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Unsteadiness Effects on Variable Thrust Nozzle Performance

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***Abstract*—**The purpose of this paper is to elucidate the flow unsteady behavior for moving plug in convergent-divergent variable thrust nozzle. Compressible axisymmetric Navier-Stokes equations are used to study this physical phenomenon. Different velocities are set for plug to investigate the effect of plug movement on flow unsteadiness. Variation of mass flow rate and thrust are compared under two conditions: First, the plug is placed at different positions and flow is simulated to reach the steady state (quasi steady simulation) and second, the plug is moved with assigned velocity and flow simulation is coupled with plug movement (unsteady simulation). If plug speed is high enough and its movement time scale is at the same order of the flow time scale, variation of the mass flow rate and thrust level versus plug position demonstrate a vital discrepancy under the quasi steady and unsteady conditions. This phenomenon should be considered especially from response time viewpoints in thrusters design.

***Keywords*—**Nozzle, Numerical study, Unsteady, Variable thrust.

I. Introduction

IMPLEMENTATION of moving plug to change the nozzle throat cross section is a common way to control the thrust level in some thrusters. At this technology, a pintle or plug that is located near the nozzle throat can move along the nozzle axis and increases or decreases the throat area. Consequently, the thrust magnitude is changed by this displacement. Numerable investigations have been carried out to study the variable thrust pintle nozzles.

Onofri et al. [1] summarized investigations that have been done on plug nozzle comprehensively in order to elucidate the flow physics of this common system. Smith-Kent et al. [2] numerically investigated the various pintle nozzle exit cone contours. They found the optimum contour that produces the highest specific impulse. Burroughs [3] experimentally studies the effect of different parameters on pintle technology for variable thrust nozzle. Xiang-geng et al. [4] experimentally investigated non-coaxial pintle nozzle solid rocket motor. They concluded that propellant plays an important role to response time of pressure at this specific system.

Lee at al. [5] experimentally measured the thrust and chamber variation at different plug locations, and they compared results with theoretical one-dimensional relations. They concluded aerodynamic throat area should be considered as actual throat area versus geometrical throat area for each plug location. Lee et al. [6] numerically and experimentally studies the flow structure and geometric factors on pintle-perturbed conical nozzle. They concluded that the pintle length, shape and tip radius are not predominant factors on thrust variation whereas thrust variation is dependent severely on chamber pressure.

None of the mentioned studies considered the effect of pintle or plug velocity on flow behavior at unsteady simulations or measurements. It should be noticed that in problems including more than one time scales due to different physical features, coupling the time scales together may leads new physics related to unsteadiness. For example, the transient burning of solid fuels arise from coupling the flowfield and heat transfer time scales, and may lead extinction or instabilities where couldn’t be studied in quasi steady simulations [7].

At this study the axisymmetric flow is simulated under two distinct conditions: first, fixed plug positions and steady simulation (quasi steady) and second, moving plug with specific velocity and unsteady simulation. The results of thrust and mass flow rate variations are compared for two defined conditions; the unsteadiness effect on flow is investigated by setting different velocities for plug movement.

Dynamic mesh feature of Fluent commercial code is used by writing proper UDFs to simulate plug movement at unsteady cases. The aim of this paper is to prove that the unsteadiness effect is dominated by increasing the plug movement speed because of nearing this movement time scale to flow global time scale. At this study, three different velocities are set for plug movement and comprehensive comparisons are carried out to prove the novel claim.

II. Governing Equations and Numerical Procedure

Axisymmetric compressible Navier-Stokes equations are governed the flow at this study. The closed system integral form of continuity, momentum and energy equations are presented below [8].

$$\frac{\partial U}{\partial t}+\frac{\partial(F+F_v)}{\partial x}+\frac{\partial(G+G_v)}{\partial y}+\frac{(G+G_v)+(G'+G'_v)}{y}=0 \qquad (1)$$

where,

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$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho e \end{bmatrix} \quad F = \begin{bmatrix} \rho u \\ \rho uu + p \\ \rho uv \\ \rho uh \end{bmatrix} \quad G = \begin{bmatrix} \rho v \\ \rho vu \\ \rho vv + p \\ \rho vh \end{bmatrix} \quad G' = \begin{bmatrix} 0 \\ 0 \\ -p \\ 0 \end{bmatrix}$$

