Effect of groove configurations on the swirling intensity of a supersonic separator

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Abstract. In the downstream process of an energy plant, a supersonic separator is a new technology that dehydrates natural gas with pressure and temperature differences using centrifugal force. Compared to other separating devices, a supersonic separator has the advantage of low cost in maintenance and its compatibility. In this study, the effect of the number of grooves on the swirling intensity of a supersonic separator was studied by numerical analysis using RNG turbulence model. Commercial CFD code ANSYS CFX 17.1 was used to determine and display a result of temperature and velocity distribution of the flow characteristics of a supersonic separator. Numerical results showed that the swirling intensity was proportional to the number of groove shapes but decreased when the number of grooves exceeded a certain number. As a result, a supersonic separator including the number of grooves with the highest swirling intensity deduced.

1. Introduction

As the natural gas usage increases due to develop industries, interest in natural gas refining and transport technologies are increasing worldwide. Inside the drilled natural gas is a variety of impurities, such as methane, water, and carbon dioxide. Among them, water causes the corrosion in pipes, pressure drops in natural gas, and reduction of gas transportation efficiency. Therefore, dehydration and purification processes to separate water from natural gas are very important technologies. Many types of dehydrator and purification devices have been developed in the past. A supersonic separator is a device that enables to separate water, and impurities in natural gas by centrifugal force. Low maintenance costs and its compacted size are advantages of supersonic device. In general, a supersonic separator consists of three main sections: a stator section to form a swirl, a nozzle section to induce supersonic flow, and a diffuser section to induce static pressure. Wen et al.[1] performed a numerical analysis using the Discrete Particle Method (DPM), which is considered as a liquid particle as a continuum, and the experimental results with the correlation between the shape of the cyclone part and the nozzle part. It was confirmed that the separation efficiency was 95% or more when the length of the cyclone portion was 10 times longer than the throat length. Liu et al.[2] studied the flow characteristics and separation efficiency of a supersonic separator using the DPM and the Reynolds Stress Model (RSM) for turbulence model and compared it with the experimental data which was performed using wet gas.
Wen et al.[3] compared and analysed the diffusers of the three different types of supersonic separator, confirming that the conical diffuser has high pressure recovery performance. Vaziri et al.[4] examined nine design variables to find the optimal design for a supersonic separator using an Artificial Neural Network (ANN) model. So far, many researches have been done on the flow characteristics and optimal design of supersonic separators. Particularly, there are many researches on the shape and position of stator blades for stator section inducing centrifugal force. However, study has been rarely done to increase the centrifugal force in other sections. In this study, numerical analysis was conducted using the groove number as a variable in the straight line region of a convergent-divergent nozzle leading to supersonic flow. The optimal model was determined by comparing the swirling intensity of the straight line region and the nozzle throat. Higher swirling intensity means that water droplet and impurities are effectively dehydrated by the formation of high centrifugal forces. In addition, the swirling intensity and the flow characteristics of a supersonic separator were compared and analysed with various flow and geometrical conditions.

2. Model Description

2.1. Reference model
As shown in figure 1, a supersonic separator consists of a stator section that forms swirling motion, a convergent-divergent nozzle section was used to accelerate to supersonic velocity, and a diffusion section that restores the flow to the initial pressure. The stator consists of a core and a blade, and the ratio of the major axis to the minor axis of the core is 2:1, and it has an elliptical shape. The blade is the shape of airfoil and was chosen from the NACA1408 model. The groove shape used in this study is a semi-circular shape with a diameter of 1.8 mm and has a rotation number (number of helical turn) of 1 for a 125 mm straight line region and is shown in figure 2.

2.2. Design of the convergent-divergent nozzle
The convergent-divergent nozzle used to accelerate natural gas at supersonic speed is designed by the following equations [5]:

\[
\frac{D - D_i}{D_t - D_i} = 1 - \frac{1}{X_m^2} \left(\frac{x}{L}\right)^3 \quad \text{for} \quad \frac{x}{L} \leq X_m
\]

\[
\frac{D - D_i}{D_t - D_i} = 1 - \frac{1}{(1 - X_m)^2} \left(1 - \frac{x}{L}\right)^3 \quad \text{for} \quad \frac{x}{L} > X_m
\]
\[ X_m = 0.3 - 0.7L \]  

