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Swirling flow structure in supersonic separators for natural gas dehydration

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Abstract: The supersonic separator is a novel compact tubular device for natural gas dehydration. The separation mechanism is not well understood for the complicated fluids with a delta wing located in the supersonic flows. We investigated the gas swirling separation characteristics in supersonic velocities using the Reynolds stress turbulence model. The results showed that the Laval nozzle designed with the cubic polynomial and Foelsch's analytical methods formed an extremely stable and uniform supersonic flow. The delta wing generated a strong swirling flow with the centrifugal acceleration of around 10^7 m/s^2 to remove the condensed liquids from the mixture. However, the supersonic flow was quite sensitive to the delta wing, which led to the disturbance and non-uniformity of the gas dynamic parameters. This violent variation in the supersonic flow would had a secondary action on the condensation, even resulted in the re-evaporation of the condensed liquids.

Keywords: natural gas; supersonic separator; swirling flow; delta wing; numerical simulation

1 Introduction

The removal of water is an important step for natural gas processing. The supersonic separation is a novel technique for natural gas dehydration, working on the supersonic expansion and cyclonic separation [1]. Firstly, a Laval nozzle is usually employed to accelerate the natural gas to supersonic velocities, resulting in a low pressure and temperature for nucleation and condensation of water vapour and heavier hydrocarbon components. Then, a swirl device is used to generate a strong swirling flow to separate and remove the condensed liquids from the gas-liquid mixture. Lastly, the dry gas goes through a diffuser for the purpose of the pressure recovery.

As a result of the complexity of the supersonic separation technique, the studies mainly focus on the flow simulation using the computational fluid dynamics (CFD) technique, while just few experiments are performed. A supersonic separation system was built on an offshore platform in Malaysia with a design capacity of 17×10^4 Nm^3/d. The comparison analysis showed a cost reduction of 24% for the offshore platform [2]. A pilot plant was constructed in Calgary, Canada, to test the supersonic separator for the removal of water vapour and heavier target components from natural gas [3]. The designed natural gas flow rate was up to 12 kg/s with an inlet pressure of 50-70 atm. 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 [4]. The dew point depression between the inlet and outlet of the separator was analysed with the various pressure loss ratios. A supersonic separator was compared to a Joule-Thomson valve with TEG in an onshore plant and demonstrated the high economic performance and natural gas liquids recovery of a supersonic separator [5].

Recently, some numerical studies are performed to predict the gas flows in supersonic separator or Laval nozzle for natural gas dehydration. Without considering the swirling flow, Jassim et al [6, 7] employed the CFD technique to evaluate the real gas effect on the natural gas flow through a supersonic nozzle at high pressure. The methane and nitrogen were adopted to analyse the changes of the shock position within the real gas and ideal gas models. A constant tube was inserted between the nozzle and the diffuser to study the influence of the geometry on the shock positions. Karimi and Abdi [8] combined the MATLAB and HYSYS packages to predict the effect of the operating parameters on natural gas flow in the high pressure Laval nozzle. Malyshkina [9] obtained the distribution of gas dynamic parameters of natural gas through a supersonic separator with a computational method. In his another study, a procedure was developed to predict the separation capability of water vapor and higher hydrocarbons from natural gas in a supersonic separator [10]. Jiang et al. [11] employed the corrected Internally Consistent Classical Theory and Gyarmathy theory to modelling the nucleation and droplet growth of natural gas in the supersonic separation process. The generalized radial basis function artificial neural networks are used to optimize the geometry of a supersonic separator [12]. 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 [13]. In our preliminary studies, a central body was incorporated in a supersonic separator with a swirling device composed of vanes and an ellipsoid [14]. The effects of swirls on natural gas flow in supersonic separators were computationally simulated with the Reynolds stress model [15]. The particle separation characteristic in a supersonic separator was calculated using the discrete particle method [16]. Also, the real gas effects and pressure recovery characteristics were simulated without considering a swirling flow [17, 18].

