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Effect of Supersonic Nozzle Structure on Vapor Spontaneous Condensation

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To study the effect of the supersonic nozzle structure on the spontaneous condensation of water vapor, the wet steam model used to study the wet steam liquefaction of steam turbine was introduced into the numerical study of supersonic nozzle in supersonic cyclone separator, and the numerical results was in good agreement with the experimental data of the related literature. The supersonic nozzles, the contraction section with the Witozinsky curve and the bicubic curve, and the expansion section with conical curve and Foelsch curves, were designed. The influence of supersonic nozzle structure on water vapour liquefaction ability was investigated. And the following research results were obtained. When the structure of the supersonic nozzle was the same, the Witozinsky curve was selected for contraction section of the supersonic nozzle, and the nucleation rate of the droplet in the nozzle increased by 21.97 % and the number of droplets increased by 32.16 %, which was helpful to the gas liquefaction in the nozzle. When the contraction curve of the supersonic nozzle was consistent, and the expansion curve was Foelsch curve, the gas nucleation rate and the number of droplets in the nozzle were greatly improved. The distribution of nozzle humidity was related to the structure of expansion section, but not to the structure of contraction section. The maximum humidity in nozzle depended on the outlet diameter of nozzle. When the other structures of the nozzle were consistent, the cone angle of divergent section increased from 2° to 8°, the peak value of the nucleation rate increased by 493.15 %, the maximum of the droplet number increased by 246.12 %, the outlet humidity of the nozzle increased by 73.37 %, which greatly improved the gas liquefaction rate. In the case of gas liquefaction, increasing the cone angle of expansion section was conducive to liquefaction of water vapor.

Introduction

Supersonic cyclone separator is a new type of natural gas dehydration and heavy hydrocarbon removal device based on adiabatic expansion of rotating airflow, which integrates condensation and separation functions (Duan et al., 2018). As one of the core components of supersonic cyclone separator, supersonic nozzle can make natural gas expand adiabatically from subsonic state to supersonic state, and provide sufficient condition of low temperature and low pressure for spontaneous condensation of water vapor in natural gas (Wen et al., 2012). The spontaneous condensation process of water vapor in natural gas is an indispensable condition for natural gas purification process in supersonic cyclone separator. The design of supersonic nozzle can directly affect the separation efficiency of supersonic cyclone separator (Wang and Hu, 2018). Therefore, the influence of supersonic nozzle structure on steam liquefaction should be considered in the design of supersonic nozzle for supersonic liquefaction. Han et al. (2016) studied the regularity of distribution of natural gas pressure, temperature, Mach number and other characteristic parameters on the axis line of the unit without considering the effect of condensation, and evaluated the performance of supersonic cyclone separator according to dew point drop and separation efficiency. Yang et al. (2017) applied nucleation and droplet growth theory to study the condensation process of water vapor in supersonic nozzle. The results showed that latent heat was released into vapor phase during spontaneous condensation, which leaded to jump of condensation parameters. Shooshtari and Shahsavand (2013) provided a new

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method for predicting droplet growth in binary mixtures in supersonic nozzles based on mass transfer rate calculation, which overcame the disadvantage that the estimation of droplet growth in pure fluids (such as steam) cannot be extended to binary or multicomponent systems. Jiang et al. (2010) established a numerical model for spontaneous condensation flow of two-component mixtures, and investigated the effect of entrance parameters on spontaneous condensation flow. Cao and Yang (2015) simulated the condensation characteristics of binary gas in supersonic nozzle by user defined function (UDF) in Fluent and analysed the effects of carrier gas, inlet pressure and inlet temperature on the distribution of condensation parameters.
At present, the research on supersonic cyclone separator mainly focuses on structural optimization and internal condensation process, and seldom considers the influence of supersonic nozzle structure on condensation and liquefaction of water vapor. To accurately and simply study the influence of nozzle structure on water vapor condensation process, the wet steam model was used to carry out relevant research. The influence of supersonic nozzle structure on vapor liquefaction was systematically studied by changing the contraction section, expansion section line and expansion section cone angle of supersonic nozzle.

