Ninth International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
10-12 December 2012

CFD SIMULATION OF SUPERSONIC SWIRLING SEPARATION OF NATURAL GAS USING A DELTA WING

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ABSTRACT

The computational fluid dynamics (CFD) technique is employed to predict the swirling separation characteristics of natural gas flow in a supersonic separator with a delta wing. The CFD model uses the Reynolds stress turbulence model and Redlich-Kwong real gas equation of state. Results show that a sufficiently low pressure and temperature can be achieved in the supersonic separator for the nucleation and condensation of water vapor and heavier hydrocarbons. The strong swirl motion generated by the delta wing will remove the condensed liquids from the mixture. The supersonic flow is quite sensitive to the delta wing, which causes the disturbance and non-uniformity of the supersonic flows and the interaction between the waves and the boundary layers. A reverse flow is observed in the diffuser.

NOMENCLATURE

a	constant for attractive potential of molecules
b	constant for volume
C_μ	constant
D	diameter
D_1	inlet diameter
D_{cr}	throat diameter
D_H	hydraulic diameter
I	turbulence intensity
k	turbulent kinetic energy
l	turbulence length scale
L	convergent length
p	static pressure
p_c	critical pressure
R	gas constant
Re	Reynolds number
T	temperature
T_c	critical temperature
u_x	x axis velocity
u_y	y axis velocity
$\overline{u}$	mean velocity
u'	fluctuating velocity
V_m	gas molar volume
X_m	relative coordinate
ε	turbulent dissipation rate

INTRODUCTION

The supersonic separation technique has been introduced to the natural gas processing for the condensation and separation of water and higher hydrocarbons (Knott, 2000; Okimoto and Brouwer, 2002; Betting et al., 2003; Alferov et al., 2004, 2005; Brouwer et al., 2004; Schinkelshoek and Epsom, 2006; Betting and Epsom, 2007; Kalikmanov et al., 2007; Wen et al., 2011a). The key concepts of supersonic separation include two principles. On one hand, the Laval nozzle is usually employed to accelerate the natural gas to the supersonic velocity, resulting in a pressure and temperature low enough for nucleation and condensation of some components. On the other hand, a swirl device is designed to generate a strong swirling flow to separate and remove the condensed liquids from the gas-liquid mixture. Therefore, a typical supersonic separator is mainly composed of a Laval nozzle, a swirl device and a diffuser for pressure recovery, as shown in Figure 1.

An indoor experiment loop was set up to test the dehydration characteristics of a designed supersonic swirling separator with the moist air by Liu et al. (2005). The dew point depression between the inlet and outlet of the separator was analyzed with the various pressure loss ratios. Jiang et al. (2008a) briefly presented the basic structure and working principles of a supersonic separator and obtained the parameter distribution of natural gas along the axis with the commercial FLUENT software. In another study, Jiang et al. (2008b) described a mathematical model to study the spontaneous condensation in the supersonic velocity and obtained the condensation parameters along the separator.

Jassim et al. (2008a, 2008b) 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 (2009) 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.

In our previous studies, a new supersonic nozzle was designed incorporating a central body and the effect of the nozzle geometric structure on the separation characteristics was analysed by the numerical simulation (Wen et al., 2011b). A new swirling device composed of some vanes and an ellipsoid was designed for the supersonic separator. The effects of swirls on natural gas flow were computationally simulated with the Reynolds

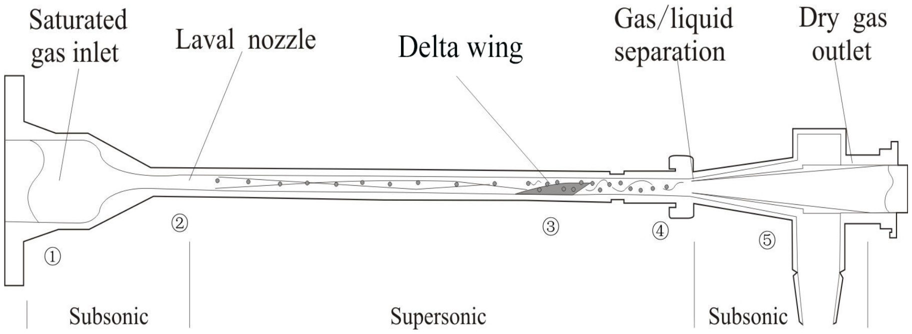


Figure 1: Schematic diagram of supersonic separator.