The purpose of this study is to reveal another complicated swirling flow by locating a delta wing in the downstream of the nozzle outlet. Unlike above mentioned work, it is expected to be a more difficult and challenging study since the delta wing is inserted in a supersonic flow condition. The gas parameters distribution along the axis and the radius will be obtained with Reynolds stress turbulence model, especially around the delta wing area.

2 Supersonic separators

In a supersonic separator, the delta wing can be located in a supersonic channel behind a nozzle exit, as shown in Fig 1. Even a tiny disturbance in the supersonic flows in the upstream of a delta wing will cause violent changes of the flow behavior in the 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. (1), was employed to calculate the converging contour of the Laval nozzle. This design of the convering part will accelerate the gas flow uniformly to achieve the sound speed in the throat area. Foelsch's analytical calculation was used to design the diverging part to generate the stable supersonic flows [19].

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

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 dimensions of the designed supersonic separator are shown in Table 1. The critical cross-section area at nozzle throat is 0.0001208 mm^2. The nozzle inlet and outlet areas are 0.005026 m^2 and 0.0002217 m^2, respectively.

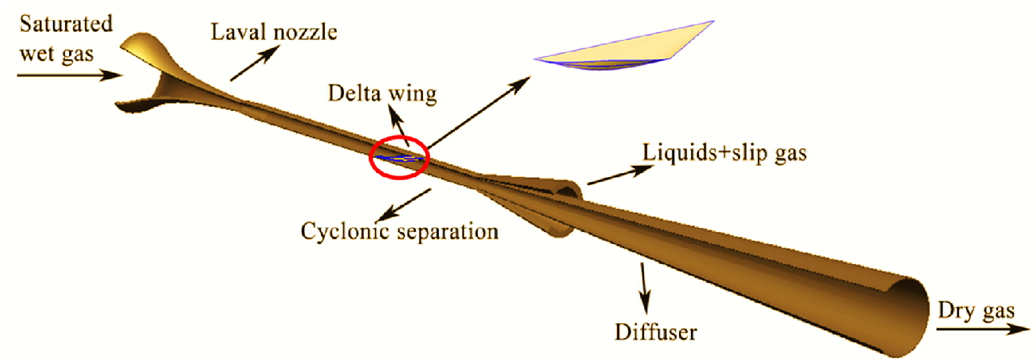

Figure 1 Schematic diagram of a supersonic separator with a delta wing

Table 1. Dimensions of the designed supersonic separator

Parameter	Value (mm)
Nozzle inlet diameter	80.00
Nozzle throat diameter	12.40
Nozzle outlet diameter	16.80
Diffuser outlet diameter	40.00
Nozzle converging length	149.00
Nozzle diverging length	37.10
Straight tube length	159.90
Cyclonic separation length	141.70
Diffuser length	221.80

3 Mathematical model

3.1 Governing equations

The natural gas can be accelerated to supersonic velocities with a Laval nozzle in a supersonic separator, and accordingly the low pressure and temperature conditions are achieved for water vapour condensation. The fluid structure of natural gas flows can be described by the conservation equations of mass, momentum and energy, described as Eqs. (2) - (4).

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j + p\delta_{ij}-\tau_{ji})=0 \tag{3}$$

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_j}(\rho u_j E + u_j p + q_j - u_i \tau_{ij})=0 \tag{4}$$

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

3.2 Real gas equation of state

An equation of state is necessary to calculate the physical property of fluids in supersonic flows. In this simulation, the Redlich-Kwong [20] real gas equation of state model was employed to predict gas dynamic parameters. The advantage of this equation is that it is easy to use and is often accurately represent the relation between temperature, pressure, and phase compositions in binary and multicomponent systems. The RK EOS only requires the critical properties and acentric factor for the generalized parameters. Little computer resources are required and those lead to good phase equilibrium correlation. The parameters related to calculate the gas properties can be found in [21], including the specific heat, enthalpy, entropy, and velocity of sound as a function of temperature and pressure.

