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Effect of swirling device on flow behavior in a supersonic separator for natural gas dehydration

Chuang Wen [a,b], Anqi Li [a], Jens Honore Walther [b,c], Yan Yang [a,*]

[a] Jiangsu Key Laboratory of Oil–Gas Storage and Transportation Technology, 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

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ABSTRACT

The supersonic separator is a revolutionary device to remove the condensable components from gas mixtures. One of the key issues for this novel technology is the complex supersonic swirling flow that is not well understood. A swirling device composed of an ellipsoid and several helical blades is designed for an annular supersonic separator. The supersonic swirling separation flow of natural gas is calculated using the Reynolds Stress model. The results show that the viscous heating and strong swirling flow cause the adverse pressure in the annular channel, which may negatively affect the separation performance. When the swirling flow passes through the annular nozzle, it will damage the expansion characteristics of the annular nozzle. The blade angles and numbers are both optimized by evaluating the swirling and expansion effects for the supersonic separation.

1. Introduction

Natural gas usually contains a certain amount of water vapor when it is extracted from the underground. When the gas reaches the wellhead, the water vapor in natural gas will condense into the liquid water as a result of the reduction in temperature, which causes a range of hazards to the pipeline for natural gas storage and transportation. For example, it may result in the formation of the hydrates that may block the pipelines. The liquid water may also react with the acid gas, namely, carbon dioxide or hydrogen sulfide, to aggravate the corrosion problem. Therefore, the gas dehydration is an important part in natural gas processing treatment.

At present, the conventional techniques for natural gas dehydration mainly include the refrigeration, adsorption [1], absorption [2,3], membrane separation [4,5]. The supersonic swirling separation is a technical innovation in the field of natural gas dehydration [6,7]. In a supersonic separator, natural gas is accelerated to a supersonic velocity using the influence of a Laval nozzle, and correspondingly forms a low pressure and temperature condition, which results in the condensation of the water vapor and heavy hydrocarbon components. The swirling device generates a larger centrifugal force that will eject the condensed droplets onto the walls, which will be discharged after they enter into the collection space. The dry gas resides in the center of the tube and flows out from the diffuser, in which the gas speed reduces to a subsonic as a result of the shock wave.

Jassim et al. [8,9] studied the supersonic flow characteristics of natural gas in a Laval nozzle under high pressure using computational fluid dynamics (CFD) simulations, focusing on the effect of the nozzle structure on natural gas dynamic parameters. The influence of the operating parameters on the high speed flow characteristics of natural gas through a Laval nozzle was mathematically investigated by Karimi and Abdi [10]. Malyshkina [11,12] took account of a strong swirl in the numerical simulation of a single gas field in a supersonic separator. Yang et al. [13,14] performed detailed CFD simulations to study the pressure recovery characteristics and real gas effects based on a single gas flow without considering a swirl. Vaziri & Shahsavand [15] optimized the axial, radial and circumferential components of the inlet velocity were optimized by evaluating the swirl strength and centrifugal acceleration with the assumption of a single gas flow in a supersonic separator. The results showed that the increasing pressure and temperature decreased the swirl number and centrifugal acceleration. Ma et al. [16] developed a two-fluid model to simulate the condensation flow in a converging-diverging nozzle based on the

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

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Nomenclature

a	centrifugal acceleration	S	swirl strength
a_c	critical velocity	S_k	source term
$C_{\varepsilon 1}$	constant	S_r	source term
$C_{\varepsilon 2}$	constant	S_ε	source term
$C_{\varepsilon 3}$	constant	t	time
$D_{L,ij}$	molecular diffusion	u	velocity
E	total energy	v_t	tangential velocity
F	external body forces	δ_{ij}	Kronecker delta
F_{ij}	production by system rotation	ε	turbulent dissipation rate
g	acceleration of gravity	ε_{ij}	turbulent dissipation
G_{ij}	buoyancy production	μ	gas viscosity
$\bar{\bar{I}}$	unit tensor	μ_t	turbulent viscosity
k	turbulent kinetic energy	ρ	gas density
M_t	turbulent Mach number	σ_k	constant
p	pressure	σ_ε	constant
P_{ij}	stress production	$\bar{\bar{\tau}}$	stress tensor
q	heat flux	ϕ_{ij}	pressure strain
r	radius		