stress model (Wen et al., 2011c). The natural gas flows in diffusers were numerically calculated using the Navier-Stokes equations with the Reynolds stress model. The results show that the shock waves appear as bifurcation structures as a result of the interaction between the shocks and the boundary layer in the diffusers (Wen et al., 2012a). Then the discrete particle method was used to predict the particle separation characteristics in a supersonic separator and the separation efficiency was obtained (Wen et al., 2012b).

The purpose of this study is to investigate the swirling separation characteristics of natural gas in the supersonic velocity using a delta wing. The ANSYS FLUENT code is employed to predict the gas parameters distribution along the axis and the radius.

MATHEMATICAL MODEL

In a supersonic separator, the natural gas is compressible and forms a strong swirling 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.

The Reynolds stress model is able to capture 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 (Pope, 2000). The Speziale-Sarkar-Gatski Reynolds stress model in FLUENT is employed to appropriately model turbulent flow with a significant amount of swirl in the supersonic separator.

Real Gas Equation of State

An equation of state must be developed to calculate the physical property of fluids in supersonic flows. In this simulation, the Redlich-Kwong real gas equation of state model was employed to predict gas dynamic parameters. The Redlich-Kwong equation of state is an equation that is derived from the van der Waals equation (Redlich, Kwong, 1949). It is generally more accurate than the van der Waals equation and the ideal gas equation. The Redlich-Kwong equation of state can be described as Eq. (1).

$$p = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T}V_m(V_m + b)} \tag{1}$$

where p is the gas pressure, R is the gas constant, T is temperature, V_m is the molar volume (V/n), a is a constant that corrects for attractive potential of molecules, and b is a constant that corrects for volume.

The constants a and b are different depending on which gas is being analysed. They can be calculated from the critical point data of the gas:

$$a = \frac{0.4275R^2T_c^{2.5}}{p_c} \tag{2}$$

$$b = \frac{0.08664RT_c}{p_c} \tag{3}$$

where T_c and p_c are the temperature and pressure at the critical point, respectively.

For the multi-components natural gas, the material properties are calculated as follows. The gas viscosity and thermal conductivity are computed by mass-weighted mixing law. The critical temperature, pressure and volume follow the van der waals mixing law, while the acentric factor is calculated by mole-weighted mixing law.

Geometry and Mesh Generation

In the supersonic separator, the delta wing is located in the supersonic channel downstream of the nozzle exit. Even a tiny disturbance in the supersonic flows upstream of the delta wing will cause violent changes of the flow behavior downstream of the wing. Thus the Laval nozzle should be designed specifically to maintain the stability of the supersonic flows. For this purpose, the cubic polynomial, shown in Eq. (4), was employed to calculate the convergent contour of the nozzle. This design of the convergent part will accelerate the gas flow uniformly to achieve the sound speed in the throat area. Foelsch's analytical calculation was selected to generate the stable supersonic flows (Foelsch, 1949).

$$\begin{cases} \dfrac{D - D_{cr}}{D_1 - D_{cr}} = 1 - \dfrac{1}{X_m^{\ 2}}\left(\dfrac{x}{L}\right)^3 & \left(\dfrac{x}{L} \le X_m\right) \\ \dfrac{D - D_{cr}}{D_1 - D_{cr}} = \dfrac{1}{\left(1 - X_m\right)^2}\left(1 - \dfrac{x}{L}\right)^3 & \left(\dfrac{x}{L} > X_m\right) \end{cases} \tag{4}$$

where D_1, D_{cr} and L are the inlet diameter, the throat diameter and the convergent length, respectively. X_m=0.45. x is the distance between arbitrary cross section and the inlet, and D is the convergent diameter at arbitrary cross section of x.

