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Theoretical and numerical analysis on pressure recovery of supersonic separators for natural gas dehydration

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HIGHLIGHTS

- Theoretical formula of maximum pressure recovery coefficient (MPRC) was deducted.
- The MPRC depended on the gas adiabatic exponent and Mach number.
- A higher gas adiabatic exponent induced a larger MPRC.
- The MPRC declined with the increase of Mach number in the upstream of a shock wave.

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ABSTRACT

The supersonic separation is a novel technology in the natural gas dehydration for its compact design and fewer emissions. The other fascinating advantage is that the diffuser can convert kinetic energy into pressure energy to improve the energy efficiency. The mechanism of the pressure recovery is not well understood for the various flow conditions in supersonic velocities. The maximum pressure recovery coefficient (PRC) was estimated in theory and a theoretical equation was obtained with the ideal gas assumption. The theoretical results indicated that the PRC depended on the gas adiabatic exponent and Mach number in the upstream of the shock wave. A computational fluid dynamics model was developed to evaluate the gas dynamic parameters with various Mach numbers and their effects on the PRC. We found that a higher adiabatic exponent induced a larger PRC when the gas Mach number is more than 1.3. The PRC declined with the increase of the Mach number in the upstream of the shock wave both in the theoretical and numerical predictions. The numerical results are smaller than the ideal data with the maximum error of about 8.69% in the whole computed gas Mach number from 1.15 to 1.87. These results have suggested that the derived theoretical equation can be employed to estimate the PRC in the supersonic separation process to improve the design efficiency.

1. Introduction

The natural gas is usually saturated with the water vapor when it is exploited from the ground in high pressure and temperatures. When the pressure and temperature decline, the phase transition occurs and water vapor condenses and forms free water. The presence of water vapor and/or free water can cause a series of problems in natural gas processing, transportation and storage [1]. Firstly, it directly declines the natural gas heating value and its fuel efficiency. Secondly, the condensed water in the pipelines decreases the effective area, resulting in the reduction of the transportation capacity. Thirdly, it also can aggravate the corrosion combined with sour gases, such as carbon dioxide and hydrogen sulfide. The most serious problem is that the condensed water can induce the formation of hydrate and consequently lead to blocking the pipelines and relevant equipments. Therefore, it is important to assure that the water vapor is removed in natural gas processing, transportation and storage.

Currently, some conventional methods have been used for natural gas dehydration, involving absorption, adsorption, refrigeration and membranes [2]. Absorption is usually performed by using liquid desiccants, and the most common working medium for dehydration is triethylene glycol (TEG) [3,4]. Absorption processing is carried out with countercurrent flows of wet natural gas and triethylene glycol. The adsorption dehydration method for water vapor is performed by a solid desiccant including molecular sieve, silica gel, alumina and so on [5,6]. In this method, the

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Nomenclature

C	turbulence constant (–)
C_μ	turbulence constant (–)
E	total energy (J)
I	turbulence intensity (–)
k	turbulent kinetic energy ($m^2\ s^{-2}$)
l	turbulence length scale (m)
M_a	mach number (–)
p	static pressure ($N\ m^{-2}$)
q	heat flux ($W\ m^{-2}$)
Re	Reynolds number (–)
S	source term (–)
t	time (s)
T	temperature (K)
u	velocity (ms^{-1})
x	axis (–)

Greek letters

γ	adiabatic exponent (–)
δ	Kronecker delta (–)
ε	turbulent dissipation rate (–)
μ	viscosity (Pas)
ρ	density ($kg\ m^{-3}$)
σ	constant (–)
τ	viscous stress ($N\ m^{-2}$)
ϕ	pressure strain (–)

Superscripts

$*$	stagnation parameter
$'$	fluctuating
–	mean

Subscripts

0	gas parameter at the inlet of supersonic separator
$d1$	gas parameter in upstream of the shock wave
$d2$	gas parameter in downstream of the shock wave
i, j	x, y axis
t	turbulent

water vapor is usually adsorbed on these working mediums. The refrigeration dehydration is performed by condensing and separating the water vapor from the mixture. The refrigeration process is usually performed by using the Joule–Thompson effect and Turbine expansion [2]. Membranes are used to remove water vapor from natural gas due to their high selectivity for water. It also has been demonstrated that an economical membrane system can be employed for CO_2 capture [7–11]. These methods usually have some disadvantages. For instance, they may need some large equipments, relatively complicated system and consequently huge investments. Also, they may pollute the environment due to the needs for chemicals.

The supersonic separation technique, a novel gas processing, has been introduced to condense and separate water vapor from natural gas [12,13]. As an alternative gas processing system, it overcomes some of the disadvantages of the previously mentioned methods. For example, it enables high reliability and availability because there are no rotating parts. The new separation process prevents the hydrate formation and eliminates the needs for inhibitor and regeneration systems due to the short residence time in the device. The most important is that a diffuser is used to recover the pressure for the purpose of the energy saving.

Alferov et al. [14] investigated the separation characteristics of a supersonic separator compared to the Joule–Thomson valve and turbo-expander for natural gas. Jassim et al. [15,16] studied the effects of real gas and nozzle geometry on high-pressure natural gas flows through the nozzle using the computational fluid dynamics technique. The influences of the vorticity on the performance of the nozzles and shock wave positions were discussed. Karimi and Abdi [17] predicted the effect of the dynamic parameters of the nozzle entrance and exit on the selective dehydration of high-pressure natural gas by using the MATLAB and HYSYS packages. Malyshkina [18,19] obtained the distribution of gas dynamic parameters of natural gas through a supersonic separator with a computational method, and a procedure was developed to predict the separation capability of water vapor and higher hydrocarbons from natural gas by using a supersonic separator determined by the initial parameters.

Zaporozhets et al. [20] introduced an expander–compressor unit namely the thermal gas-dynamic separator. In essence, it is a supersonic separator as it consists of a swirler, a nozzle, a separation part and a diffuser. A supersonic separator was compared to a Joule–Thomson valve with TEG and demonstrated the high economic performance and natural gas liquids recovery of a supersonic separator [21]. The generalized radial basis function artificial neural networks were used to optimize the geometry of a supersonic separator [22]. Rajaee Shooshtari and Shahsavand developed a new theoretical approach based on mass transfer rates to calculate the liquid droplet growth in supersonic conditions for binary mixtures [23]. In our preliminary studies, a central body was incorporated in a supersonic separator with a swirling device composed of vanes and an ellipsoid [24]. The effects of swirls on natural gas flow in supersonic separators were computationally simulated with the Reynolds stress model [25]. The particle separation characteristic in a supersonic separator was calculated using the discrete particle method [26].

The capability of the pressure recovery is one of the advantages of the supersonic separation technique, and also is a substantial difference from other separation techniques. But there is little attention on pressure recovery characteristics as mentioned above. This study focuses on the prediction of PRC of the supersonic separator. The theoretical equation of PRC will be derived with the assumption that the fluid follows the ideal gas law. Then the computational fluid dynamics technique will be employed to predict the real PRC with Redlich–Kwong real gas model.

2. Mathematical model

2.1. Governing equations

In a supersonic separator, the natural gas is compressible and forms a supersonic flow. The fluid flow characteristics in the separator can be depicted by the partial differential equations, including mass equation (continuity equation), momentum equation, and energy equation, which are the basis for the calculation and simulation. Without considering a condensation flow, a gas phase is simulated as a steady state, as described in Eqs. (1)–(3).

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$