Table 1. Boundary conditions applied in this study.

| Boundary conditions | Values                  |
|---------------------|-------------------------|
| Turbulence model    | SST model               |
| Inlet temperature   | 303.15 K                |
| Inlet pressure      | 4 atm                   |
| Heat transfer       | Total energy            |
| Working fluid       | Ideal gas (air)         |
| Wall condition      | Adiabatic, no slip wall |

![Figure 2. Description of the groove shape.](image)

where \( D_i, D_t \) and \( L \) are the inlet diameter, the throat diameter and the length of the convergent nozzle, respectively. \( X_m \) is the relative coordinate of this convergent curve. The divergent angle of the nozzle is set to 4° for the numerical analysis.

2.3. Design of the conical diffuser

The conical diffuser of a supersonic separator was used from the following formula [3]:

\[
q(Ma) = \frac{\rho v}{\rho \gamma v_i} = \frac{A_i}{A} = \frac{Ma}{\left[ \left( \frac{2}{k+1} \right) \left( \frac{1 + \frac{k-1}{2} Ma^2}{2(k+1)} \right) \right]^{\frac{k+1}{2(k-1)}}}
\]

where \( q, \rho, Ma \) and \( k \) are the ratio of flow rate, density, Mach number and adiabatic exponent of natural gas, respectively. The axial length of the conical diffuser can be simplified as follows:

\[
L = \frac{r_2 - r_1}{\tan \alpha}
\]

where \( r_1 \) and \( r_2 \) are the inlet and outlet radius of the conical diffuser and \( \alpha \) is the divergence angle.
3. Numerical Analysis

3.1. Grid systems

Figure 3 shows the grid systems used in this study. The grid systems of the fluid domain used tetrahedral grids, and the stator section and supersonic separator wall were applied with five layers of pentahedral grids to improve the calculation accuracy. The number of grid elements is set to approximately 5,700,000. The $y^+$ value, which is a non-dimensional distance based on the local cell fluid velocity from the wall to the first mesh node, is configured so as not to exceed 70. In case of the Shear Stress Transport (SST) turbulence model used in this study, a low-Re formulation was used when $y^+$ was less than 2, and a blend of wall and low-Re formulations were used from 2 to 11. When $y^+$ is above 300, the SST model cannot be used, but in this case, since all the $y^+$ values were less than 70, the SST model could be used.

3.2. Boundary conditions

Numerical analyses were conducted using the commercial code, ANSYS CFX 17.1. As the boundary conditions, the static pressure and temperature of the inlet are set to 4 atm and 303K, respectively, and the walls and blades are set to adiabatic and no-slip conditions. In order to calculate the compressible flow and consequential thermal effects of a supersonic separator, the total energy equation was solved as well as the mass and momentum equations.

$$\frac{d\rho}{dt} + \nabla \cdot (\rho U) = 0$$

$$\frac{\partial}{\partial t} (\rho U) + \nabla \cdot (\rho U U) = -\nabla p + \nabla \cdot \tau$$

$$\tau = \mu [\nabla U + (\nabla U)^T - \frac{2}{3} \delta_{ij} \nabla \cdot U]$$

$$\frac{\partial \rho h_w}{\partial t} + \nabla \cdot (\rho U h_w) = -\nabla \cdot (k \nabla T) + \nabla \cdot (U \cdot \tau)$$

$$h_{tot} = h + \frac{1}{2} U^2$$

where $U$ is the velocity vector, $\mu$ is the dynamic viscosity, $\delta_{ij}$ is the Kronecker delta function and $h$ is the static enthalpy, which is a function of the pressure and temperature. To consider the compressibility, the ideal air governed by the equation of state was used as the working fluid.
3.3. Performance of a supersonic separator

In order to evaluate the performance of a supersonic separator through numerical analysis, the following swirling intensity equations at the throat of the nozzle \( (S_n) \) and the end of the straight line region \( (S_s) \) were used:

\[
S_n = \frac{u_{n,t}}{u_{n,a}} \tag{11}
\]
\[
S_s = \frac{u_{s,t}}{u_{s,a}} \tag{12}
\]

where \( u_{n,t} \) and \( u_{s,t} \) represent the tangential velocity of the nozzle throat and the straight line end, and \( u_{n,a} \) and \( u_{s,a} \) represent the axial velocity of the nozzle throat and straight line end.