3.3 Turbulence model

The Reynolds stress model (RSM) 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]. A strong swirling flow presents in a supersonic separator and accordingly the RSM turbulence model is employed to model this fluid structure here.

3.4 Computational method and validation

In this case, we adopted the finite volume method to solve the governing equations, while the SIMPLE algorithm [23] was employed to couple the velocity field and pressure. The ANSYS FLUENT software was employed for our simulation. A structured grid was generated for the Laval nozzle, the cyclonic separation section and the diffuser, while the delta wing section was meshed using a tetrahedral grid due to its complexity. The pressure boundary conditions were assigned for the inlet and outlet of the supersonic separator. No-slip and adiabatic boundary conditions were specified for the walls.

The convergence criterion was 10^{-6} for the energy equation and 10^{-3} for all other equations. When the residuals dropped 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 was below 1×10^{-4}, the solutions were considered to reach the convergence.

In our previous studies [24], the computational fluid dynamics technology was employed to predict the effect of swirls on supersonic flows with a swirl device located in the entrance of a nozzle. The numerical results were compared with the experimental data. The agreement with each other validated that the Reynolds stress model with pressure boundary conditions could accurately predict the strong swirling flow in supersonic velocities. The details of the validation and verification can be found in [24].

4 Results and discussion

The flow characteristics of a natural gas were numerically simulated in our new designed supersonic separator using our developed mathematical methods. The multi-components gas mixture in Baimiao gas well of Zhongyuan Oil Field was selected for the calculation. The gas composition in mole fraction is as follows: 91.36% CH_4, 3.63% C_2H_6, 1.44% C_3H_8, 0.26% i-C_4H_{10}, 0.46% n-C_4H_{10}, 0.17% i-C_5H_{12}, 0.16% n-C_5H_{12}, 0.03% H_2O, 0.45% CO_2, 2.04% N_2.

4.1 Gas dynamic parameters in supersonic separators

Figure 2 presents the gas dynamic parameters along the flow direction, namely, the gas Mach number, the static pressure, the static temperature and the tangential velocity. 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 supersonic velocity is obtained in the nozzle divergent part when the back pressure is assigned to 57% of the inlet pressure in this calculation. The gas Mach number is about 2.00 at the nozzle exit. The static pressure and temperature decline in Laval nozzle due to the gas contraction in converging part and the expansion in diverging part, respectively. The pressure and temperature at the nozzle outlet are about 10 bar and -79 ˚C, respectively, which creates essential conditions for the nucleation and condensation of the water vapor and higher hydrocarbons.

When the natural gas flows run out the nozzle exit, the delta wing, located in the downstream of the nozzle exit, generates a swirling motion. The strong swirls have been 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 300 m/s, which corresponds to a centrifugal acceleration of about 10^7 m/s2. 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 velocities. 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.

