Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

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Performance characteristics of a pintle nozzle using the conformal sliding mesh technique

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ARTICLE INFO

Article history:
Received 14 April 2016
Received in revised form 3 October 2016
Accepted 25 November 2016
Available online xxxx

Keywords:
Pintle nozzle
Variable thrust
Moving grid
Supersonic flow separation
Hysteresis thrust
Rocket motor

ABSTRACT

Numerical and non-linear internal ballistics analyses are conducted to investigate the performance characteristics of a pintle reciprocating in a nozzle. A conformal sliding mesh is successfully implemented to maintain smooth and continuous flow properties at the boundary of a moving pintle block. The proper mesh size is determined via a grid dependency test. The pintle nozzle operates under over-expansion conditions so that flow separation occurs at the nozzle wall at certain pintle stroke positions. Both the chamber pressure and thrust have hysteresis loci to allow for the reciprocation of the pintle's insertion and extraction motions, which have different trace-to-pintle speeds. The hysteresis loci reduce as the pintle speed increases. The thrust coefficient (rather than the thrust itself) is able to precisely determine the effects of the nozzle flow separation on overall performance.

1. Introduction

The use of pintle nozzles is a very effective method of changing thrust levels during the operation of a solid motor, particularly when a continuous change in thrust is required. A pintle nozzle is able to control the nozzle throat area based on the pintle's shape and position. By changing the throat area, the magnitude of the thrust and chamber pressure can be easily controlled. In addition, the shape and position of the pintle affect the chamber pressure, which in turn influences the burning rate of the propellant. As such, it is important to understand the performance characteristics of the pintle nozzle comprehensively when considering design parameters [1]. The proper information on the pintle nozzle is, however, very limited. Dumortier numerically investigated the cone-shape pintle to minimize the perturbation of a combustion chamber [2]. Also, Lafond developed the pintle nozzle for divert thruster and applied a hole in pintle to reduce the driving load. Different operating conditions, from closed to open, were analyzed in order to establish the characteristics of the propulsive efficiency and the aerodynamic load on the pintle [3]. A sudden movement of the pintle usually induced the rapid change of flow fields; pressure oscillation in the combustor, shock train and flow separation in the nozzle, and so on [4,5]. The shock train and flow separation due to the pintle position in the nozzle were a highly unsteady phenomena which may cause flow instability and the sliding mesh with interpolation scheme causes flow properties discontinuity in moving block boundary [6]. Precisely capturing the shock wave is important, because the interaction of a shock wave and the turbulent boundary layer significantly influences the entire flow field, especially in the case of a shock strong enough to induce flow separation. The comparison of experimental data allowed for a suitable compression correction turbulence model to be selected for this study [7].

To take into account the effects of the pintle speed and movement, a moving grid technique was applied. Moving grids techniques generally divided into following three methods. (1) Chimera grid method, (2) Layering method, (3) Sliding method (non-conformal grid). Chimera grid method is one example of overlapping grid method. Overlapping grid method is a superposition method that creates grids having no common boundaries so that they don't have any sharing area after independently creating more than two grid systems. Layering method allows adding or removing layers of cells adjacent to a moving boundary. In the sliding method, the non-conformal grids at the interface exist between the two or more sliding zones. The zones will move relative to each other along the mesh interface. In research of the moving grid technique, Auweraert studied in blades of the wind turbines

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[2] Currently ADD.

http://dx.doi.org/10.1016/j.ast.2016.11.022
1270-9638/

Nomenclature

a	propellant coefficient of burn rate
A_t	nozzle throat area
A_b	burning area
$C_{\varepsilon 1}, C_{\varepsilon 2}$	turbulent energy dissipation parameter
E	energy
h	specific enthalpy
κ	heat transfer coefficient, conductivity coefficient
k	turbulent kinetic energy
L	grain length
M	Mach number
M_t	turbulent Mach number
$\dot{m}_b$	mass flow rate of void volume effect
$\dot{m}_{out}$	mass flow rate exiting the nozzle
$\dot{m}_p$	mass flow rate entering the chamber from propellant surface
n	propellant exponent of burn rate
P	static pressure
P_c	chamber pressure
P_k	production of kinetic energy
$\overline{P''d''}$	pressure dilatation
q	heat diffusion
R	specific gas constant
$\dot{r}$	burn rate
t	time
T	static temperature
T_c	chamber temperature
T_{turb}	turbulent time scale
τ	viscous stress
u	velocity
V	volume
x	spatial coordinate
y^+	dimensionless wall distance
$\alpha_1, \alpha_2, \alpha_3$	model constants for compressible correction of k–ε model
δ_{ij}	Kronecker delta
γ	specific heat ratio
ε_c	compressible dissipation
ε_s	dissipation rate
μ	molecular viscosity
μ_t	turbulent viscosity
ρ	density
ρ_p	propellant density
ρ_g	gas density
$\sigma_k, \sigma_\varepsilon$	model constants
τ_{ij}	viscous stress tensor
Λ	damping function

