1}{2} \cdot M_e^2\right)^{\frac{\gamma}{\gamma-1}} \tag{3}$$

Where P_e represents the static pressure in nozzle exit.

The x-coordinate net thrust is the most important value in this study. The force in x-coordinate is defined by followed equation.

$$F = C_F \cdot P_c \cdot A_t = \dot{m} \cdot V_e + (P_e - P_a) \cdot A_e \tag{4}$$

Where F is the net thrust, C_F is the thrust coefficient, V_e is the velocity in nozzle exit, P_a is the atmosphere pressure.

The analytical results can be obtained by solving the combined expression of equation (1), (3) and (4).

$$F = \dot{m} \cdot a_e \cdot M_e + \frac{\dot{m}}{C^*} \cdot \frac{A_e}{A_t} \cdot \left(1 + \frac{\gamma - 1}{2} \cdot M_e^2\right)^{\frac{\gamma}{1-\gamma}} - P_a \cdot A_e \tag{5}$$

$$a_e = \sqrt{\gamma \cdot R \cdot T_e} \tag{6}$$

Where a represents the sonic speed, T_e represents static temperature in nozzle exit with the isentorpic hypothesis, R is gas constant. The Mach number M_e in nozzle exit has been calculated by equation (2).

CFD STUDY

Numerical procedure

To properly model the flow field, selection of suitable turbulent model is very important. The flow field has been simulated using both k-ε and k-ω turbulent models. Fig.2 demonstrates the pressure distributions along divergent nozzle with different turbulent models in the case of pintle stroke X=30mm. The pressure distribution using k-ω sst turbulent models is good agreement with the experimental data.

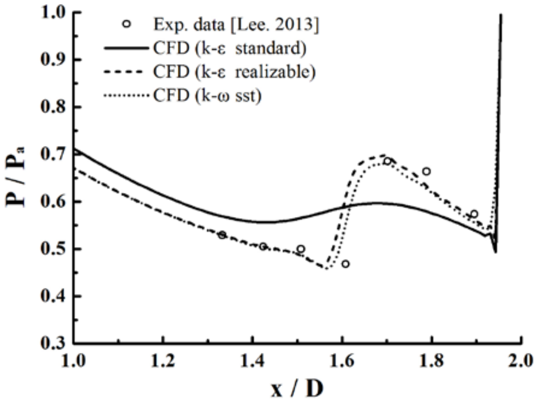


Figure 2. Pressure distribution along the wall of divergent nozzle (X=30mm)

Computational domain and boundary conditions

ANSYS Fluent 14.0 is chosen to calculate the flow field of the pintle nozzle. Computational fluid dynamics with dynamic mesh motion were adopted to understand the flow structure, thrust and chamber pressure variation in terms of pintle movement. Unsteady phenomena of pintle nozzle have been studied in this paper. The working fluid has been considered as ideal gas. A fully implicit finite volume scheme of the compressible, Reynolds-Averaged, Navier-Stokes equations had been employed.

The 2D axisymmetry model has been built based on previous experimental model. Static and dynamic CFD models have been estimated at different pintle strokes based on second order scheme. The numerical scheme used in this study is summarized. The length of divergent section L is 48mm, throat diameter D is 25mm, expansion ratio A_e/A_t is 2, and pintle radius R is 11mm. The domain is extended to $20H\times30H$ for better numerical accuracy. Structured mesh is used during all regions. The boundary conditions in CFD model are shown in Fig.3.

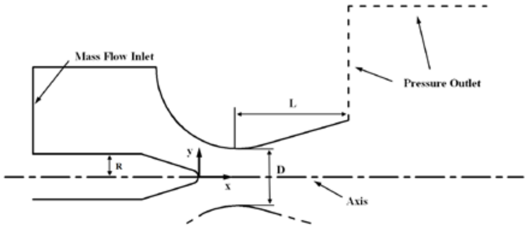


Figure 3. Boundary conditions of CFD model in the zero pintle stroke (X=0mm)

Mesh independent study has been conducted with different grid distributions in order to select the better grid. The mesh of nozzle domain is composed of 0.2 million mapped hexagonal elements, and external domain consists of 0.1 million mapped hexagonal elements. Mass flow inlet boundary condition has been set at stream inlet of the pintle nozzle. Mass flow inlet has been set in 1.744kg/s. The stream outlet of pintle nozzle have been extended to stabilize the computational results. Pressure outlet boundary condition has been set in atmosphere pressure .