The quality of the mesh plays a significant role in the accuracy and stability of the numerical calculation. Polyhedral meshes allow the flexibility of an unstructured mesh to be applied to a complex geometry. A structured grid was generated for the Laval nozzle, the supersonic channel and the diffuser, while the delta wing section was meshed using a tetrahedral grid due to its complexity, as shown in Figure 2. After the grid independence was tested, 276020 structural cells and 110856 tetrahedral cells were employed for our calculation.

Boundary Conditions and Convergence

Pressure boundary conditions were assigned for the inlet and outlet of the supersonic separator. No-slip and adiabatic boundary conditions are specified for the walls. The turbulent kinetic energy and turbulent dissipation rate were used for the turbulence parameters at the inlet.

$$I = \frac{u'}{\bar{u}} = 0.16\left(Re_{D_H}\right)^{-0.125} \tag{5}$$

$$k = \frac{3}{2}\left(\bar{u}I\right)^2 \tag{6}$$

$$\varepsilon = C_\mu^{0.75}\frac{k^{1.5}}{l} \tag{7}$$

where I is the turbulence intensity, Re_{D_H} is the Reynolds number, D_H is the hydraulic diameter, and l is the turbulence length scale.

The convergence criterion is 10^{-6} for the energy equation and 10^{-3} for all other equations. When the residuals drop below 1×10^{-6} for the energy equation and 1×10^{-3} for all other equations with reaching stationary, while simultaneously total mass error in inlet/outlet mass flow rates is below 1×10^{-4}, the solutions are considered converged.

RESULTS AND DISCUSSION

The flow characteristics of a natural gas were numerically simulated in our new designed supersonic separator based on the above mentioned mathematical methods. The multi-components gas mixture in Baimiao gas well of Zhongyuan Oil Field was selected for the calculation. The composition of natural gas in mole fraction is shown in Table 1.

Gas Dynamic Parameters in the Supersonic Separator

Figure 3 presents the distribution of main dynamic parameters of natural gas along the flow direction, namely, the gas Mach number, the static pressure, the static temperature and the tangential velocity. It can be seen that the gas velocity increases in the convergent part of the Laval nozzle and reaches the sonic velocity at the throat. After the critical condition is achieved, the divergent part will further accelerate the gas flow to the supersonic velocity when the back pressure is assigned to 60% of the inlet pressure in this calculation. The gas Mach number is about 2.02 at the nozzle exit. As a result of the expansion of the gas flow, the static pressure and temperature decline in the Laval nozzle. The pressure and temperature at the nozzle outlet are about 6 bar and -73 ˚C, respectively,

Natural gas composition	Mole fraction (%)
CH_4	91.36
C_2H_6	3.63
C_3H_8	1.44
i-C_4H_{10}	0.26
n-C_4H_{10}	0.46
i-C_5H_{12}	0.17
n-C_5H_{12}	0.16
H_2O	0.03
CO_2	0.45
N_2	2.04

Table 1: Mole composition of natural gas.