Supersonic nozzle design

At present, the design of supersonic nozzle for contraction section is mainly based on Witozinsky curve and Bicubic curve, and the design of expansion section is based on Foelsch curve method and conical curve method.

1.1 Contraction section design

Witozinsky curve:

$$\left(\frac{R_{\mathrm{cr}}}{R}\right)^2 = 1-\left[1-\left(\frac{R_{\mathrm{cr}}}{R_1}\right)^2\right]\frac{\left[1-\left(\frac{x}{L_1}\right)^2\right]^2}{\left[1+\frac{1}{3}\left(\frac{x}{L_1}\right)^2\right]^3} \tag{1}$$

Bicubic curve:

$$\begin{cases} \dfrac{R-R_{\mathrm{cr}}}{R_1-R_{\mathrm{cr}}} = 1-\dfrac{1}{X_{\mathrm{m}}^2}\left(\dfrac{x}{L_1}\right)^3, \left(\dfrac{x}{L_1}\leqslant X_{\mathrm{m}}\right) \\ \dfrac{R-R_{\mathrm{cr}}}{R_1-R_{\mathrm{cr}}} = \dfrac{1}{(1-X_{\mathrm{m}})^2}\left(1-\dfrac{x}{L_1}\right)^3, \left(\dfrac{x}{L_1}\geqslant X_{\mathrm{m}}\right) \end{cases} \tag{2}$$

Where x is the axial distance of the nozzle, R is the radius of the cross section at x, and X_{m} is the relative position of the intersection of the front and back curves ($X_{\mathrm{m}}=0.5$).

1.2 Expansion section design

Foelsch curve is designed based on method of characteristic curve, including throat transition section, straight line section and eliminate wave section. Because the design process of this method is rather complicated, it is no longer discussed here, and detailed design steps can be referred to literature (Liu et al., 2000). To simplify the design procedure and calculation of the expansion section of supersonic nozzle, the conical curve method can be employed to design the expansion section curve.
Based on the above design method of supersonic nozzle, the main structural parameters of the designed supersonic nozzle are as follows: the length of contraction section L_1 = 40 mm, the length of expansion section L_2 = 110 mm, inlet diameter R_1 = 40 mm, throat diameter R_{cr} = 10 mm.

Numerical method

The wet steam model in ANSYS Fluent 16.0 was employed to calculate the spontaneous condensation liquefaction process of water vapor in supersonic nozzle. The density-based implicit solver was utilized to solve the numerical calculation. The RNG k-ε model was employed for turbulence model and the second-order upwind scheme was employed for discretization of governing equations. In order to ensure the accuracy of solution, the standard residual of convergence was set to 10^{-6}. The inlet boundary of supersonic nozzle was pressure inlet, and the total inlet pressure, static pressure, total temperature, turbulence intensity and hydraulic radius were set. The outlet boundary was pressure outlet, and the wall boundary of supersonic nozzle was non-slip, stationary and adiabatic wall.

Results and analysis

1.3 Model validation

To validate the rationality and accuracy of the wet steam model used in this paper, the experiment of Moses and Stein (Moses and Stein, 1977) was employed to the model verification. In the experiment of Moses and Stein, the condensation process of water vapor in supersonic nozzle was studied. The throat of the nozzle is located at x=82.2 mm, and the throat cross section size is 10 mm×10 mm. The geometry of the supersonic nozzle used in the experiment is described in Figure 1. The subsonic part is composed of an arc with a radius of 53 mm, while the transonic and supersonic part is consisted of an arc with a radius of 686 mm. Under the conditions of inlet pressure 70,727.32 Pa and inlet temperature 377.15 K, the pressure value obtained by the experiment decreases gradually along the central axis of the nozzle, and when the water vapor condenses spontaneously, the pressure rises slightly and then decreases gradually, as shown in Figure 2. This is due to the condensation wave generated by latent heat of condensation released from the condensation process of water vapor, which leads to the increase of pressure. The wet steam model employed in this paper accurately predicts the spontaneous nucleation process of water vapor in supersonic nozzle, and the simulated pressure distribution is in good agreement with the experimental date of literature, which proves that the application of the wet steam model is completely credible in the study of water vapor liquefaction in supersonic nozzle.