RESULTS AND DISCUSSION

Validation

To validate the ability of the numerical model, the experimental data of Lee et al. (2013) has been used for comparison. The net thrust of pintle nozzle with different strokes are shown in Fig.4. The x-coordinate thrust distributions in CFD model have been compared with the analytical and experimental results. Numerical result shows the similar trend compared to analytical and experimental results.

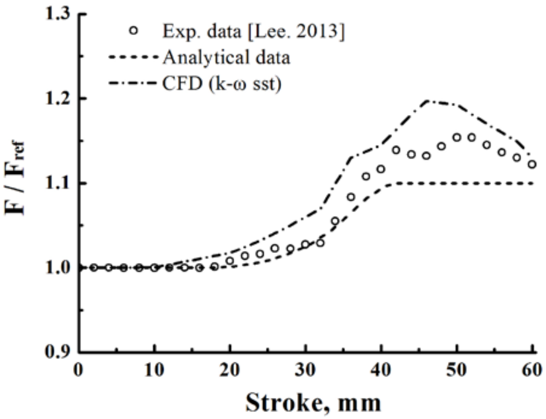


Figure 4. Numerical, analytical and experimental thrust distributions with different strokes

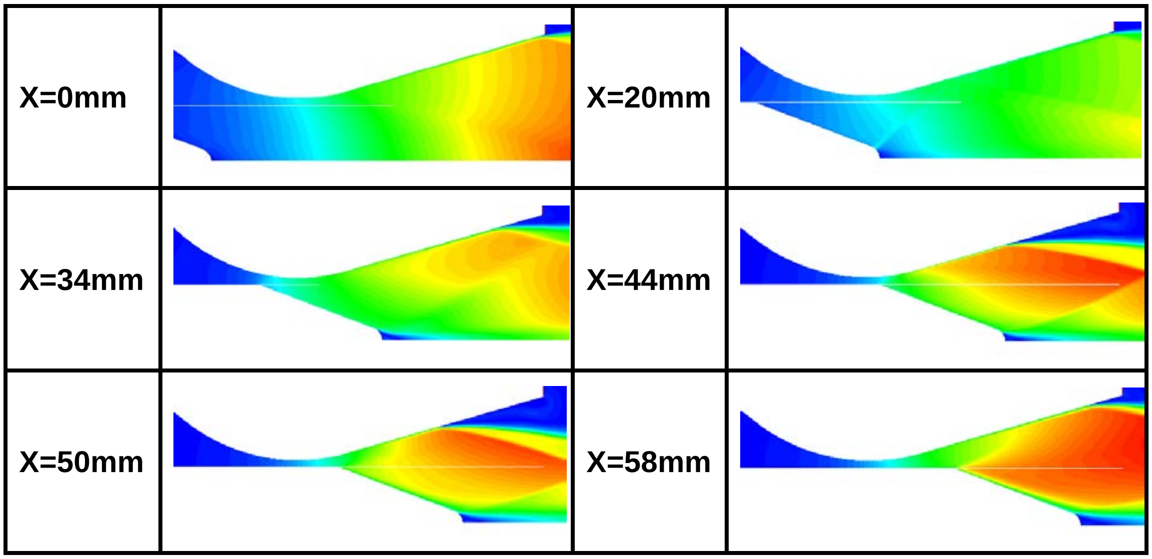


Figure 5. Mach contours with different pintle strokes

Static performance with pintle strokes

The pintle strokes has been changed from 0mm to 60mm by inserting the pintle into the nozzle throat. Fig.5 shows Mach contours with different pintle strokes. The boundary layer separation does not appear in X=0mm, even though the flow is in over-expended condition. When the area ratio increases gradually, the boundary layer separation appears and the separation point is moving upstream. After the area ratio reaches the maximum value, the separation point is moving downstream as the pintle inserts into the deeper position. Pressure distributions along the divergent nozzle is shown in Fig.6. The moving trend of separation point with different pintle strokes can be observed clearly in this figure.

