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CFD modeling of particle behavior in supersonic flows with strong swirls for gas separation

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ABSTRACT

The supersonic separator is a novel technique to remove the condensable components from gas mixtures. But the particle behavior is not well understood in this complex supersonic flow. The Discrete Particle Method was used here to study the particle motion in supersonic flows with a strong swirl. The results showed that the gas flow was accelerated to supersonic velocity, and created the low pressure and temperature conditions for gas removal. Most of the particles collided with the walls or entered into the liquid-collection space directly, while only a few particles escaped together with the gas flow from the dry gas outlet. The separation efficiency reached over 80%, when the droplet diameter was more than 1.5 μm. The optimum length of the cyclonic separation section was approximate 16–20 times of the nozzle throat diameter to obtain higher collection efficiency for the supersonic separator with a delta wing.

1. Introduction

The supersonic swirling separation is a new technology for the gas processing. Its main structure includes a Laval nozzle, a vortex generator, a diffuser, and so on [1–3]. This unique technique possesses a simple and compact tubular structure without any moving parts to ensure a high reliability. It also does not use any chemicals to reduce the emissions and protect the environment. Therefore, the supersonic separator conforms to the development requirements of the gas processing including the safety, environmental protection and energy saving.

The current research on the supersonic separation was mainly focused on the single phase gas flow with and without a swirl, and the condensation flow of water vapor. In the single gas flow, Jassim et al. [4,5] used the numerical simulation method to study the natural gas behavior in a high pressure supersonic nozzle. Karimi et al. [6] discussed the effect of the flow parameters on the single phase gas flow field in a Laval nozzle by the computational model linked to MATLAB and HYSYS package. Wen et al. studied the effect of the real gas model on the flow behavior and mass flow rate through a supersonic separator [7,8]. The swirling flow was not considered in the above mentioned studies. Malyshkina [9,10] numerically studied the single phase gas flow with a swirling flow in a supersonic separator with an Euler two-dimensional model, and analyzed the influence of different Mach number and temperature on the pressure recovery characteristic. The artificial neural network was employed by Vaziri et al. [11] to optimize the structure of a supersonic separator and obtained the effect of the inlet parameters on gas phase flow field. In our previous studies, the single phase gas flow was discussed in detail through a supersonic separator with and without a swirl [12–14].

In the condensation flow of water vapor in a supersonic separator, Alfyorov et al. employed the CFX software to study the formation process of a liquid droplet in a supersonic flow, and analyzed the distribution of the liquid droplets along radial and axial sections of the nozzle [15]. Schooshtari and Shahsavand [16] developed a new theoretical approach based on the mass transfer rates to calculate the liquid droplet growth in supersonic conditions for binary mixtures, and they [17] also analyzed the condensation flow of the multi-components gas mixtures with the nucleation theory. Castier [18] also carried out the numerical simulations of natural gas flow within a Laval nozzle both in consideration of the single phase flow and the phase equilibrium. But the swirl was not included in the numerical work as well. Ma et al. [19] established an Euler two fluid flow model to investigate the spontaneous condensation flow of water vapor. Then, they [20] studied the effect of the location, where the external particles were added, on the droplet condensation by using the heterogeneous

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Nomenclature

C_D	drag coefficient	q_j	heat flux
d_{ij}	deformation tensor	Re	relative Reynolds number
d_l	particle diameter	t	time
E	total energy	u_g	gas velocity
F	gas-particle interaction force	u_l	particle velocity
F_a	additional force	V_l	particle volume
F_d	drag force	δ_{ij}	Kronecker delta
F_s	Saffman's lift force	μ_g	gas viscosity
g	acceleration of gravity	ν_g	gas dynamic viscosity
K_s	constant	ρ_g	gas density
l	liquid phase	ρ_l	particle density
m_l	particle mass	$\tau = ij$	viscous stress
p	pressure		

nucleation theory. They proposed that it was reasonable to add external nuclei to increase the size of the condensed droplets.