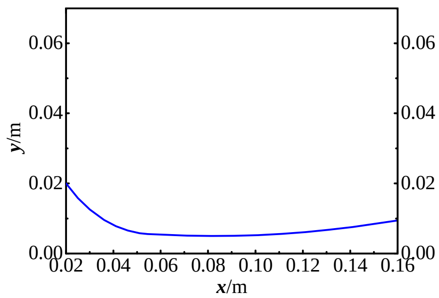

Figure 1: Geometry and dimensions of supersonic nozzles in the literature

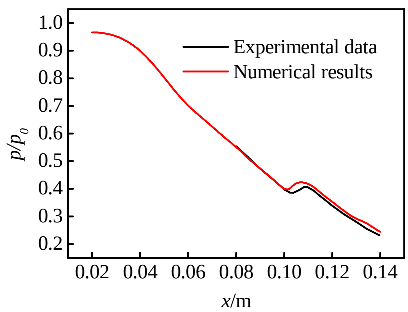

Figure 2: Comparison of numerical results in this paper with experimental data in literature

1.4 Effect of nozzle contraction curve on spontaneous condensation

Under the same structure of expansion section of supersonic nozzle, the geometric models of supersonic nozzle with the contraction section of Witozinsky curve and bicubic curve (hereinafter referred to as nozzle A and nozzle B) were established respectively to study the influence of the contraction section curve of supersonic nozzle on the variation of vapor liquefaction parameters. The inlet undercooling of nozzle A and B were -11.6 K and -12.6 K respectively, and with the expansion of water vapor in the nozzle, the undercooling increased continuously. The undercooling of nozzle A reached a peak value of 36.9 K at x= 46.5 mm, and nozzle B reached a peak value of 36.6 K at x= 45.5 mm. Water vapor began to condense, and the latent heat of condensation was generated to heat the water vapor in the nozzle. The increase of temperature led to the decrease of undercooling until the final stable value of 2 K was reached, as indicated in Figure 3(a). The undercooling of nozzle A was always higher than that of nozzle B in the contraction section (x=0~40 mm), which indicated that nozzle A could provide low temperature environment and power for droplet nucleation and growth for condensation of water in natural gas at the earliest stage. As can be seen from Figure 3(b), the maximum nucleation rates of nozzle A and B were 3.72×10^{22} and 3.05×10^{22} $m^{-3}\cdot s^{-1}$, respectively. Compared with nozzle B, the nucleation rate of nozzle A increased by 21.97 %. Figure 3(c) indicated that the maximum droplet number of nozzle A and B was 2.63×10^{22} and 1.99×10^{22} m^{-3}, respectively. Compared with nozzle B, the droplet number of nozzle A increases by 32.16 %. Figure 3(d) described the distribution of humidity, and the nozzle contraction curve had little effect on humidity. Under the same structure, the humidity of steam in nozzle was related to the number of droplets and the diameter of droplets. The imbalance of flow was gradually restored by the combination of the number of droplets and the radius of the droplet, whether it was a large number of small droplets or a smaller number of droplets (Han et al., 2011). The above results showed that when the contraction curve was Witozinsky curve, the nucleation rate and droplet number in the nozzle were better than those of the bicubic curve, and the contraction curve of the nozzle had little effect on the humidity.