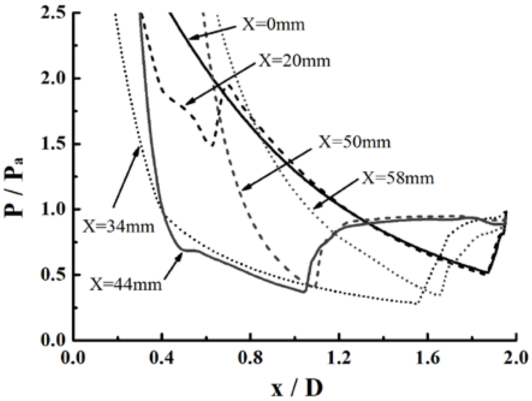
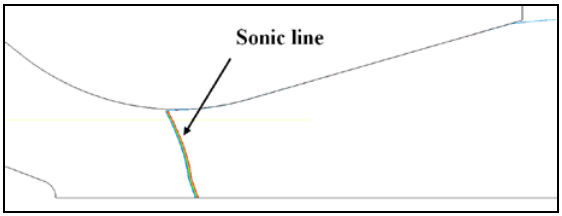
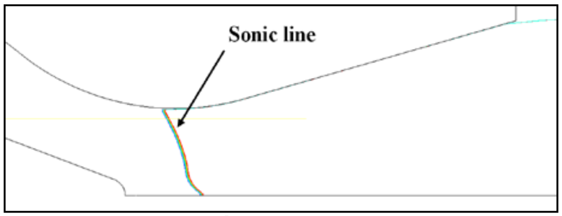


Figure 6. Pressure distributions along the divergent nozzle with different pintle strokes

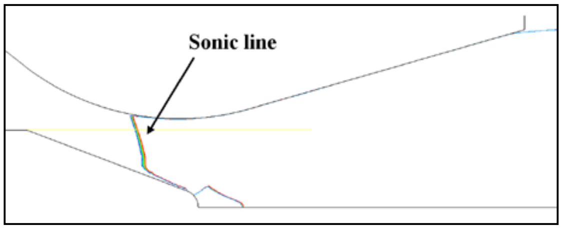
The definition of throat position is very important in the performance prediction. Fig.7 shows the numerical results with different pintle strokes. The various sonic lines can be observed in detail in different pintle strokes. The sonic line is located in the nozzle throat in first two cases. The sonic line is moving upstream as the area ratio goes down increasingly. It is difficult to define the throat area in the process from 10mm to 34mm. Because the throat position depends not only the minimum gap size but also the flow direction. So the empirical method should be used to define the actual throat by referring the sonic line variation in numerical work.



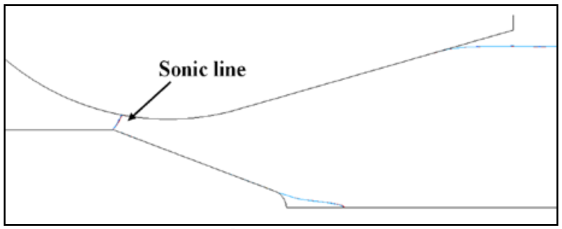
a) X=0mm



b) X=10mm



c) X=20mm

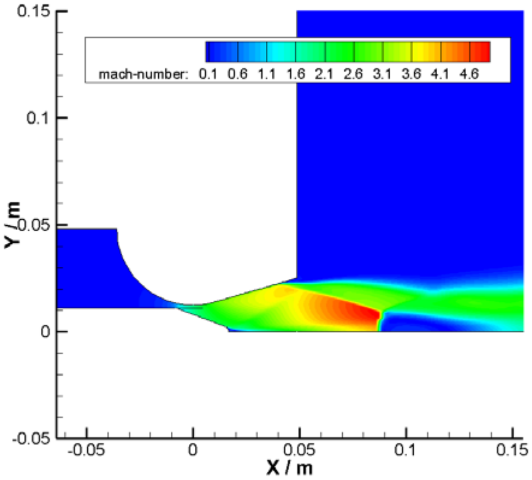


d) X=34mm

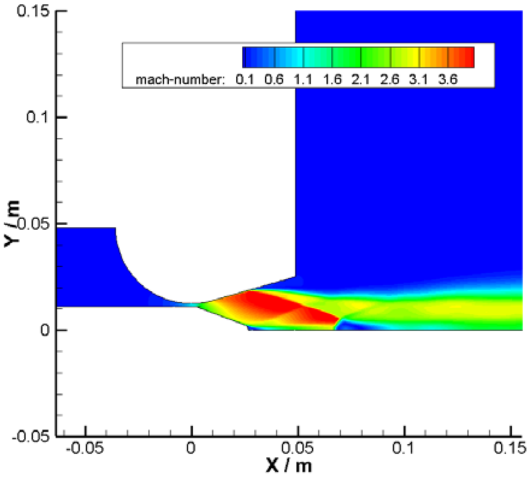
Figure 7. Sonic line profiles with different pintle strokes

