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Effect of delta wing on the particle flow in a novel gas supersonic separator

Chuang Wen [a,b], Yan Yang [a,*], Jens Honore Walther [b,c], Kar Mun Pang [b], Yuqing Feng [d]

[a] Jiangsu Key Laboratory of Oil-Gas Storage and Transportation Technology, School of Petroleum Engineering, Changzhou University, Changzhou 213016, China
[b] Section of Fluid Mechanics, Coastal and Maritime Engineering, Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, 2800 Kgs. Lyngby, Denmark
[c] Chair of Computational Science, ETH Zürich, Clausiusstrasse 33 ETH-Zentrum, CLT F 11, CH-8092 Zürich, Switzerland
[d] CSIRO Mineral Resources, Clayton, VIC 3169, Australia

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ABSTRACT

The present work presents numerical simulations of the complex particle motion in a supersonic separator with a delta wing located in the supersonic flow. The effect of the delta wing on the strong swirling flow is analysed using the Discrete Particle Method. The results show that the delta wings re-compress the upstream flow and the gas Mach number decreases correspondingly. However, the Mach number does not vary significantly from the small, medium and large delta wing configurations. The small delta wing generates a swirl near its surface, but has minor influences on the flow above it. On the contrary, the use of the large delta wing produces a strong swirling flow in the whole downstream region. For the large delta wing, the collection efficiency reaches 70% with 2 μm particles, indicating a good separation performance of the proposed supersonic separator.

1. Introduction

The separation of the water vapor and heavy hydrocarbons is an essential procedure in natural gas processing. The supersonic separation is a newly designed device for this purpose by using the cryogenic effect due to the gas expansion in a supersonic flow [1–4]. The supersonic separator has several advantages compared to the conventional gas separation technologies. For example, it is a relatively compact device without rotating parts. It does not need chemicals to prevent the formation of the hydrate, which can eliminate pollution of the environment.

A number of studies have been focused on this novel supersonic separation technology. In particular, computational fluid dynamics (CFD) simulations were carried out to investigate the complex flow under supersonic conditions. Studies of single phase flow include the work of Jassim et al. [5,6] and Karimi and Abdi [7], who considered the flow of natural gas through a Laval nozzle under a high pressure condition. The effect of the geometrical structure and operating parameters on natural gas was analysed in detail but without considering a swirling flow. On the other hand, Malyshkina [8,9] took account of a strong swirl in the numerical simulation of the natural gas field in a supersonic separator, in which a swirling device was installed in the upstream of a Laval nozzle. Yang et al. [10–12] performed simulations to study a single phase flow in supersonic separators with and without swirls.

Some efforts have also been made to study the condensation process of water vapor in a supersonic separator. Based on the ideal gas assumption, Ma et al. [13] developed a two-fluid model to simulate the condensation flow without a swirl in a Laval nozzle. Their CFD model was validated using the experimental nozzle data from the literature. The same mathematical model was subsequently used to calculate the nucleation and condensation processes in a supersonic separator with a strong swirl flow [14]. Shooshtari and Shahsavand [15,16] numerically studied the nucleation and particle growth behavior in a supersonic nozzle without considering a swirling flow. Castier [17] carried out numerical simulations of natural gas flow within a Laval nozzle both in consideration of the single phase flow and the phase equilibrium. However, the swirling flow was not included in the numerical work.

It is noteworthy that the above mentioned studies focused on the single phase flow or condensation flow in a supersonic separator, but very little attention has been paid to the particle flow. In this paper, we focus on the particle flow in the supersonic separator with the swirling device located at the downstream of the Laval nozzle. The Discrete Particle Method (DPM) is employed to study the particle behavior. The effects of the delta wing height on the particle flow are then investigated in our newly designed supersonic separator.

2. Supersonic separators

This paper considers a supersonic separator using a delta wing. The primary structure includes a Laval nozzle, a delta wing, a cyclonic separation part, and a diffuser. These are illustrated in Fig. 1. The delta wing

* Corresponding author.
E-mail address: yyan-petroleum@cczu.edu.cn (Y. Yang).

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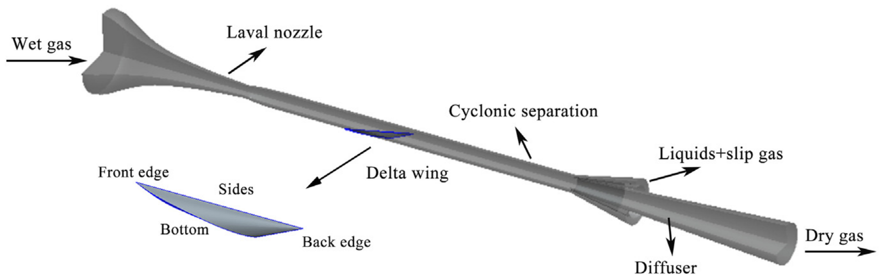