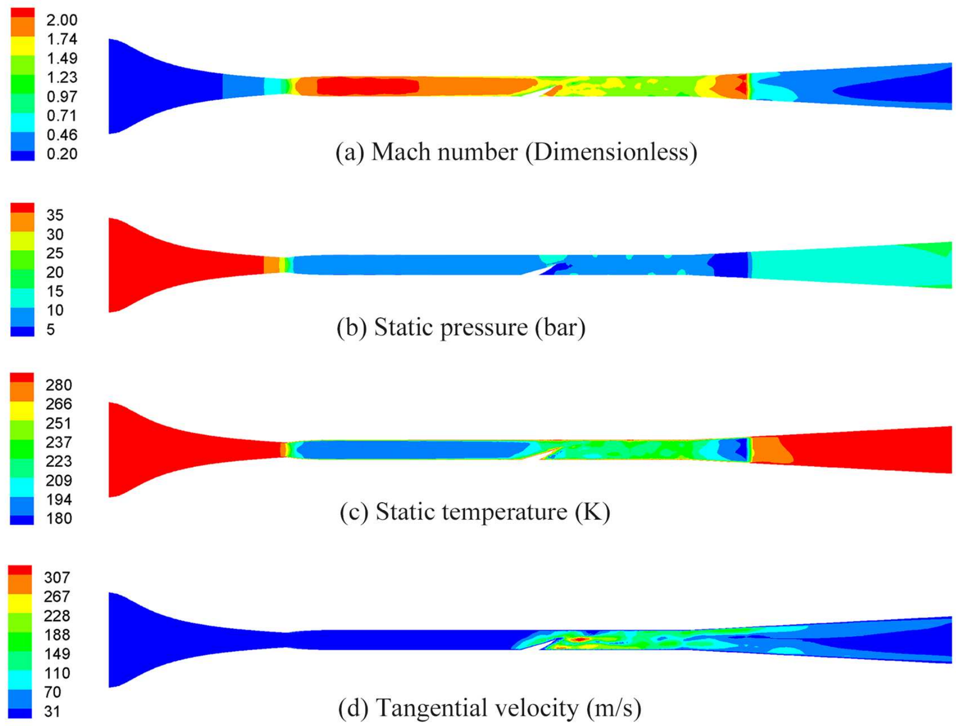

Figure 2 Gas dynamic parameters in a supersonic separator with a delta wing

4.2 Gas Mach number at downstream of nozzle outlet

The gas Mach number at the axial and radial direction is detailed depicted at the downstream of the Laval nozzle, as shown in Figure 3. The gas Mach number presents an extremely uniform distribution at the nozzle outlet and a certain distance downstream of it. This demonstrates that the cubic polynomial and Foelsch's analytical method are a good choice to calculate the converging and diverging curve of a Laval nozzle to generate a stable and uniform supersonic flow. However, the delta wing located in the constant tube reduces the effective flow area, which leads to the insufficient expansion of the natural gas in this area. The radial gradient of gas Mach number near the wall increases along the axial direction, especially at the upstream of the delta wing. Also, this re-compression process will result in the increase of the gas Mach number and temperature. In this condition, the condensed droplets will re-evaporate to gas phase and decline the separation performance.

