The Effect of Swirl Strength on the Flow Characteristics and Separation Efficiency of Supersonic Gas Separator

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Abstract **— Swirl strength is one of the key factors that have great influence on the flow fields and separation efficiency of supersonic gas separator (SGS) with two dimensional (2-d) guide vane. Both numerical simulation and experiment are conducted to investigate the mechanism of the effect of swirl strength on the separation efficiency and dew point depression of SGS. The research results show that swirl strength is increased with decreasing height of the guide vane; Mach number is decreased and static temperature is increased resulting from increasing the swirl strength; the separation efficiency and dew point depression reach maximum when the separator with the height of 60 mm is used as swirl generator.**

Keywords - supersonic gas separator; swirl strength; Mach number; gas mixture separation

I. INTRODUCTION

Natural gas is widely used as a kind of clean fossil fuel. However, it usually contains certain quantities of water vapor and heavy hydrocarbon with high dew point. Water vapor and heavy hydrocarbon in natural gas can result in the formation of hydrate, which greatly reduced the performance of the equipment. Therefore, natural gas dehydration is a significant step in natural gas process. The traditional methods of natural gas dehydration contain tri-ethylene glycol dehydration, desiccant adsorption and condensation separation [1-4]. However, those methods not only need high investment cost, but also need to add hydrate inhibitor leading to a series of environmental problems.

Supersonic gas separator (SGS) used as new dehydration equipment overcomes the disadvantage of the dehydration methods mentioned before. It has advantages of compact structure, small-occupied space, low energy consumption and investment cost, and high iso-efficiency etc. It also can finish the whole process of expansion, cyclone separation and recompression to realize natural gas dehydration [5]. Meanwhile, because the residence time of medium in SGS is short, there is no demand to add any chemical substance and hydrate inhibitor in the downstream of SGS [6].

At present, the research on SGS is not just restricted to supersonic nozzle, swirl generator used as an important part of SGS has attracted great interest. The swirl generator is used to provide enough centrifugal force to separate the condensation droplet with the size of 1μm in the nozzle. There are two kinds of swirl generators: 2-d tangential flow vane and three dimensional (3-d) axial flow vane. Compared with 2-d tangential flow vane, 3-d axial flow vane is widely used in separation equipment [7-9] because of the lower pressure drop. Eriqitai [10] and Wen [11], et al, employ 3-d axial flow vane to generate swirl flow in SGS. However, most researches concentrate on numerical simulation resulting from the high processing cost, the related experiment investigation reported rarely. What's more, the research on the effect of swirl strength on the performance of SGS is not comprehensive. In a few following articles some common and general aspects of swirl effect on SGS have been taken into consideration.

Wen, et al, investigated the effect of swirl on the flow rate, velocity and temperature of natural gas in SGS [12]. The experimental platform was also built, the result indicated that increase in the swirl strength would decrease the flow rate and Mach number at nozzle outlet. However, there is no report about the influence of swirl strength on the separation efficiency in SGS. Shahsavand [13], et al, summarized five swirl numbers mentioned in references of [14]-[19] to measure the swirl strength. The influence of inlet axial, tangential, radial velocity on the five swirl numbers and centrifugal acceleration were analyzed. The results indicated that four of the five swirl numbers have the same variation trend with centrifugal acceleration, therefore centrifugal can be used to measure swirl strength. The optimal inlet parameters were obtained as well which lead to the largest centrifugal acceleration. However, Wen concluded that the non-uniformity of radial distribution of gas main parameters (velocity, static temperature and static pressure) increases due to the increase of swirl strength, while it have a great influence on the separation performance in SGS.

Therefore, there is a tight link between swirl strength and separation efficiency in SGS, meanwhile the variation trend between them has not been obtained. The relationship between non-uniformity of radial distribution of main parameters along the axial distance also has not been investigated.

This paper adopted 2-d tangential flow vane whose processing is sample and cost is low, combined with both numerical simulation and experiment to investigate the change relation between swirl strength and separation performance in SGS. Internal mechanism of the relationship also has been analyzed.

