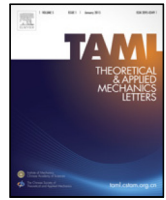




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Letter

Analysis of choked two-phase flows of gas and particle in a C-D nozzle

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HIGHLIGHTS

- Theoretical analysis and numerical simulations were carried out to investigate particle–gas flows in a C-D nozzle.
- Mass flow rate and sound speed of mixture flows were theoretically calculated by homogeneous equilibrium model and compared with numerical results.
- Shock wave structure and particle number density were also obtained to be different at different particle mass loading and operating pressure conditions.

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ABSTRACT

Particle–gas two-phase flows show significantly different behaviors compared to single gas flow through a convergent–divergent nozzle. Non-equilibrium effects, thermal and velocity lag results to the inefficiency of nozzle performance. In the present studies, theoretical analysis and numerical simulations were carried out to investigate particle–gas flows in a C-D nozzle. Homogeneous equilibrium model that no lag in velocity and temperature occurs between particles and gas phase was used to derive mass flow rate and sound speed of multiphase flows. Two-phase flows are regarded as isentropic flows that isentropic relations can be used for homogeneous equilibrium model. Discrete phase model (DPM) where interaction with continuous phase and discrete random walk model were considered was used to calculate particle–gas flows. Particle mass loadings were varied to investigate their effects on choking phenomena of particle–gas flows. Mass flow rate and sound speed of mixture flows were theoretically calculated by homogeneous equilibrium model and compared with numerical results. Shock wave structure and particle number density were also obtained to be different at different particle mass loading and operating pressure conditions.

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Needle-drug delivery devices have been widely used for drug injection in medical fields. Solid drug powders can be directly injected to human bodies without any sharp metal needles and skin injury. Supersonic nozzles are used to accelerate momentum of drug powders. However, it is significantly difficult to control momentum of drug powders due to non-equilibrium effects of powder–gas flows. Particle–gas flows through supersonic nozzle show greatly different behaviors from single gas flow. Solid particles in the exhaust result to inefficiency in expansion process in propulsive nozzle due to the non-equilibrium effects and thermal lags between gas phase and solid particles as well as velocity slip. Interaction between gas phase and particle phase, particle collision and thermal transfer lead to the loss in momentum and

energy of multiphase flows. Therefore, investigations of particle–gas two-phase flows induced by supersonic nozzles have significantly practical meaning in improving performance of aircrafts and needle-free drug delivery devices in aerospace and medical engineering fields.

A theoretical model was derived to predict the maximum mass flow rate of single gas flow and equilibrium two-phase mixture flows through a convergent nozzle by Moody [1]. The maximum mass flow rate was obtained to depend on local slip ratio and stagnation pressure at initial state. Fauske et al. [2,3] theoretically investigated mass flow rate and heat transfer rate of multiphase flows through a convergent nozzle and compared obtained results with previous experimental ones. The new theoretical model contained the most available data to predict reliable heat transfer process instead of using frozen or complete equilibrium mass and heat transfer process. Critical mass flow rate was calculated to

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agree experimental results well. Akmandor and Nagashima [4] investigated vapor–liquid flows through a convergent–divergent nozzle by using equilibrium and non-equilibrium models. Sound speed of mixture was homogeneously calculated. Mass flow rate and sound speed of mixture were obtained under choked and unchoked conditions at throat respectively. Choked mass flow rate of particle–gas flows at nozzle throat was also analytically calculated by using homogeneous and equilibrium model by Wang et al. [5]. Particle–gas flows were regarded as isentropic flows which all isentropic equations can be used. Experimental studies were also carried out to compare with theoretical results.

Rudinger [6,7] carried out theoretical analysis on sound speed and mass flow rate of particle–gas flows. Particle mass loadings and particle volume fractions were investigated to have obvious influence on sound speed of mixture and choked mass flow rate through a convergent–divergent nozzle. Particle velocity and thermodynamics were also considered. Hwang and Chang [8] performed numerical studies on gas–particle flows through a rocket nozzle. Particle Mach number and temperature was obtained and different particle diameter was investigated. Quasi-one-dimensional model was proposed to calculate supersonic particle–gas flows through JPL nozzle by Forde [9]. Shock wave location and structure were observed to be influenced by particle loading ratios and particle diameter. In addition, shock wave strength was strongly determined by particle loading ratios. Particle behaviors were shown to be greatly different in supersonic and subsonic flows based on Henderson's studies [10]. He proposed different drag force models for calculating subsonic and supersonic particle–gas flows respectively.

In this paper, theoretical and numerical studies were carried out to investigate choked phenomena and sound speed of particle–gas flows. Mass flow rate and sound speed of particle–gas flows were theoretically calculated by homogeneous and equilibrium model and compared with numerical results at different nozzle pressure ratios (NPRs) and particle mass loadings (PMLs). Particle concentration and particle number density (PND) were also considered.