$$F_v = \begin{bmatrix} 0 \\ -\tau_{xx} \\ -\tau_{xy} \\ q_x - u\tau_{xx} - v\tau_{xy} \end{bmatrix} \quad G_v = \begin{bmatrix} 0 \\ -\tau_{yx} \\ -\tau_{yy} \\ q_y - u\tau_{yx} - v\tau_{yy} \end{bmatrix} \quad G'_v = \begin{bmatrix} 0 \\ 0 \\ \tau_{\theta\theta} \\ 0 \end{bmatrix} \tag{2}$$

and

$$\tau_{xx} = \mu\left(2\frac{\partial u}{\partial x} - \frac{2}{3}\nabla.V\right) \qquad \tau_{xy} = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$
$$\tau_{yy} = \mu\left(2\frac{\partial v}{\partial y} - \frac{2}{3}\nabla.V\right) \qquad \tau_{\theta\theta} = \mu\left(2\frac{v}{y} - \frac{2}{3}\nabla.V\right) \tag{3}$$

The above equations accompanied by ideal gas relation are solved by finite volume cell center method where the inviscid fluxes are discretized by AUSM scheme. Nitrogen (N2) gas is considered as fluid at this study.

Fig. 1 shows schematic view for convergent-divergent nozzle with plug. Slip boundary condition is chosen for walls if flow is simulated without viscous fluxes, and no slip boundary condition is set for walls if both inviscid and viscous fluxes are computed at simulation. Total pressure and total temperature at nozzle inlet are set to satisfy boundary conditions at this problem. Flow at nozzle exit releases into vacuum ambient at this study (for space missions), so the static pressure is equaled zero at outlet boundary for thrust calculations.

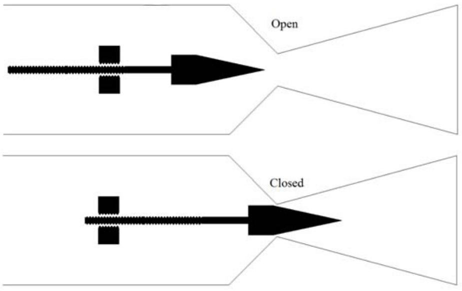

Fig. 1 Schematic view of nozzle with moving plug system

Fig. 2 depicts computational domain and geometrical characteristics of simulated problem. Plug position is defined by the plug head location related to throat. The plug coordinate is characterized by minus sign if plug head position is at the back of throat, while the plug coordinate is specified by plus sign if plug head position is at the front of throat. Unstructured grid is used to discretize the computational domain to adequate control volumes for Euler equation simulation, and structured grid with the cluster of cells near the walls is utilized for complete Navier-Stokes equation simulation. At the next section, results and justification for the effect of movement velocity on flow unsteadiness behavior are presented.

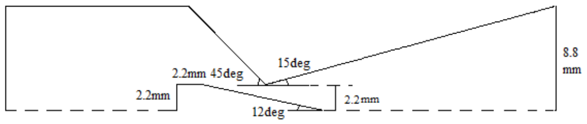

Fig. 2 Computational domain and geometrical characteristics of variable thrust nozzle

III. RESULTS AND DISCUSSIONS

The aim of this study is to illustrate the effect of plug movement speed on unsteadiness nozzle response behavior. First, plug is placed at different locations related to nozzle throat, and flow is simulated to reach the steady condition. At this case, moving mesh option of Fluent is not active. Second, plug is moved with specific velocity along the nozzle axis, and governing equations are solved at the same time with plug movement. Flow is simulated unsteady, and UDFs are hooked to solver.

Figs. 3, 4 show comparisons for mass flow rate and total thrust with analytical quasi one dimensional result from [9]. The discrepancies appear due to the two dimensional effects on flowfield such as aerodynamic and geometric throat difference which should be predicted using numerical simulations. In addition, Fig. 5 presents net axial force acts on plug. It illustrates that significant force being applied on plug especially when it more penetrates is important for such nozzles and proper actuator design.