II. NUMERICAL METHOD

A. Structure and Working Principle

Structural diagram of the SGS is shown in Fig. 1. The basic size is also reflected in the picture, O point is used as the origin of coordinates. The core inserted in the nozzle to form convergent and divergent channels and ended in the diffuser because the annular section only used along the nozzle. Here’s how it works: the high pressure mixture gas enters into the 2-d tangential flow vane. Under the action of static guide vane, gas generates tangential velocity; then gas enters into the inner-cone nozzle, the velocity of gas reaches sonic in the nozzle throat, supersonic in the nozzle divergent section creating low temperature environment. The heavy components begin condensate under the low temperature environment, then attached to the wall surface under the centrifugal force, discharged through liquid outlet finally. The mixture gas contains little dehydrated named as dry gas, it enters into diffusion section to recover pressure energy and discharge through dry gas outlet finally.

Swirl generator is installed in the front of supersonic nozzle to generate swirl gas flow to provide centrifugal force. The 2-d vane applies streamline design to form converging channels between vanes. Under the action of guide vane, the gas is compressed to accelerate and generate large tangential velocity. Fig. 2 shows its structural diagram. When operating parameters and the size of supersonic nozzle are given, the gas swirl strength in the nozzle can be adjusted by changing minimum flow area of the separator. The minimum flow area can be calculated as following:

$$A_{\min} = Hwn_{sb} \tag{1}$$

$A_{\min}$ --- the minimum flow area;

H --- the height of the separator;

w ---the minimum distance between vanes (refer to Fig. 2);

n_{sb} --- the number of vanes;

Keeping H changes in the range of 30 to 70 mm, w and n_{sb} are 8 mm and 8 respectively.

Centrifugal acceleration is used to measure swirl strength, which can be obtained by the equation as following:

$$a_c = v_c^2 / r \tag{2}$$

a_c --- the centrifugal acceleration;

v_c --- the tangential velocity;

r ---the radial distance;

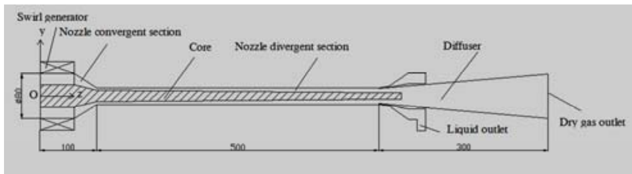


Figure 1. Structural diagram of the SGS device.

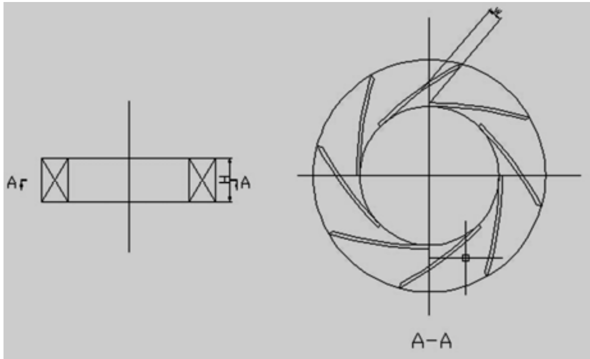


Figure 2. Structural diagram of the swirl generator.

Figure 3. The grid diagram of SGS.

B. Numerical Method

Gambit software is adopted for hexahedral mesh generation, the swirl generator and nozzle are connected by an interface after they were meshed respectively. The local mesh refinement is used in the important location, especially in nozzle throat and liquid outlet vicinity. Based on grid independence analysis, grid number is determined and about 29169 grids. The mesh diagram of the whole model is shown in Fig. 3.

CFD software fluent is applied to solve continuity, momentum and turbulence equation discretely. Second-order windward finite volume scheme is used for space discrete. The fully implicit time integrations used in time domain. RNG turbulence model is adopted for turbulence equation [11][20]. Compressible ideal gas is selected as the working medium. Total pressure and temperature are given as the inlet boundary conditions, which are 0.15 MPa, 290 K respectively. The atmospheric pressure is given for outlet boundary condition. The wall is set to be smooth, no slip and adiabatic.

III. EXPERIMENTAL METHOD

A. Experimental Process

Design and process four swirl generators with H are 30 mm, 45 mm, 60 mm and 70 mm respectively. Ethanol-air is used as working medium to conduct experiment. Fig. 4 shows schematic diagram of the experimental process of SGS device. The air enters into storage tank after compressed by a compressor; the compressed air mixed with ethanol vapor which is provided by vapor generation facility, forming air-ethanol mixed gas; After the liquid