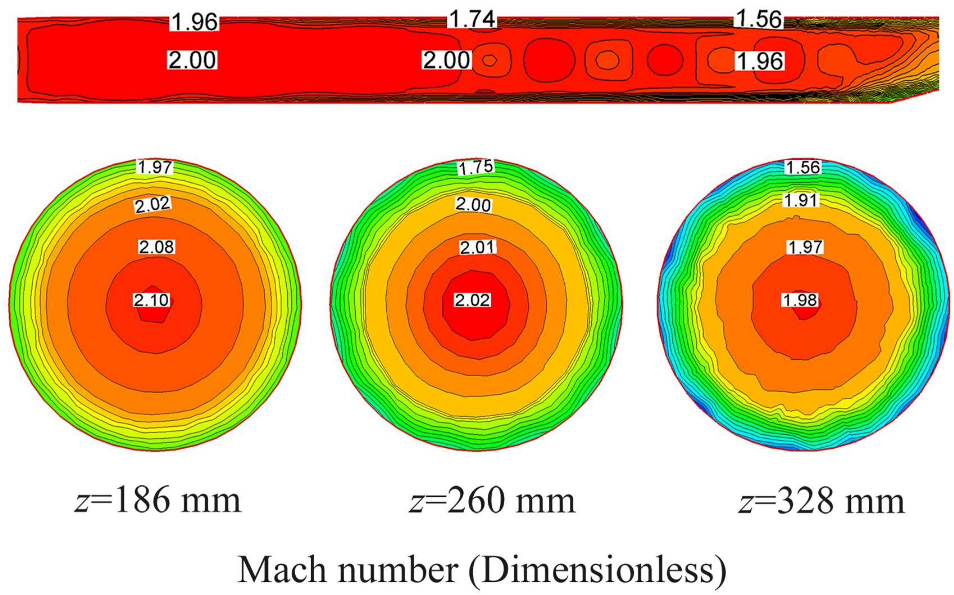

Figure 3 Gas Mach number at the downstream of the nozzle outlet

4.3 Delta wing effect

The effect of a delta wing on the gas velocities in supersonic conditions is numerically simulated and the results are shown in Figure 4. We can see that the delta wing located in the supersonic area leads to the variation of the gas Mach number at the cross section. The gas Mach number can reach a peak of about 2.00 at one edge of the delta wing, while it also appears a very small value on the other edge, i.e. 1.15. Moreover, the delta wing can generate a large tangential velocity. The tangential velocity presents an extremely non-uniform distribution at the cross section. At the tail end of the delta wing, the tangential velocity achieves a maximum of more than 300 m/s. This indicates that the centrifugal acceleration in this area can reach 10^7 m/s^2, which provides a strong force to separate the condensed liquids from the mixtures.