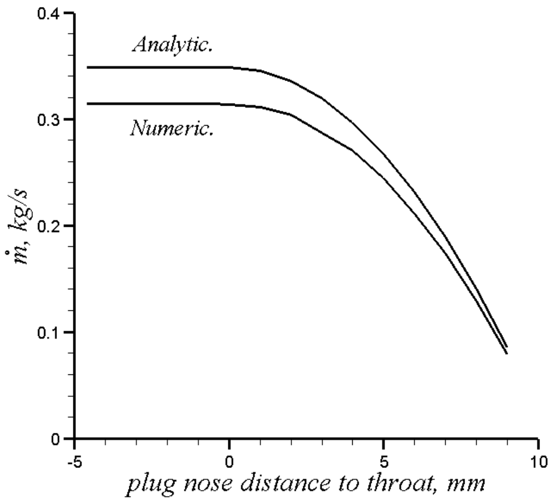

Fig. 3 Comparison of mass flow rate variation versus plug positions between numerical and analytical result

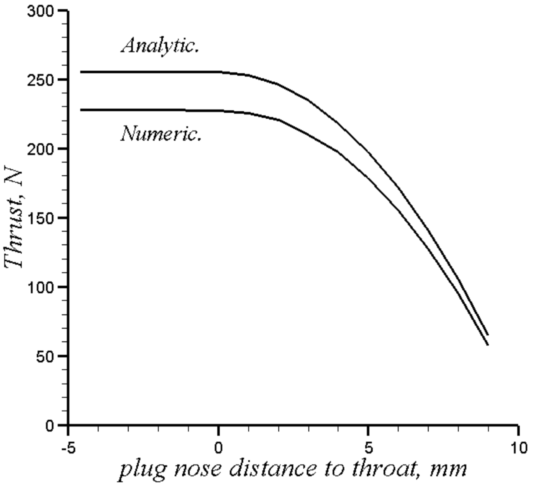

Fig. 4 Comparison of thrust variation versus plug positions between numerical and analytical result

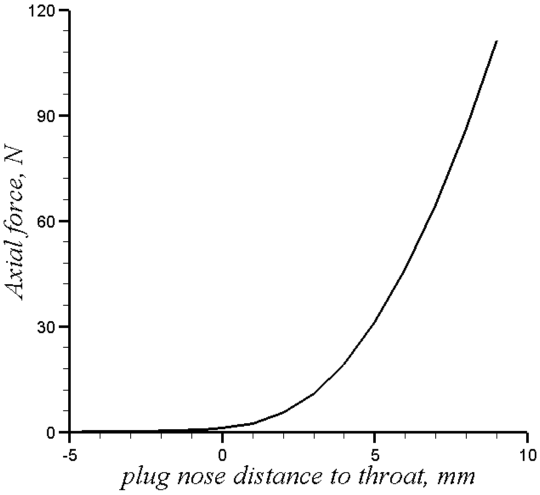

Fig. 5 Variation of axial force over plug surface versus plug positions

Viscous terms may affect three aspects of flow at this specific simulated geometry: axial force over plug surface, flow separation at nozzle exit and nozzle mass flow rate. In order to investigate the importance of viscous force at this study, viscous fluxes are computed beside inviscid fluxes for the case where plug head location is 9mm in front of throat section. The results show that the net viscous force acts on plug surface is negligible and around 0.15 Newton for this case. In addition, due to zero back pressure at this study, the flow separation at exit section is not observed at this investigation, so the viscous flux importance is omitted. Boundary layer thickness at throat section which may be a predominant factor on mass flow rate is negligible here and doesn't affect the mass flow rate. Therefore, these results prove that viscous terms are not dominant at this specific geometry and flow conditions, and simulation can be done without considering the effect of viscosity.

In order to study the effect of plug movement speed on flow unsteadiness, three different velocities: 1, 10 and 50 (m/s) are set for plug movement. Figs. 6, 7 present comparisons for unsteady thrust and mass flow rate variation with quasi steady results during plug movement along nozzle axis.

It is obvious from figures that discrepancy between quasi steady results and real time simulations (unsteady results) becomes vital as plug movement velocity is increased. For specific geometry and flow conditions at this study, there exists two time scale: the flow global time scale and plug movement time scale. As plug movement time scale closes to the flow global time scale, flow doesn't has enough time to adapt itself with new geometry that comes from plug movement. Consequently, flow behavior shows some lags related to quasi steady behaviors. This difference is a paramount factor to design proper thrusters. The required time to reach steady flow behavior after plug reaches to its final position is shown at Fig. 8 for velocity of 50 *m/s*. This response time is very important for systems that design to react accurately and rapidly and considering response time in design procedure is inevitable.