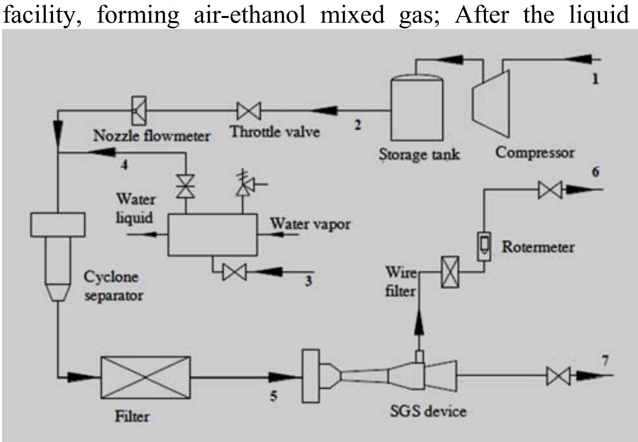


Figure 4. Schematic diagram of the experimental process of SGS device.

1-low pressure air, 2-compressed air, 3-ethanol liquid with purity of 99%, 4-ethanol vapor, 5-air-ethanol mixed gas, 6-wet gas, 7-dry gas

contained in the mixed gas is moved by cyclone separator and horizontal filter gas-liquid separator, the finally mixed gas is used as experimental medium. When the heavy components are moved by SGS device, the mixed gas is divided into two streams, one of them called dry air due to the smaller humidity is discharged from dry air outlet 7, the other one called wet gas is discharged from liquid outlet 6.

B. Performance Evaluation Index

In order to evaluate the separation performance of SGS device, heavy components removal efficiency and dew point depression are adopted as performance evaluation index. The heavy components removal efficiency steam can be calculated by the equation as following:

$$\delta_{\text{stream}} = \frac{x_{\text{steam}}^{\text{in}} - x_{\text{steam}}^{\text{dry}}}{x_{\text{steam}}^{\text{in}}} \times 100\% \tag{3}$$

Where $x_{\text{steam}}^{\text{in}}$ and $x_{\text{steam}}^{\text{out}}$ are the ethanol mole fraction contained in mixed gas at inlet and dry gas outlet of SGS device, respectively, which are measured by the chromatographic analyzer.

The dew point depression ΔT_{d} can be obtained by the following equation:

$$\Delta T_{\text{d}} = T_{\text{d}}^{\text{in}} - T_{\text{d}}^{\text{dry}} \tag{4}$$

Where T_{d}^{in} and $T_{\text{d}}^{\text{out}}$ are the dew point of mixed gas at inlet and dry gas outlet of SGS device respectively, which are measured by dew-point instrument directly.

IV. RESULTS AND DISCUSSION

A. Effect of Height of Swirl Generator H

Fig. 5 shows the change of centrifugal acceleration ac along nozzle axial distance z under different height of swirl generator H. Obviously, a_c decreases with the increase of H. As mentioned before, Amin becomes larger with the increase of H, which leads to reduce the swirl strength. For different H, the change trends of ac are basically identical, they all reduce gradually along the axial distance because of friction loss on the nozzle wall. When H is more than 60 mm, a_c can stay above $1.2\times10^6\,\text{m}\cdot\text{s}^{-2}$.

Fig. 6 indicates the change of Mach number *Ma* along nozzle axial distance under different height H. When H is less than 60 mm, sonic is not reached at nozzle throat and there is no supersonic flow in separation section; When H is more than 60 mm, supersonic flow appears in the nozzle separation section, and *Ma* becomes larger with the increase of H. This is because the swirl strength becomes weakened with the increase of H, that is to say the influence of swirl on the gas flow in the nozzle is weakened.

Compared and analyzed the result above, we can see that Ma and a_c present the opposite variation trend. In order

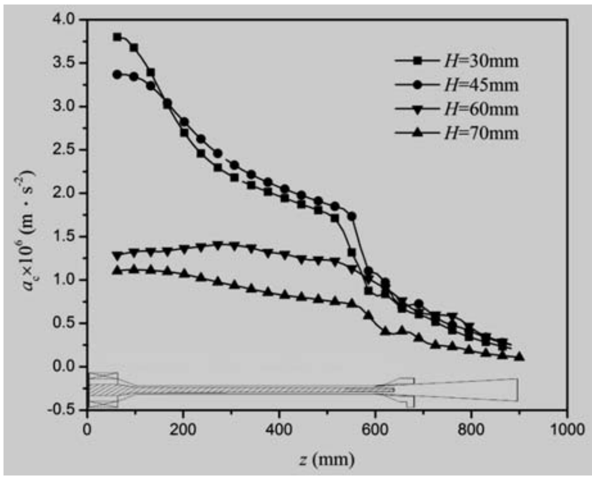


Figure 5. Variation of a_c with z under different H.