There is no slip in velocity and temperature between particle phase and gas phase, and particle–gas flows can be regarded as isentropic flows, which are described by equilibrium model [4,5]. Particle–gas flows are choked at nozzle throat as operating pressure ratio is high enough. Mass flow rate is an important parameter to indicate choked characteristics of particle–gas flows. Particle mass loading x is the main factor that affects mass flow rate of particle–gas flows. It is defined as:

$$x = \frac{\dot{m}_p}{\dot{m}_p + \dot{m}_g}. \quad (1)$$

As particle mass loading increases, particle volume fraction ε also increases. Based on different particle volume fraction, particle–gas flows can be described as dilute and dense flows. Particle volume fraction ε which is related to particle mass loading, particle and gas density is calculated by Eq. (2).

$$\varepsilon = \frac{\frac{x}{1-x} \frac{\rho_g}{\rho_p}}{1 + \frac{x}{1-x} \frac{\rho_g}{\rho_p}}. \quad (2)$$

Specific heat ratio of mixture γ_e and a new two-phase constant parameter R_e are different from properties of single gas phase, which are calculated based on Eqs. (3) and (4).

$$\gamma_e = \gamma_g \frac{1 + \frac{x}{1-x} \frac{c_{pg}}{c_{pg}}}{1 + \gamma_g \frac{x}{1-x} \frac{c_{pg}}{c_{pg}}}, \quad (3)$$

$$R_e = \frac{1 - \varepsilon}{1 - x} R_g. \quad (4)$$

As particle–gas flows are choked, the isentropic relation between static and total pressure at critical conditions can be used

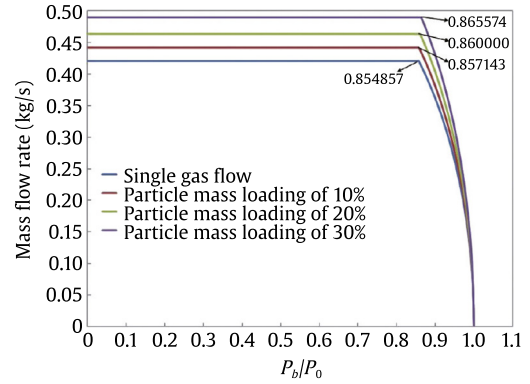


Fig. 1. Comparison on theoretical mass flow rate at different PMLs.

as shown in Eq. (5).

$$\frac{p^*}{p_0} = \left(\frac{\gamma_e + 1}{2} \right)^{\frac{-\gamma_e}{\gamma_e - 1}}. \quad (5)$$

The Area–Mach number relation is also considered as:

$$\frac{A}{A^*} = \frac{1}{M} \sqrt{\left[\frac{2}{\gamma_e + 1} \left(1 + \frac{\gamma_e - 1}{2} M^2 \right) \right]^{\frac{\gamma_e + 1}{\gamma_e - 1}}}. \quad (6)$$

As $P_t \leq P^*$, particle–gas flows are not choked at nozzle throat and mass flow rate of two-phase flows at nozzle throat is calculated as shown in Eq. (7).

$$\dot{m} = \frac{P_0 A}{\sqrt{R_e T_0}} \sqrt{\frac{2\gamma_e}{\gamma_e + 1} \left[\left(\frac{P_0}{P_t} \right)^{\frac{-2}{\gamma_e}} - \left(\frac{P_0}{P_t} \right)^{\frac{-\gamma_e + 1}{\gamma_e}} \right]}. \quad (7)$$

As $P_t > P^*$, particle–gas flows are choked at nozzle throat and mass flow rate of two-phase flows at nozzle throat keeps constant if operating conditions at upstream is fixed. The change of downstream flow conditions has no effect on upstream flow of nozzle throat. The mass flow rate of particle–gas flows is calculated as a constant based on Eq. (8)

$$\dot{m} = \frac{P_0 A}{\sqrt{R_e T_0}} \sqrt{\gamma_e} \left(\frac{2}{\gamma_e + 1} \right)^{\frac{\gamma_e + 1}{2(\gamma_e - 1)}}. \quad (8)$$

Mass flow rate of particle–gas flows at nozzle throat was calculated at different particle mass loading and compared with mass flow rate of single gas flow as shown in Fig. 1. Mass flow rate of two-phase flows was higher than that for single gas flow due to the presence of particles. As particle mass loading gradually increases, mass flow rate of two-phase flows also increases. Based on choked nozzle pressure ratios at different particle mass loading, particle–gas flows were much easier to be choked than single gas flow and particle–gas flows at higher particle mass loading were observed to be more easily choked.

The equilibrium sound speed of two-phase flows is another important parameter to indicate choking phenomena of gas–particle flows. Based on foundations of gas dynamics, for single gas flow, sound speed of gas phase is calculated by following equation.

$$a_g^2 = R \gamma_g T. \quad (9)$$

For gas–particle isentropic flows, sound speed of mixture is obtained by using Eq. (10) which is derived by Rudinger [6].

$$\left(\frac{a_m}{a_g} \right)^2 = \frac{\gamma_e}{\gamma_g \left(1 + \frac{x}{1-x} \right) (1 - \varepsilon)^2}. \quad (10)$$

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