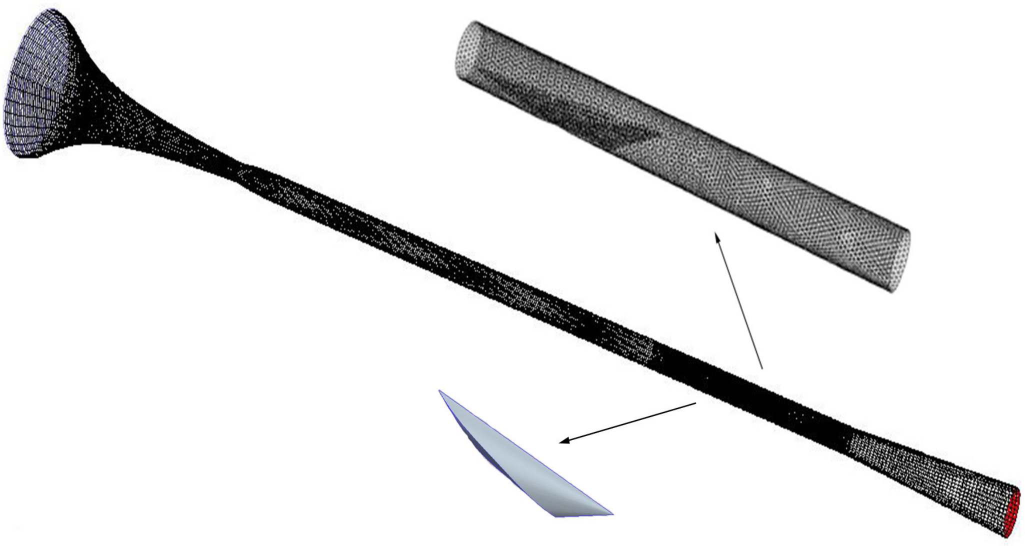


Figure 2: Structure of the new designed supersonic separator with a delta wing and the grid system.

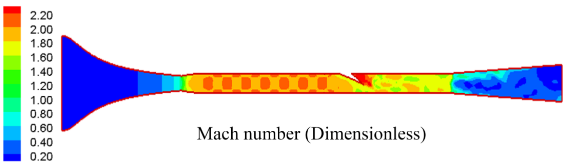
which creates essential conditions for the nucleation and condensation of the water vapor and higher hydrocarbons. But the shock reflections in the cylindrical section behind the nozzle outlet indicate a degree of non-uniformity, as shown in Fig 3 (a). The oscillation appearing in the supersonic flow will have a secondary action on the condensation, even cause the re-evaporation of the condensed liquids.

When the natural gas flows from the nozzle exit, the swirling motion is generated by the delta wing located downstream of the nozzle exit. The strong swirls are obtained since the change of the velocity occurs under the conditions of the supersonic velocity. In our separator, the maximum tangential velocity is up to 342 m/s, which corresponds to a centrifugal acceleration of about 1.9×10^7 m/s^2. The centrifugal force will swing the condensed liquid droplets onto the walls and create a liquid film. However, the gas flow is quite sensitive to the delta wing in the supersonic velocity. Once the supersonic fluid flows past the front of the delta wing, a great disturbance occurs. This disturbance causes the non-uniform distribution of the flow fields, especially the increases of the static pressure and temperature.

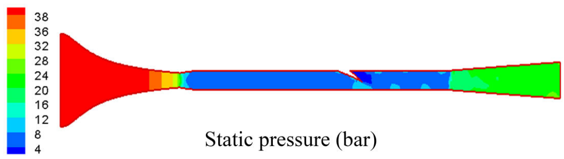
Swirling characteristics of gas flows

Figure 4 displays the velocity contour and the local velocity vector profiles on the vertical plane in the delta wing area and the diffuser. It can be seen that $\sqrt{u_x^2+u_y^2}$ velocity changes violently in the delta wing section, from 20 m/s to 340 m/s. On the other hand, it also demonstrates that the supersonic flow is quite sensitive to the delta wing as discussed above. Another interesting finding is that the reverse flow does not emerge easily in the delta wing area, although the dramatic change of the gas flow field is observed behind the delta wing. This is unlike the expected phenomenon in the initial design. On the contrary, the axial velocity presents the negative value in some parts of the diffuser and the maximum negative axial velocity even appears in the center of the channel. It indicates that the reverse flow appears in this area, just as described in the velocity vector profiles. The negative axial velocity declines with the increase of the distance from the entrance of the diffuser. The reverse flow nearly disappears at the exit of the diffuser.