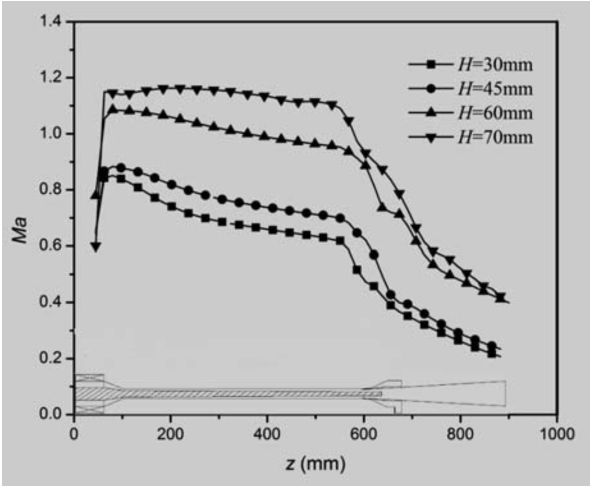


Figure 6. Variation of *Ma* with *z* under different *H*.

to attain higher separation efficiency in SGS, not only enough ac need to attain, but also supersonic flow should be kept in the nozzle separation section to provide low temperature environment for heavy components condensation. Therefore, swirl generator plays a significant role in the performance of SGS. Based on the analysis, we can conclude that choosing the swirl generator with the H is 60 mm, a_c can reach above $1.2\times10^6\,\mathrm{m\cdot s^{-2}}$ and Ma can keep about 1.05, providing a good environment for condensation and separation.

Fig. 7 and Fig. 8 are the contours of main gas flow parameters with the height of swirl generator is 60 mm, which shows that *Ma* can keep about 1.05 and static temperature *T* is below 260 K in the nozzle separation section. This flow state not only provide low temperature environment for heavy components condensation, but also avoid excessive axial velocity which assure the residue time of condensation liquid in the nozzle.

B. Effect of Height of Swirl Generator on Flow Characteristics

Fig. 9 are the isolines of *T* at different position of the nozzle separation section, the axial distance *z* are 250 mm, 350 mm and 450 mm respectively. The origin of coordinates that is identified in Fig.1 at point O. The isolines indicate non-uniformity of radial distribution of *T*,

T decreases at first, then increases with the increase in the radial distance. In the area that is far away from wall, *T*

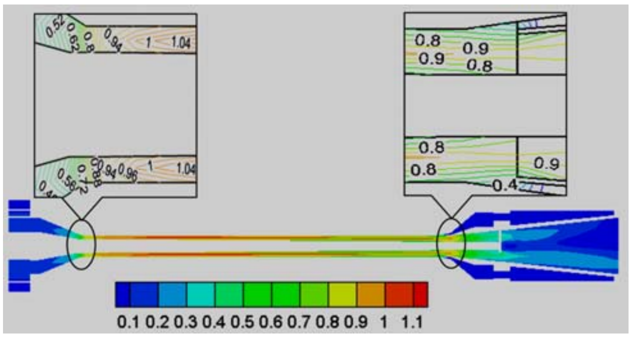


Figure 7. The contour of *Ma*.

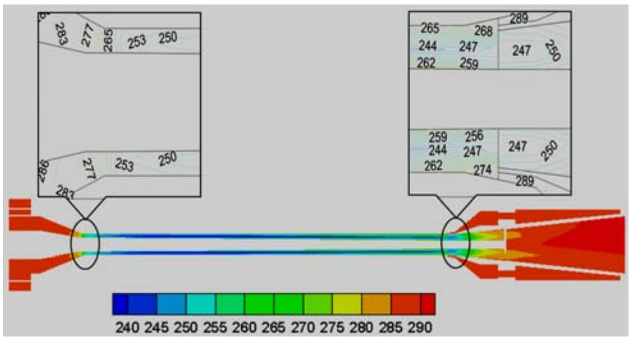
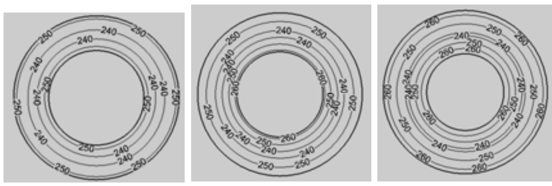


Figure 8. The contour of *T*.