ideal gas assumption. The CFD model was validated with experimental data. The mathematical model was used to calculate the nucleation and condensation process in a supersonic separator with a strong swirling flow [17]. Numerical simulations have been conducted on the condensation processes of the water vapor under the supersonic conditions by Shooshtari and Shahsavand [18,19]. The effect of the nozzle geometry on the condensing parameters was analyzed with one-dimensional assumption. Castier [20] also carried out some numerical simulations of natural gas flow within a Laval nozzle both in consideration of the single flow and the phase equilibrium. Haghighi et al. [21] addressed the recent developments of the supersonic separation technique, and pointed out that the swirl generation device was an important part of the design of these separators and further research could potentially increase the knowledge base to improve the swirl generation effectiveness significantly.

One of the complex issues for the supersonic separation technology is to employ the centrifugal force to remove the condensed droplets from the gas-liquid mixtures. Therefore, it is necessary to further study the swirling characteristic of natural gas under supersonic flow conditions. In this paper, a swirling device is newly designed and installed in the upstream of the converging part of a Laval nozzle. The swirling characteristic of the natural gas flow is analyzed in detail using CFD simulations, while the effect of the structure of the swirling device on the swirling flow is also discussed in the newly designed supersonic swirling separator.

2. Supersonic separators

For a supersonic separator, there are two different methods to design and install the swirling device. One is that the swirling device is designed as a delta wing and installed after the nozzle exit. The other is that a set of helical blades is designed as the swirling device and located in the upstream of the nozzle entrance. For the first method, the swirling flow is generated in the supersonic velocity, which causes some complex shock waves and increases the flow resistance. Consequently, the second approach is employed here to design a new swirling device for our supersonic separator.

In this kind of supersonic separator, on one hand, the existence of the swirling flow may damage the expansion effect of the Laval nozzle. On the other hand, the swirling device also produces some resistance when natural gas flows through it. It means that we not only enable the swirling device to produce a large centrifugal field to separate the water and heavy hydrocarbons, but also need to control the swirling flow to prevent the damage of the expansion characteristics of the Laval nozzle. Depending on this requirement, the swirling device is designed as a set of helical blades located on the surface of an ellipsoid body, as shown in Fig. 1. The whole length of the designed supersonic separator is 1140.50 mm, involving the nozzle converging part of 149.00 mm, the diverging part of 306.60 mm, and the diffuser section of 384.90 mm. The diameters for the separator inlet and outlet are 80.00 mm and 40.00 mm, respectively. The diameters of the outer wall and inner body at

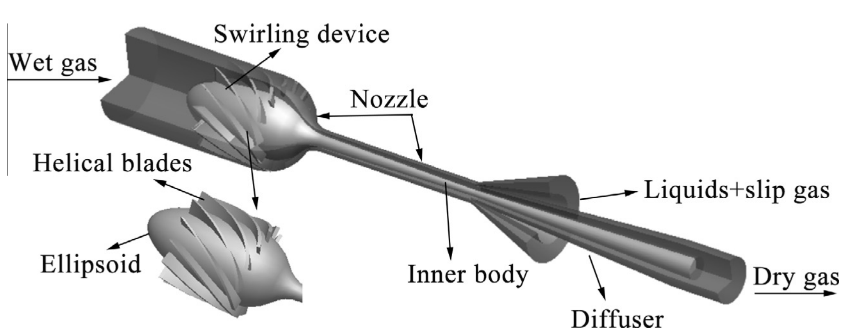

Fig. 1. Structure of a supersonic separator and swirling device.