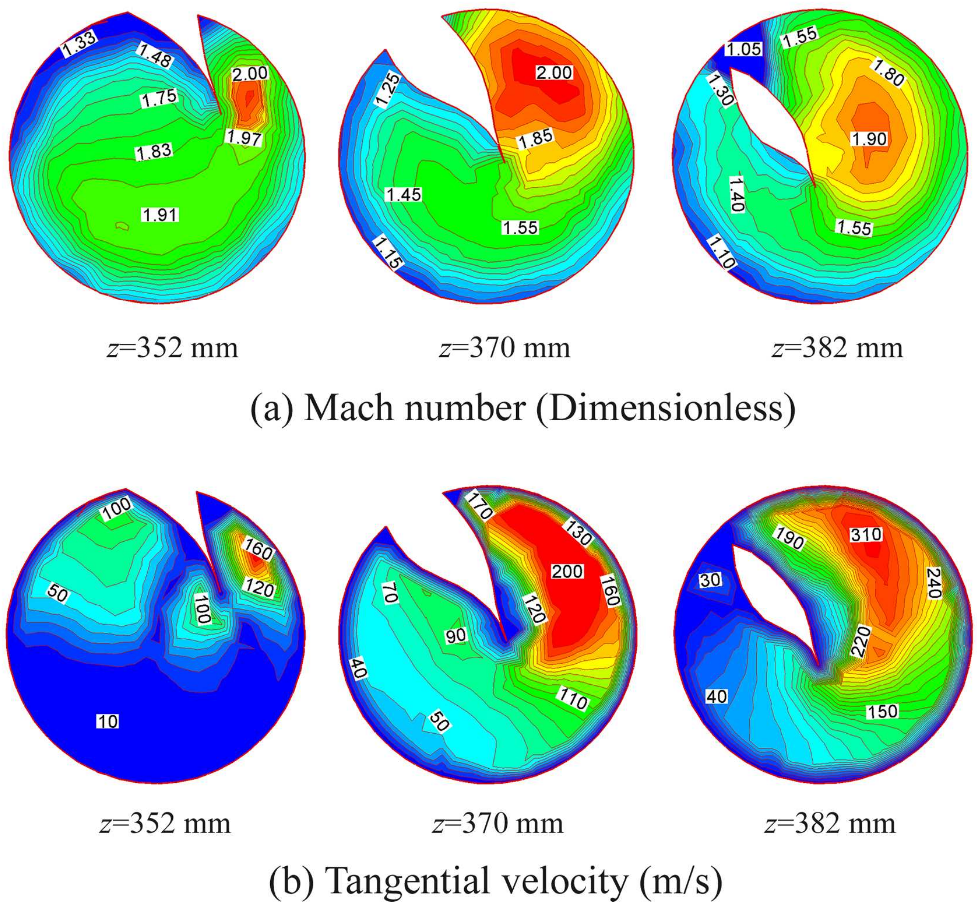

Figure 4 Gas Mach number and tangential velocity around a delta wing

4.4 Gas swirling characteristics in cyclonic separation section

Figure 5 displays the gas Mach number, tangential velocity contours and the local velocity vector profiles in the cyclonic separation section. In the downstream of the delta wing, the gas Mach number is extremely non-uniform along the axis from 1.12 to 2.02. The gas Mach number declines along the axis in general, which indicates that the oscillation appearing in the supersonic flow will have a secondary action on the condensation, even cause the re-evaporation of the condensed liquids. The tangential velocity also changes violently from 30 m/s to 230 m/s. It also demonstrates that the supersonic flow is quite sensitive to the delta wing. 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 that the delta wing installed in the supersonic zones will result in a reverse flow.

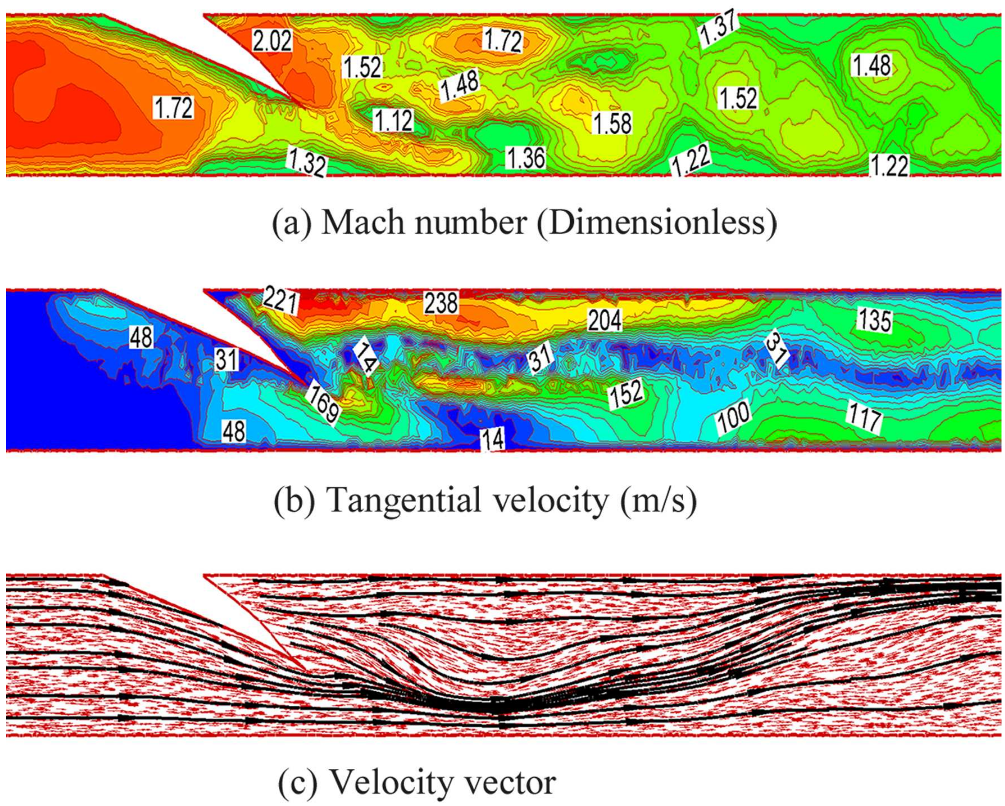

Figure 5 Gas dynamic parameters in the cyclonic separation section

To illustrate the non-uniformity of the gas flows in the cyclonic separation section, the gas Mach number, tangential velocity and vector profiles at the cross section are given in Figure 6. 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. It reveals that it is quite complicated to generate the swirling flow at the supersonic flow regions. The delta wing used here increases the complexity and non-uniform distribution of the flow field.