(a) *z*=250 mm (b) *z*=350 mm (c) *z*=450 mm

Figure 9. The isolines of *T* at different position of the nozzle separation section (K).

can reach minimum 240 K; On different sections, *T* has the same change trend, but the central low temperature area becomes smaller with the increase in *z*. All of those demonstrate that non-uniformity of radial distribution becomes more obvious with the increase in *z*.

C. Effect of Height of Swirl Generator on SGS Performance

Fig. 10 and Fig. 11 show the variation trend of steam and ΔT_d with the increase in *H* respectively. Both of them have the same change trend, increasing at first and then decreasing. When *H* is smaller than 60 mm, steam and ΔT_d increase gradually with the increase of *H*, reaching maximum values when *H* is 60 mm, 17.1% and 11.2 K respectively. When *H* is larger than 60 mm, steam and ΔT_d decrease gradually with the increase in *H*. So the performance of SGS device increase at first and then decrease.

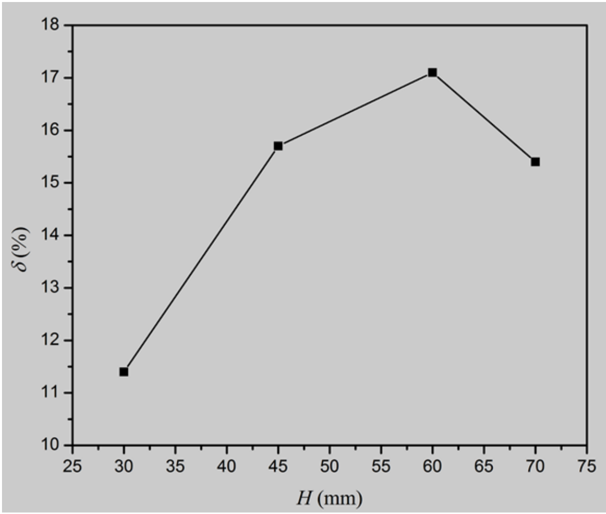


Figure 10. Variation of δ_{steam} with *H*.

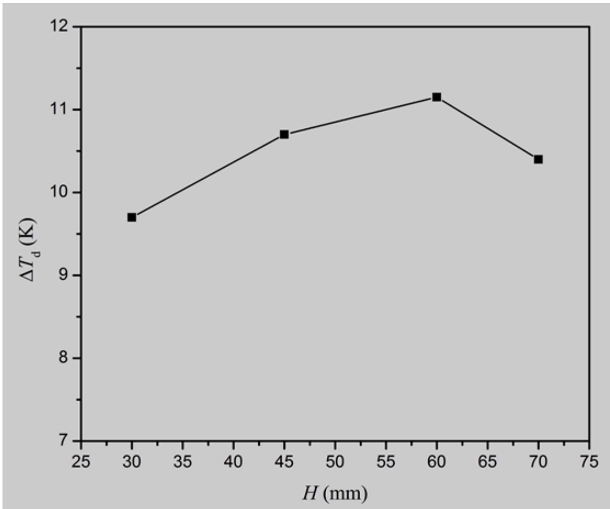


Figure 11. Variation of ΔT_d with *H*.

Based on the numerical simulation analyzed before, increase of *H* results in decreasing ac of the gas in the nozzle, increasing *Ma* and decreasing *T* at nozzle exit at the same time. Considering the influence of *H* on *Ma* and *T* at nozzle exit and ac comprehensively indicate that choosing the swirl with *H* is 60 mm not only can provide enough centrifugal acceleration, but also can keep the *Ma* in the nozzle above 1.05 and *T* below 260 K. Therefore, both numerical simulation and experiment conclude that the swirl generator with *H* is 60 mm can create the optimal condition for heavy components separation.

V. CONCLUSIONS

The mechanism of the effect of swirl strength on the separation efficiency and dew point depression of SGS was investigated both in numerical simulation and experiment. The conclusions can be drawn as following:

1) With the increase in the height of swirl generator, the centrifugal acceleration decreases gradually, the Mach number increases and static temperature decreases at nozzle outlet.

2) Swirl leads to non-uniformity of radial distribution of static temperature, meanwhile the non-uniformity becomes more obvious along axial distance.

3) The experimental result indicates that the swirl generator with the height of 60 mm is the best choice for the SGS investigated in this paper, which make the separation efficiency and dew point depression reach maximum values reaching 17.1% and 11.2 K respectively, which has a good agreement with numerical simulation.

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