The above mentioned studies focused on the single phase gas flow or condensation flow in a supersonic separator, and very little attention was paid to the particle flows. Haghighi et al. [21] addressed the recent developments of the supersonic separation technique, and pointed out that the liquid flow was an important issue for this novel gas separation technology and further study would improve the separation performance significantly. Liu et al. tried to predict the particle flows in a supersonic separator using the Discrete Particle Method [22]. However, the particle diameter used in their simulation was assumed from 10 μm to 50 μm, which was extremely exaggerated from the typical particle size of $1.0 * 10^{-7}$–$2.0 * 10^{-6}$ m (0.1–2 μm) [23] in the supersonic separator.

In this paper, we employ the Discrete Particle Method to predict the particle flows at the supersonic speed. The separation efficiency is evaluated at various particle diameters in our designed supersonic separator. The effect of cyclonic separation section on collection efficiency is predicted using the Computational Fluid Dynamics (CFD) technology.

2. Mathematical model

2.1. Gas phase flow

The mass, momentum and energy conservation equations are adopted for the numerical calculation of the gas phase as follows:

$$\frac{\partial}{\partial x_i}(\rho_g u_{gi}) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho_g u_{gi} u_{gj} + p\delta_{ij} - \tau_{ji}) = 0 \tag{2}$$

$$\frac{\partial}{\partial x_j}\left(\rho_g u_{gj} E + u_{gj} p + q_j - u_i \tau_{ij}\right) = 0 \tag{3}$$

2.2. Particle flow

A particle motion in a supersonic separator is described as translation and rotation, and the governing equation for a discrete liquid particle is:

$$m_l \frac{du_l}{dt} = m_l g - \rho_g g V_l + F \tag{4}$$

In a supersonic separator, the centrifugal force plays a much more significant role than the gravity force, therefore, the gravity force can be neglected. The gas-particle interaction force F includes the drag force F_d and the additional force F_a. That is:

$$\boldsymbol{F} = \boldsymbol{F}_D + \boldsymbol{F}_a \tag{5}$$

The F_d is given as:

$$\boldsymbol{F}_D = \frac{18\mu_g}{\rho_l d_l^2} \frac{C_D R_e}{24} (\boldsymbol{u}_g - \boldsymbol{u}_l) \tag{6}$$

where ρ_l and d_l are the density and diameter of the liquid particle, respectively. u_g is the fluid phase velocity, μ_g is the molecular viscosity of the fluid, C_D is the drag coefficient. Re is the relative Reynolds number:

$$Re = \frac{\rho_g d_l |u_l - u_g|}{\mu_g} \tag{7}$$

The strong shear and swirling flow exist in a supersonic separator, and correspondingly the Saffman's lift force significantly affects the particle motion. Hence, the Saffman's lift force is involved in our simulation as the additional force to predict the droplet behavior. It can be described as:

$$\boldsymbol{F}_S = \frac{2K_s\sqrt{\nu_g}\rho_g d_{ij}}{\rho_l d_l (d_{lk} d_{kl})^{0.25}} (\boldsymbol{u}_g - \boldsymbol{u}_l) \tag{8}$$

where $\boldsymbol{F_S}$ is the Saffman's lift force [24], $K_s = 2.594$, ν_g is the gas dynamic viscosity, d_{ij} is the deformation tensor.

3. Numerical method

3.1. Geometry and mesh strategy

The supersonic separator structure used in this simulation case includes a wet gas inlet, a Laval nozzle, a swirling device, a straight tube, a cyclonic separation part, a diffuser, a dry gas exit, and a liquid exit, as shown in Fig. 1. The key sizes for the supersonic separator include the nozzle throat and exit diameters. The nozzle throat area determines the mass flow rate, while the expansion characteristics depend on the nozzle outlet area. The diameters at the nozzle throat and outlet are 12.40 mm and 16.80 mm, respectively. The entrance (nozzle inlet) and dry gas exit (diffuser outlet) diameters of the supersonic separator are 80.40 mm and 40.00 mm, respectively. A straight tube is used to form a stable flow located at the downstream of the Laval nozzle. The delta wing is designed as a swirling device, which is installed between the straight tube and cyclonic separation part.