Fuel Processing Technology 156 (2017) 265–270

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Optimization of static vanes in a supersonic separator for gas purification

Yan Yang, Anqi Li, Chuang Wen *

School of Petroleum Engineering, Changzhou University, Changzhou 213016, China

ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 7 September 2016
Accepted 10 September 2016
Available online 21 September 2016

Keywords:
Supersonic flow
Static vane
Swirl
Purification

ABSTRACT

In the present work, a set of static vanes are employed as the swirling flow generator in the supersonic separator for gas purification application. The computational fluid dynamics modeling is developed to optimize the vane structures. The numerical results show that the swirling flow is strengthened in the diverging part of the Laval nozzle due to the decreasing radius of the inner body along the flow direction. The expansion characteristic and swirling separation performance are opposing for the supersonic separator. It means that strengthening the swirling flow is bound to weaken expansion effect, and vice versa. The swirl angle, height and number of the static vane are optimized using the numerical model taking into consideration the balance between the expansion characteristic and swirling separation performance. The optimization results indicate that 45°–60° swirl angle, 0.125–0.3 dimensionless height and 8–16 vanes are reasonable for gas purification using the supersonic separator.

1. Introduction

The gas purification is one of the key parts for the gas industry. Currently, the conventional technology for the gas purification includes the cryogenic cooling, absorption, adsorption, and membranes. The principle of cryogenic cooling for gas separation is that the content of the water vapor or other condensable components declines with the decrease of the gas temperature [1]. There are various methods to be used for the purpose of the gas cryogenic cooling, mainly including direct cooling, pressurized cooling, expansion refrigeration and vapor compression refrigeration. Applications of which kind of cooling methods to be used depend on the gas temperature, pressure and the technological requirements.

The absorption approach works on the theory that the various components of gases have a different solubility in the liquid [2,3]. This processing can contain the chemical reaction in the gas purification. The absorbent is one of the most important parts for the absorption method, which should have the high absorption capacity and thermal stability. It also needs to be easy to regenerate and low cost. So far, the common absorbents used in the gas industry include calcium chloride, ethylene glycol, diethylene glycol, triethylene glycol, and tetraethylene glycol, in which the triethylene glycol is the most widely applied one for the gas absorption.

The adsorption method is a kind of mass transfer phenomena on the solid surface [4]. The gas molecules are adsorbed on the porous solid surface under the influence of the molecular attraction or chemical bonds. It can be the physical or chemical process based on the surface forces, which will achieve a very low concentration. The common solid adsorbents for the gas industry include the activated alumina, silica gel and molecular sieve.

In the membrane separation technology [5,6], the gas component is removed depending on the selective permeation from one side of a membrane barrier to the other side. The concentration gradient is maintained by a high partial pressure of the key components in the gas on one side of the membrane barrier and a low partial pressure on the other side. The most important issue for this advanced process is the membrane material. The ideal membrane material should have the advantages of high permeability and selectivity, good mechanical strength and chemical stability.

Compared to the above mentioned conventional methods, the supersonic separation is a relatively novel technology for the gas purification [7]. The supersonic separator is a compact tube apparatus without rotating parts, which ensures the high stability, low space and weight. This kind of separator is a friendly environmental device because it does not need any chemical to discharge the pollutions.

Jassim et al. [8,9] and Karimi and Abdi [10] employed a Laval nozzle to study the single phase flow behavior of natural gas under high pressures. The effects of the nozzle geometry and operating parameters on the flow structure were analyzed using the computational fluid dynamics (CFD) approach. Yang et al. [11] numerically investigated the effects of the real gas flows on the high pressure natural gas in a supersonic separator by evaluating the cubic real gas models. Wen et al. [12] pointed out that the mass flow rate error reached 16.5% at the inlet condition of 100 atm and 283 K, if the ideal gas model was used to calculate the processing capacity of the supersonic separator. The pressure recovery

* Corresponding author.
E-mail address: chuang.wen@cczu.edu.cn (C. Wen).

http://dx.doi.org/10.1016/j.fuproc.2016.09.006
0378-3820/

coefficient was evaluated both in theoretical and numerical methods by Yang et al. [13]. The swirling flow and the condensation process were both not considered in the above mentioned studies.

Malyshkina [14] numerically studied the single gas flow in a supersonic separator considering a strong swirl. Yang et al. [15] obtained the detailed information of the swirling flow field of the single phase natural gas in the supersonic separator with a delta wing using CFD modeling. Wen et al. [16] optimized the geometry of the diffuser for the supersonic separator based on the single phase flow of high pressure natural gas. These studies focused on the single gas flow with swirls, but did not involve the condensation process in the supersonic flows.

Based on the ideal gas assumption, Ma et al. [17] proposed a two-fluid model to study the condensation process in a converging-diverging nozzle. Malyshkina [18] investigated the effect of the Mach number on the liquid fraction by assuming that the condensation process followed the theoretical relationship of the gas compositions phase changes. It was proposed that the optimization of the Mach number was 1.4–1.8 for a supersonic separator. Shooshtari and Shahsavand [19,20] numerically studied the nucleation and droplet growth behavior in a supersonic nozzle without considering a swirling flow. Castier [21] also carried out numerical simulations of natural gas flow within a Laval nozzle both in consideration of the single flow and the phase equilibrium. However, the swirling flow is not included in these numerical studies as well.