Dynamic performance with pintle speeds

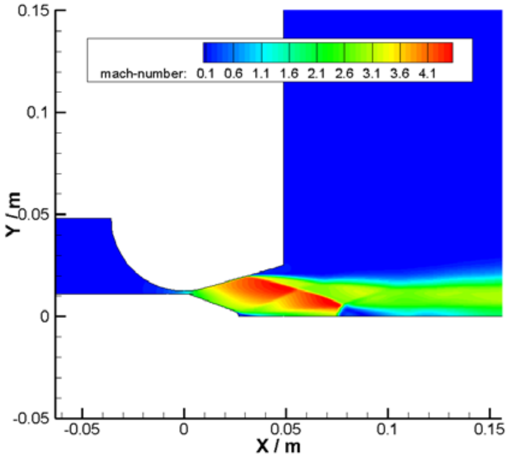
The most important feature in dynamic process is the pintle speed. For optimum dynamic thrust, different pintle speeds should be researched. The Mach number contours in the speed of 12.5mm/s are shown in Fig.8 for t=0s,0.8s,2s. When the pintle is inserted into the nozzle throat, the area of throat becomes smaller and chamber pressure goes up. The mass flow rate of the throat becomes smaller at the beginning of this process, and then it goes up as the chamber pressure increases further. Fig.8 presents three time points in the moving process in the range from 34mm to 44mm. The pintle moving process is finished in the case of t=0.8s and X=44 (Fig.8b). The shock system is not stable in 0.8s, and it moves upstream as the time goes on. It is because of the delayed increasing of the chamber pressure.



a) t=0s,X=34mm



b) t=0.8s,X=44mm



c) t=2,X=44mm

Figure 8. Mach number contours in the speed of 12.5mm/s

The chamber pressure and thrust variations in the pintle moving process are shown in Fig.9 and Fig.10. The pintle has been moved from 34mm to 44mm during this dynamic process. Chamber pressure suddenly goes up and then tends to remain constant. It is because the throat area changes in this process. The period of various process becomes longer when the pintle speed decreases. At the beginning of the process, the area variation causes the changing of the throat mass flow rate. The chamber pressure tends to increase obviously due to the constant of inlet mass flow. When pintle movement is finished, the throat area keeps constant and the variation of chamber pressure becomes smaller. Net thrust suddenly decreases at the beginning and then goes up obviously due to the delayed increasing of chamber pressure. Finally, the net thrust keep constant after the chamber pressure tends to be constant.

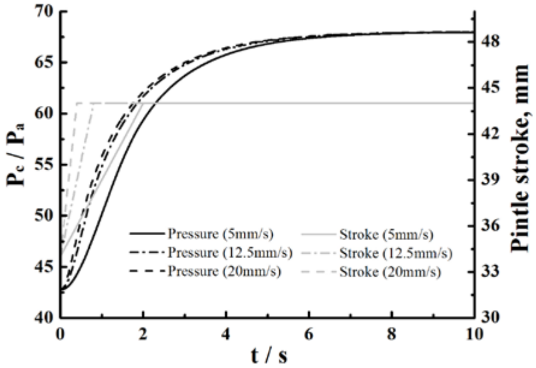


Fig.9 Chamber pressure variation in pintle moving process

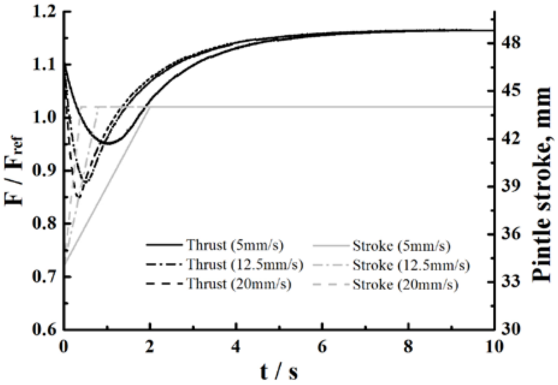


Fig.10 Thrust variation in pintle moving process

CONCLUSIONS

Fluent 14 has been used in order to simulate and analyze the flow field. Numerical simulation has been taken in order to investigate the steady and unsteady processes of pintle nozzle. The flow field has been simulated using k-ε and k-ω turbulent models for the selection of suitable model. The k-ω sst turbulent model shows high precision compared with other turbulence models. Analytical model has been established for comparison. Numerical result has been compared with analytical and experimental results. Overall thrust various trend shows quite good match with the experimental results. The definition of throat position depends not only the minimum gap size but also the flow direction in steady numerical study. For optimum vectoring effect, pintle speed has been researched in unsteady numerical model. Chamber pressure suddenly goes up at the beginning and then tends to remain constant. Net thrust suddenly decreases at the beginning and then goes up obviously. Finally, the net thrust keep constant after the chamber pressure tends to be constant. The period of various process becomes longer when the pintle speed decreases. And there is a delay between of thrust variation and pintle movement.

ACKNOWLEDGMENT

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