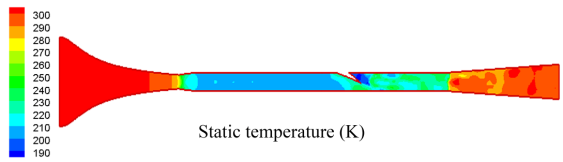
It also can be concluded that the compression and expansion waves arise along and behind the delta wing as a result of its specially designed geometry. The interaction between the waves and the boundary layers enables the flow velocity to fluctuate from time to time. It reveals that it is quite complicated to generate the swirling flow at the supersonic flow regions. The delta wing used here



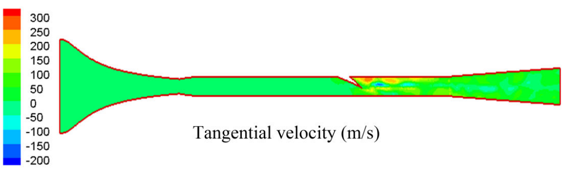
(a) Mach number



(b) Static pressure

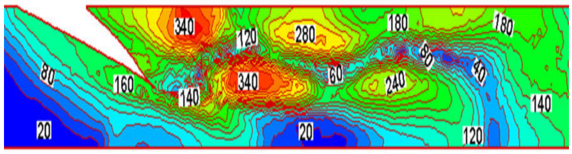


(c) Static temperature

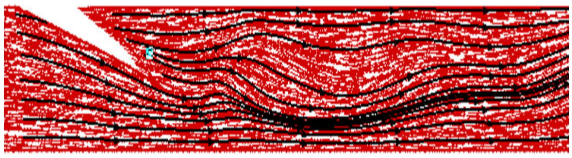


(d) Tangential velocity

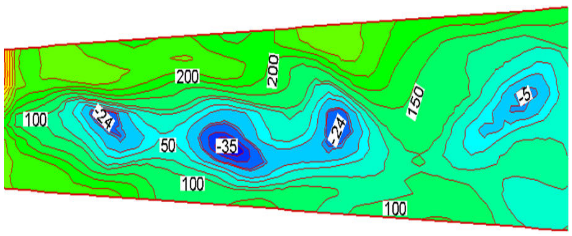
Figure 3: Dynamic parameters of natural gas in the new designed supersonic separator with a delta wing.



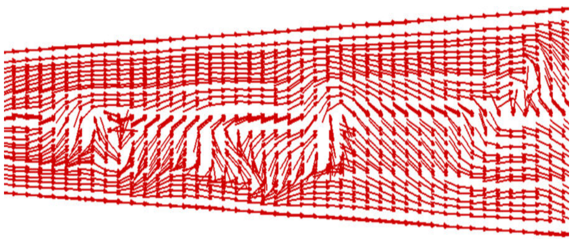
(a) $\sqrt{u_x^2+u_y^2}$ velocity (m/s) in the delta wing area



(b) Local velocity vector in the delta wing area

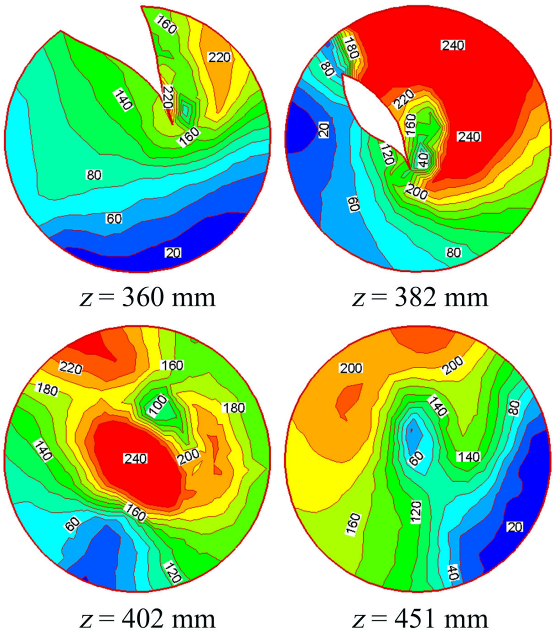


(c) Axial velocity in the diffuser (m/s)