Superscripts

–	time averaging
~	Favre-averaged resolved-scale
$''$	fluctuation associated with mass-weighted mean

using chimera mesh according to the mesh sizes and provided the quality assessment of the results [8]. Heo studied the pintle performance using non-conformal sliding method to assessment for the unsteadiness characteristics of the pintle [7]. Ng et al. predicted the flow in a vessel stirred by a Rushton impeller to compare with the LDA measurements. The prediction employed rotating mesh with conformal grid [9]. Bakker used a conformal sliding mesh method to analyze the unsteady effects of blade turbine for various Reynolds numbers in the laminar regime [10]. Foulquie et al. presents the acoustic pulse problem using the high-order preserving sliding mesh techniques. They proposed the stability solution as the MLS-based (Moving Least Squares approximation [11]) sliding mesh interface [12]. Also, a sliding mesh technique using a high-order discontinuous Galerkin method was proposed by Ferrer [13]. In this study, a layering method with sliding mesh which has conformal grids at the interface is adopted. Using this method, the dynamic effects of the pintle movement are investigated without any discontinuity at moving block boundary. An analysis is carried out on the characteristics of the chamber pressure and thrust depending on the pintle's reciprocating stroke with different pintle speeds. In addition, the thrust variation and thrust coefficient in the separation flow are also investigated.

2. Numerical formulation

2.1. Governing equations and numerical technique

The Favre-averaged governing equation based on the conservation of mass, momentum, and energy for a compressible flow can be written as

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial \overline{\rho}\widetilde{u}_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \overline{\rho}\widetilde{u}_i}{\partial t} + \frac{\partial(\overline{\rho}\widetilde{u}_i\widetilde{u}_j + \overline{p}\delta_{ij})}{\partial x_j} = \frac{\partial(\overline{\tau}_{ij} - \overline{\rho u''_j u''_i})}{\partial x_j} \tag{2}$$

$$\frac{\partial \overline{\rho}\widetilde{E}}{\partial t} + \frac{\partial((\overline{\rho}\widetilde{E} + \overline{p})\widetilde{u}_j)}{\partial x_j} = \frac{\partial(\widetilde{u}_i\overline{\tau}_{ij} - \overline{\rho h'' u''_i})}{\partial x_j} - \frac{\partial \overline{q}_j}{\partial x_j} \tag{3}$$

$$\overline{\tau}_{ij} = \mu\left(\frac{\partial \widetilde{u}_i}{\partial x_j} + \frac{\partial \widetilde{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial \widetilde{u}_k}{\partial x_k}\delta_{ij}\right) \tag{4}$$

$$\overline{q}_j = -\kappa\frac{\partial \overline{T}}{\partial x_j} \tag{5}$$

And equation of state is based on ideal gas assumption.

To account for the important features in the high-speed flow, two models – the compressible dissipation and pressure dilatation model proposed by Sarkar [14] and the low Reynolds number k–ε model [15] – are combined and used in this study. Also, the turbulent kinetic energy and its dissipation rate are calculated from the turbulence transport equation as follows.

Low-Reynolds $k - \varepsilon$ Turbulent Model

$$\frac{\partial \overline{\rho}k}{\partial t} + \frac{\partial(\overline{\rho}\widetilde{u}_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + P_k - \overline{\rho}(\varepsilon_s + \varepsilon_c) + \overline{p''d''} \tag{6}$$

$$\frac{\partial \overline{\rho}\varepsilon_s}{\partial t} + \frac{\partial(\overline{\rho}\widetilde{u}_j\varepsilon_s)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon_s}{\partial x_j}\right) + \frac{(C_{\varepsilon 1}P_k - C_{\varepsilon 2}\overline{\rho}\varepsilon_s)}{T_{turb}} + \Lambda \tag{7}$$

$$\varepsilon_c = \alpha_1 M_t^2 \varepsilon_s \tag{8}$$

$$\overline{p''d''} = -\alpha_2 P_k M_t^2 + \alpha_3\overline{\rho}\varepsilon_s M_t^2 \tag{9}$$

where ε_c and $\overline{P''d''}$ represent the compressible dissipation and pressure dilatation, respectively. The closure coefficients for the compressible corrections are

Sarkar's Model

$$\alpha_1 = 1.0, \quad \alpha_2 = 0.4, \quad \alpha_3 = 0.2, \quad M_t^2 = 2k/c^2 \tag{10}$$