The swirling flow is an essential issue for the gas purification using a supersonic separator. One of the most important works is to improve the swirling characteristic to remove the condensed droplets. In this paper, a set of static vanes are designed to generate an appropriate swirling phase flow for the gas supersonic separation. The CFD modeling is employed to evaluate the effect of the static vanes both on the gas expansion and swirling flow.

2. Mathematical model

2.1. Conservation equations

The steady state flow characteristics in the supersonic separator are governed by the partial differential equations describing conservation of mass, momentum and energy, described as Eqs. (1)–(3).

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

$$\frac{\partial}{\partial x_j}(\rho u_i u_j + p - \tau_{ji}) = 0 \tag{2}$$

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

where ρ, u, p are the gas density, velocity, and pressure, respectively. E is the total energy; q_j is the heat flux. τ_{ij} is the viscous stress, given by

$$\tau_{ij} = \mu\left[\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\frac{\partial u_k}{\partial x_k}\right)\delta_{ij}\right] \tag{4}$$

where μ is an effective viscosity, δ_{ij} is Kronecker delta function.

2.2. Species transport equation

The multi-components natural gas is employed to conduct our simulation cases, and the species transport can be used to model this mixing and transport

$$\frac{\partial}{\partial t}(\rho Y_k) + \nabla \cdot (\rho u Y_k) = -\nabla \cdot J_k \tag{5}$$

where Y_k is the mass fraction of the kth species. J_k is the diffusion flux of the species k, which arises due to gradients of concentration and temperature.

$$J_k = -\left(\rho D_{k,m} + \frac{\mu_t}{Sc_t}\right)\nabla Y_k - D_{T,k}\frac{\nabla T}{T} \tag{6}$$

where $D_{k,m}$ is the mass diffusion coefficient, and $D_{T,k}$ is the thermal diffusion coefficient. Sc_t the turbulent Schmidt number.

2.3. Turbulence model

The Reynolds stress model presents the characteristics of anisotropic turbulence and requires the solution of transport equations for each of the Reynolds stress components as well as for dissipation transport [22]. The Reynolds stress turbulence model is therefore employed to appropriately model turbulent flow with a significant amount of swirl in the supersonic separator. Among the Reynolds stress model, the Linear Pressure-Strain model, proposed by Gibson & Launder [23] and Launder [24], is implemented for our simulations.

2.4. Numerical scheme

In our simulation cases, the finite volume method is adopted to solve the governing equations. The numerical solution of the above equations is achieved with the commercial package ANSYS FLUENT [25]. The SIMPLE algorithm [26] is employed to couple the velocity field and pressure. The second-order upwind scheme is used for an accurate prediction. The pressure boundary conditions are assigned for the inlet and outlet of the supersonic separator. Non-slip and adiabatic boundary conditions are specified for the walls. The convergence criterion is 10^{-6} for the energy equation and 10^{-3} for all other equations. When the total mass error of the inlet/outlet mass flow rates is simultaneously below 1×10^{-4}, the solutions are considered converged.

The quality and density of the grid system are very important for the numerical simulation. The structured and unstructured grids are employed for the supersonic separator in order to obtain the high-quality mesh. The tetrahedral elements are utilized for the vanes and cyclonic separation sections as a result of the complicated geometry. The hexahedral elements are performed for all the other parts of the supersonic separator. The mesh sensitivity is tested to obtain the mesh independent results. Four kinds of mesh cells are carried out including the coarse (278,484), medium (431,847), fine (781,873) and very fine (1,574,773) mesh. The Mach numbers along the nozzle axis are

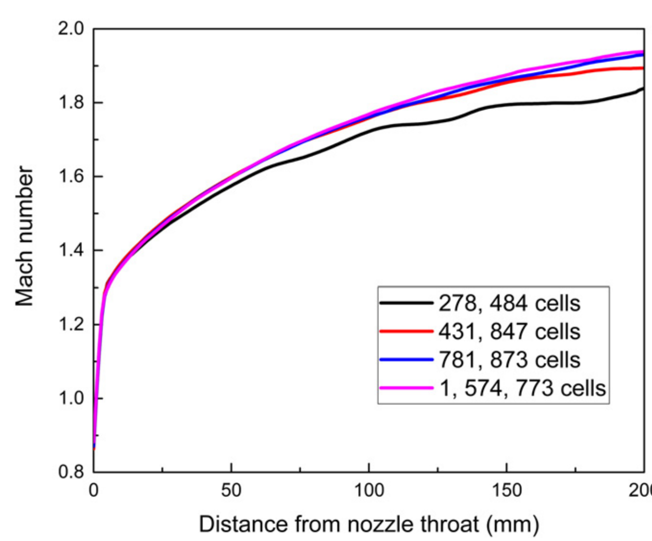

Fig. 1. Mach numbers with different grid cells.