4. Results and Discussion

4.1. Numerical analysis of the reference model

Through the numerical analysis, the swirling intensity, flow characteristics and temperature distributions at the throat of nozzle and the end of the straight line were obtained and displayed graphically. Figure 4 shows representative cases of internal flow characteristics and stream lines. The flow was supersonically expanded and confirmed to reach \( \text{Ma}=1.6 \). It also shows the temperature distribution inside a supersonic separator. The lowest temperature dropped to 215K, which is low enough to dehydrate the water droplet from natural gas.

4.2. Swirling intensity at nozzle throat

The results of swirling intensity at the nozzle throat are shown in figure 5. It is seen that the value of the reference model is 0.1229, and the highest value of the Case 5 is 0.1899, which is 65% higher than the reference model. The values of swirling intensity at the nozzle throat were increased proportionally as the number of grooves increased.
Table 2. Number of groove and swirling intensity with each Case.

| Case   | Number of groove | Swirling intensity (Straight line section) | Swirling intensity (Throat of nozzle) |
|--------|------------------|------------------------------------------|--------------------------------------|
| Case 1(ref) | 0                | 0.122                                    | 0.1268                               |
| Case 2  | 1                | 0.2506                                   | 0.1303                               |
| Case 3  | 2                | 0.2620                                   | 0.1296                               |
| Case 4  | 4                | 0.2998                                   | 0.1442                               |
| Case 5  | 6                | 0.3689                                   | 0.1452                               |
| Case 6  | 8                | 0.3264                                   | 0.1870                               |
| Case 7  | 10               | 0.3061                                   | 0.1896                               |

Figure 5. Effect of groove number on the swirling intensity.

4.3. Swirling intensity at straight line section
The results of the swirling intensity at the straight line section are shown in figure 5. The highest value in Case 3 is 0.3689, which is increased by 300%. As can be seen from the results of the reference model, it could be noted that the value of the swirling intensity decreases after the flow passes through the nozzle. By adding the groove shape in the straight line section, more centrifugal force could be induced, which means an increase in separation efficiency. The number of groove shapes and the value of the swirling intensity were not proportional. When the number of grooves was 6, the highest swirling intensity was shown, and when the number of grooves was increased to more, the swirling intensity value was decreased. It can be deduced that if the number of groove increases more than a certain value, it interferes with the formation of swirl and its intensity.
5. Conclusions
In this study, the effects of the number of groove at the straight line section of a supersonic separator on the swirling intensity were studied numerically for 7 different cases. Each part of a supersonic separator was formally designed and the fluid domains were formed. The swirling intensity was compared and analysed with different number of grooves. In particular, the swirling intensity at the nozzle throat was increased proportionally as the number of groove increased. In case of the straight line section, the swirling intensity showed the highest value with a certain groove number. It can be deduced that if the number of grooves increases more than a certain value, it disturbs the fluid flow and adversely affects the formation of swirl and its intensity. The results presented in this study can be used as a research guide for numerical analysis and optimal design of supersonic separators.

References
[1] C. Wen, X. Cao, Y. Yang, J. Zhang, 2011, "Evaluation of natural gas dehydration in supersonic swirling separators applying the discrete particle method", Adv. Powder Tech., 23, 2, pp. 228-233.
[2] X. Liu, Z. Liu, Y. Li, 2014, "Investigation on separation efficiency in supersonic separator with gas-droplet flow based on DPM approach", Separation Science and Technology, 49:17, pp. 2603-2612.
[3] C. Wen, X. Cao, Y. Yang, and W. Li, 2012, “Numerical simulation of natural gas flows in diffusers for supersonic separators,” Energy, 37, 1, pp. 195-200.
[4] B. M. Vaziri and A. Shahsavand, 2013, “Analysis of supersonic separators geometry using generalized radial basis function (GRBF) artificial neural networks,” J. of Natural Gas Sci. and Eng., 13, pp. 30-41.
[5] C. Wen, X. Cao, Y. Yang, 2011, “Swirling flow of natural gas in supersonic separators,” Chemical Engineering and Processing, 50, 7, pp. 644-649.
[6] I. Y. Song, 2017, “Design optimization of a supersonic separator for natural gas refinement”, M.S. Thesis, Sungkyunkwan University, Korea.