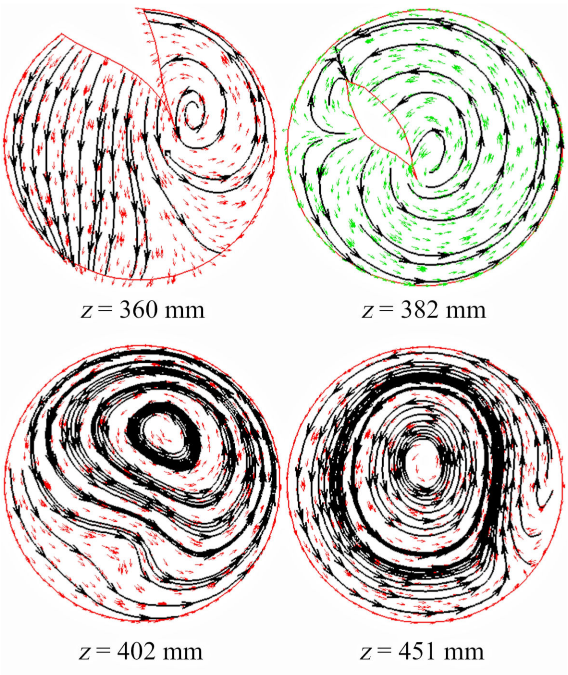


(d) Local velocity vector in the diffuser

Figure 4: Velocity contour and local velocity vector profiles in the delta wing area and diffuser.



(a) $\sqrt{u_x^2 + u_y^2}$ velocity contour (m/s)



(b) Local velocity vector

Figure 5: $\sqrt{u_x^2 + u_y^2}$ velocity and local velocity vector profiles in the cross section of the delta wing area.

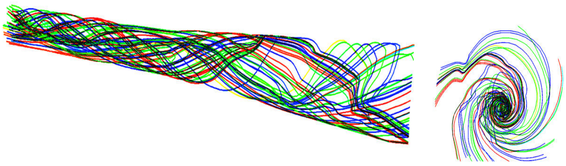


Figure 6: Streamlines downstream of the delta wing.

increases the complexity and non-uniform distribution of the flow field.

To illustrate the non-uniformity of the gas flows in the delta wing section, the $\sqrt{u_x^2 + u_y^2}$ velocity and the local velocity vector profiles at the cross section are given in Figure 5. It clearly shows that the delta wing located in the supersonic velocity channel results in the turbulence of the supersonic flow. The peak of this turbulence appears just behind the end of the delta wing and then declines slowly. It also can be seen that the center of the vortex diverges from the center of the flow channel.

However, one advantage of the current design is that the $\sqrt{u_x^2 + u_y^2}$ velocity maintains a larger value in the whole area, which creates a strong centrifugal field for liquids. The centrifugal acceleration can reach 10^6 m/s^2 near the exit of the delta wing section. Figure 6 depicts the streamline of natural gas flows past the delta wing. It is also demonstrated that the huge rate of acceleration will generate a strong helical motion to remove the water and higher hydrocarbons.

CONCLUSION

The cubic polynomial and Foelsch's analytical calculation were employed to calculate the convergent and divergent contour of the Laval nozzle, while the delta wing was used to generate the swirl motion located downstream of the nozzle exit. The dynamic parameters of natural gas in the supersonic separator were obtained by using the Reynolds stress model and Redlich–Kwong real gas equation of state models. In our newly designed supersonic separator, the gas flow is accelerated to the supersonic velocity and the gas Mach number is up to 2.02 at the nozzle exit, resulting in low pressure and temperature at the nozzle exit of 6 bar and -73 ˚C, respectively. The swirling motion is generated by the delta wing and the centrifugal field can reach 1.9×10^7 m/s^2. The delta wing causes a great disturbance to the supersonic flow and a non-uniform distribution of the dynamic parameter. The reverse flow appears in the diffuser.

ACKNOWLEDGEMENTS

This work was supported in part by the National Natural Science Foundation of China (No. 51274232), the Fundamental Research Funds for the Central Universities (No. 11CX06079A), the Research Program for Excellent Doctoral Dissertation of China University of Petroleum and the PostGraduate Top-up Research Scholarships of Australia-China Natural Gas Technology Partnership Fund. The authors acknowledge the support of the Australian and Western Australian Governments and the North West Shelf Joint Venture Partners, as well as the Western Australian Energy Research Alliance (WA: ERA).

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