However, one advantage of the current design is that the tangential velocity maintains a larger value in the whole area, which creates a strong centrifugal field for liquid droplets. The centrifugal acceleration can reach 10^6-10^7 m/s^2 in the cyclonic separation section. The huge rate of acceleration will generate a strong helical motion to remove the water and higher hydrocarbons.

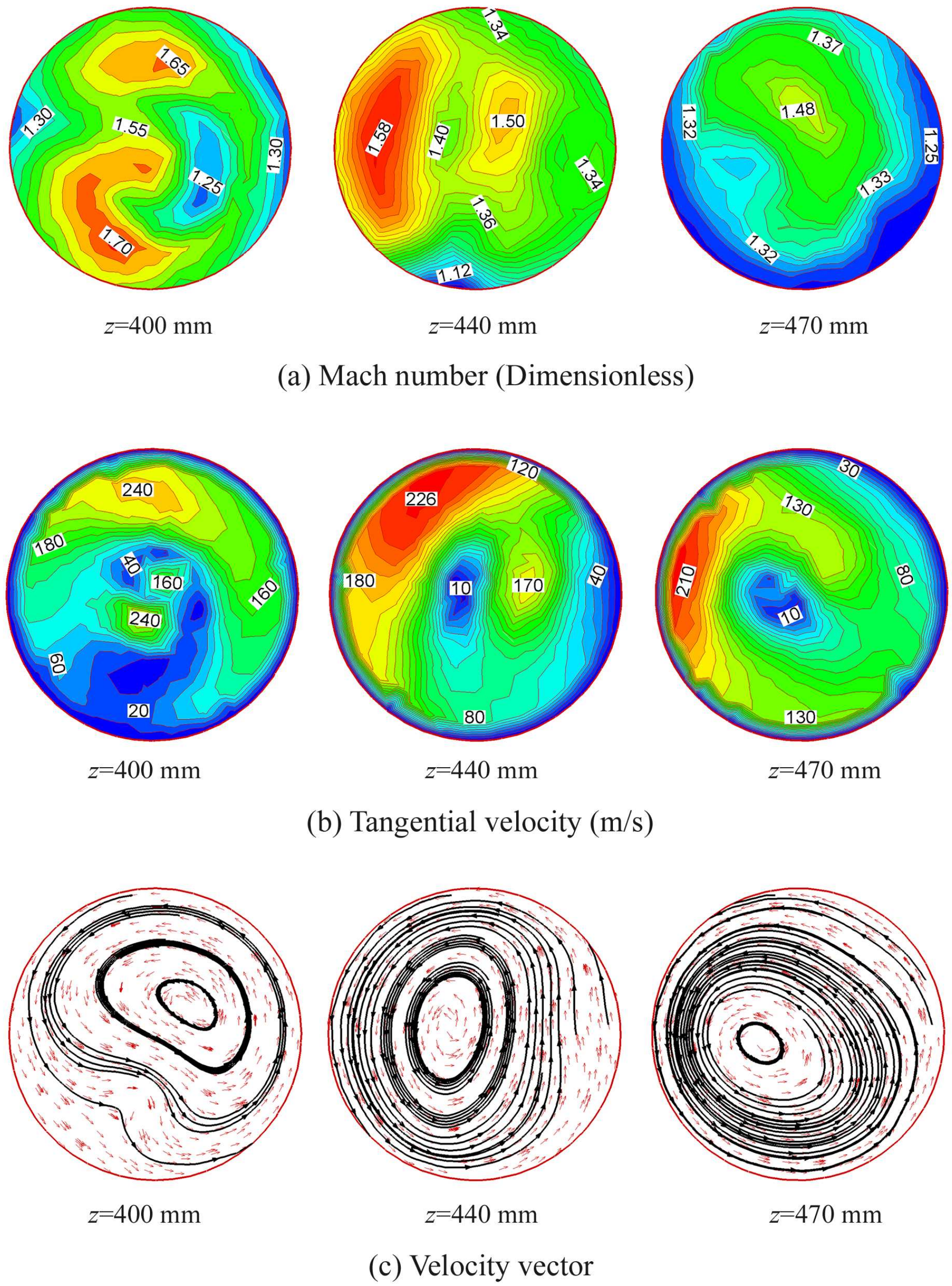

Figure 6 Gas dynamic parameters at the cross section of the cyclonic separation

5 Conclusions

The flow structure of natural gas in a supersonic separator was simulated using the Reynolds stress turbulence model and Redlich–Kwong real gas model. A delta wing was installed in the supersonic constant tube to generate a swirling flow. The gas dynamic parameters were obtained both in the axial and radial directions. The effect of the delta wing on the flow distribution are analysed in the supersonic conditions. The centrifugal acceleration can reach 107 m/s^2, which provides a strong force to separate the condensed liquids from the mixtures. The delta wing also causes a great disturbance to the supersonic flow and a non-uniform distribution of the gas dynamic parameter. It also demonstrates that the supersonic flow is quite sensitive to the delta wing.

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Nomenclature

a	[-]	constant for attractive potential of molecules
b	[-]	constant for volume