Fig. 1. Schematic diagram of the supersonic separator with a delta wing.

is installed at the downstream of the Laval nozzle. The cyclonic separation part is a straight tube, where there is a strong swirling flow to separate the particles from the gas liquid mixtures. One of the major components is the Laval nozzle that is specifically designed to form a stable supersonic flow. The converging part of the nozzle is described by the cubic polynomia in Eq. (1), while the Foelsch's analytical method is used to curve the diverging contour [18].

$$\begin{cases} \frac{D(x)-D_{cr}}{D_1-D_{cr}} = 1-\frac{1}{0.45^2}\left(\frac{x}{L}\right)^3 & \left(\frac{x}{L}\leq 0.45\right) \\ \frac{D(x)-D_{cr}}{D_1-D_{cr}} = \frac{1}{(1-0.45)^2}\left(1-\frac{x}{L}\right)^3 & \left(\frac{x}{L}>0.45\right) \end{cases} \tag{1}$$

Here D_1 and D_{cr} are the inlet and throat diameters, respectively. x is the distance from the nozzle inlet. $D(x)$ is the diameter at x. Lastly, L represents the length of the convergent region.

The swirling device is another key part for the supersonic separator located at the downstream of the Laval nozzle. Several requirements have to be fulfilled by the design. Firstly, the geometric volume should be small to reduce its occupied space in the straight pipe. Secondly, the front edge of the delta wing (Fig. 1) needs to be sufficiently small to prevent the formation of shock waves, which can lead to the changes of the flow from supersonic to subsonic. Thirdly, the sides (Fig. 1) are designed to have smooth surface for reducing the flow resistance. Lastly, the back edge should be high and curved to generate the swirling flow for the removal of the particles. The delta wing is designed according to the above mentioned requirements. In addition to these, the wing bottom (Fig. 1) is designed such that the cylindrical surface transitions smoothly to the pipe wall. It also ensures that the front edge starts from the surface. The profiles are paraboloid and smoothly transit to the back edge. Three different wings are used to evaluate the effects on the particle flow, including the small, medium and large wings with different bottom lengths.

The length of the entire supersonic separator is 709.5 mm. The critical diameter at nozzle throat is 12.4 mm. The diameters of the nozzle inlet and outlet are 80.0 mm and 16.8 mm, respectively. The detailed dimensions of the designed supersonic separator are shown in Table 1.

Table 1
Dimensions of the designed supersonic separator.

Parameter	Value (mm)
Nozzle inlet diameter	80.0
Nozzle throat diameter	12.4
Nozzle outlet diameter	16.8
Diffuser outlet diameter	40.0
Nozzle converging length	149.0
Nozzle diverging length	37.1
Straight tube length	159.9
Cyclonic separation length	141.7
Diffuser length	221.8

3. Mathematical model

3.1. Continuous phase

The conservation equations describing the natural gas flow in a supersonic separator involve the continuity, momentum and energy equations. Their general forms can be described as:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{2}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho \boldsymbol{u}) + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) + \boldsymbol{F} \tag{3}$$

where ρ, $\boldsymbol{u}$ and p are the density, velocity and, pressure respectively. $\boldsymbol{F}$ is the external body forces. $\bar{\bar{\tau}}$ is the stress tensor and given by

$$\bar{\bar{\tau}} = \mu\left[\left(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T\right) - \frac{2}{3}\nabla \cdot \left(\boldsymbol{u}\bar{\bar{I}}\right)\right] + \nabla \cdot \left(-\rho \overline{\boldsymbol{u}'\boldsymbol{u}'}\right) \tag{4}$$

where $\bar{\bar{I}}$ is the unit tensor, $\boldsymbol{u}'$ is the fluctuating velocity component.

Energy equation:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho \boldsymbol{u} E) = -p\nabla \cdot \boldsymbol{u} - \nabla \cdot q + \nabla \cdot \left(\boldsymbol{u}\bar{\bar{\tau}}\right) \tag{5}$$

where E is the total energy; q is the heat flux.

The Redlich-Kwong, Soave-Redlich-Kwong, and Peng-Robinson equations of state are widely used in oil and gas industry. The advantage of these equations is that they often accurately represent the relation between temperature, pressure, and phase compositions in binary and multicomponent systems. These real gas equations of state predicted almost similar results [19,20]. Therefore, the Redlich-Kwong [21] equation of state model is adopted to calculate the real gas flow in high pressure and low temperature in a supersonic separator as follows:

$$p = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T}V_m(V_m + b)} \tag{6}$$

$$a = \frac{0.4275R^2T_c^{2.5}}{p_c} \tag{7}$$

$$b = \frac{0.08664RT_c}{p_c} \tag{8}$$

where V_m and T are the molar volume and temperature, respectively. R is the gas constant. The coefficients a and b are given for the equation of state as functions of the critical temperature, T_c and critical pressure, P_c.

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