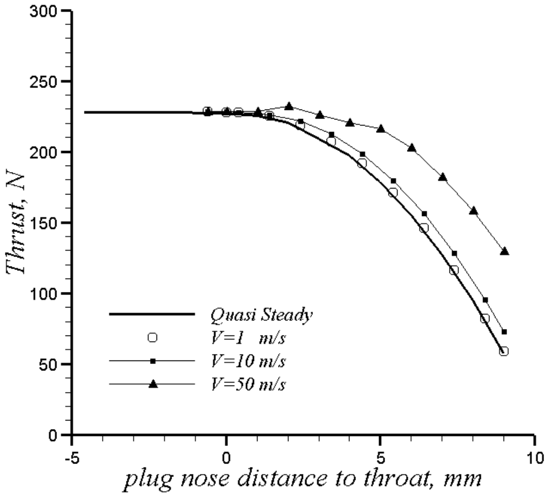

Fig. 6 Comparison for Thrust variation between quasi steady and unsteady simulation

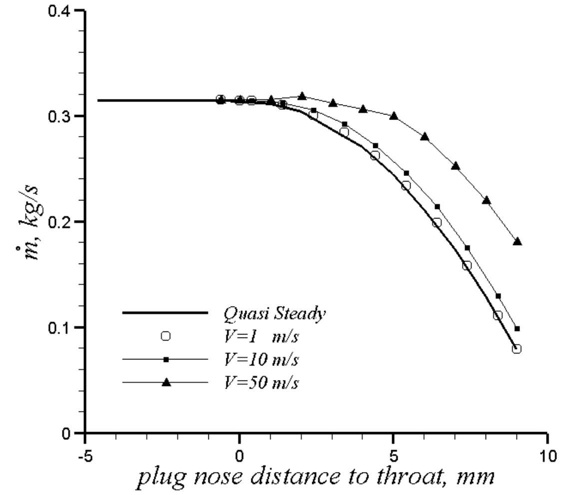

Fig. 7 Comparison for mass flow rate variation between quasi steady and unsteady simulation

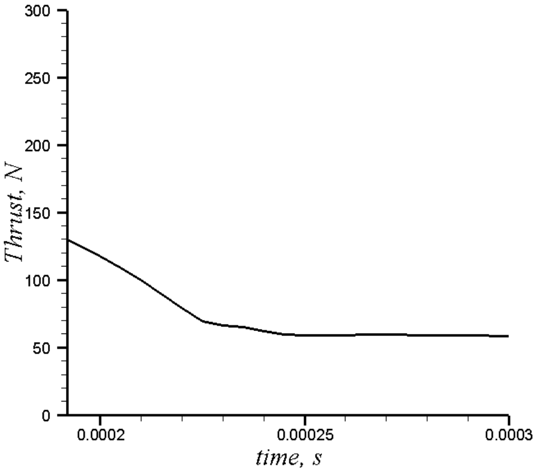

Fig. 8 Required time to reach steady behavior after plug reaches the final position

IV. CONCLUSION

The effect of plug movement speed on flow unsteadiness is investigated at this study for variable thrust nozzle with moving plug system. Flow behavior is simulated under two distinct conditions: fixed plug positions and steady simulation (quasi steady), movable plug and unsteady simulation. In order to clarify the effect of plug movement on flow behavior, three different velocities 1, 10 and 50 *m/s* are set for plug motion. Variation of thrust and mass flow rate versus plug locations are compared under two mentioned conditions. Flow behavior shows vital discrepancy with quasi steady results if plug velocity is increased. This phenomenon can be explained by existing two different time scales at this specific geometry and flow conditions. Convective time scale that is determined by flow mean velocity and nozzle length is global or flow time scale at this study, and plug movement time scale that is determined by plug movement velocity and plug displacement is another time scale for this defined system. If plug movement time scale closes to flow time scale, flow doesn't have enough time to adapt itself with new geometry that comes from plug motion, so system confronts some lags compared to quasi steady results. Therefore, the required time to reach steady state condition for flow after the plug is situated at desired location becomes a paramount factor to design accurate thrusters.

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