$C_{1\varepsilon}$	[-]	constant
$C_{\varepsilon 2}$	[-]	constant
C_{μ}	[-]	constant
D_1	[m]	inlet diameter
D_{cr}	[m]	throat diameter
D_H	[m]	hydraulic diameter
$D_{L, ij}$	[-]	molecular diffusion
F_{ij}	[-]	production by system rotation
G_{ij}	[-]	buoyancy production

E	[J]	total energy
I	[-]	turbulence intensity
k	[m^2s^{-2}]	turbulent kinetic energy
l	[m]	turbulence length scale
L	[m]	convergent length
M_t	[-]	turbulent Mach number
p	[Pa]	static pressure
p_c	[Pa]	critical pressure
P_{ij}	[-]	stress production
q_j	[Wm^{-2}]	heat flux
R	[$JK^{-1}mol^{-1}$]	gas constant
Re	[-]	Reynolds number
Sm	[-]	source term
Sk	[-]	source term
S_ε	[-]	source term
t	[s]	time
T	[K]	temperature
T_c	[K]	critical temperature
u	[ms^{-1}]	gas velocity
$\overline{u}$	[ms^{-1}]	mean velocity
u'	[ms^{-1}]	fluctuating velocity
V	[m^3]	gas volume
V_m	[m^3mol^{-1}]	gas molar volume
X_m	[-]	relative coordinate

Greek letters

δ_{ij}	[-]	Kronecker delta
ε	[-]	turbulent dissipation rate
ε_{ij}	[-]	turbulent dissipation
μ	[m^2s^{-1}]	gas viscosity
μ_t	[m^2s^{-1}]	turbulent viscosity
ρ	[kgm^{-3}]	gas density
σ_k	[-]	turbulent Prandtl number
σ_ε	[-]	turbulent Prandtl number
τ_{ij}	[Nm^{-2}]	viscous stress;
ϕ_{ij}	[-]	pressure strain

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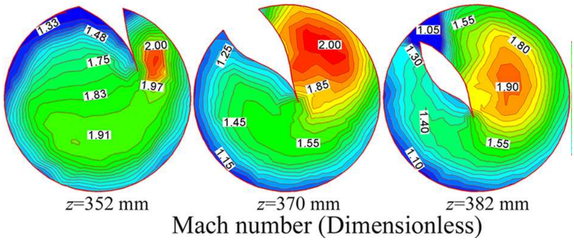

The delta wing resulted in a violent variation of the supersonic flows, inducing the re-evaporation of the condensed liquids.