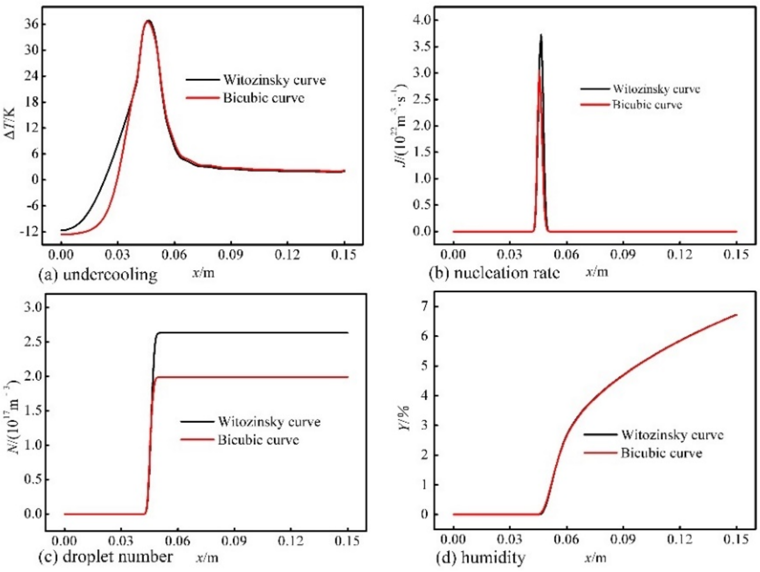

Figure 3: Effect of contraction section curve on condensation liquefaction parameters

1.5 Effect of nozzle expansion curve on spontaneous condensation

Under the condition that the contraction section of supersonic nozzle was consistent and the outlet diameter was the same, the geometrical model of supersonic nozzle with expansion section curve as conical curve and Foelsch curve (hereinafter referred to as nozzle C and nozzle D) were established respectively to study the effect of the curve of supersonic nozzle expansion section on the process of water vapor liquefaction.

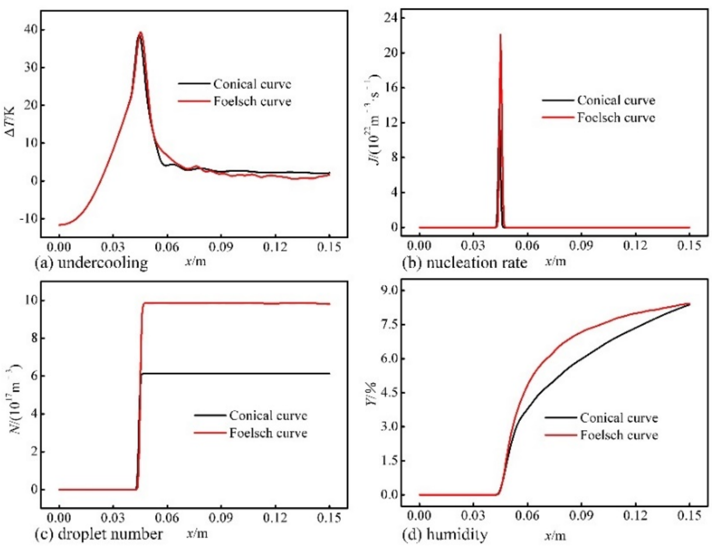

Figure 4: Effect of contraction section curve on condensation liquefaction parameters

In the region of droplet nucleation (x = 42.5~47 mm), the undercooling of nozzle C was lower than that of nozzle D. Correspondingly, in terms of droplet nucleation rate and droplet number distribution, nozzle D was better than nozzle C, as shown in Figure 4. The maximum nucleation rates of nozzle C and D were 14.82×10^{22} and 22.09×10^{22} $m^{-3}\cdot s^{-1}$ respectively, and the droplet numbers were 6.13×10^{22} and 9.85×10^{22} m^{-3} respectively. Compared with nozzle C, the maximum nucleation rate and droplet number of nozzle D increased by 49.06 % and 60.69 %, respectively. Figure 4(d) showed the influence of nozzle contraction section curve on humidity distribution, and combining with Figure 3(d), it can be seen that the distribution of humidity in nozzle was only related to the structure of nozzle contraction section. The contraction section curve of nozzle affects the distribution of humidity, and the nozzle outlet diameter determined the value of the outlet humidity. The above analyses indicated that when the curve of expansion section was designed by the Foelsch curve, the nucleation rate and droplet number of water vapor in the nozzle were greatly improved, and the distribution of nozzle humidity was related to the structure of the expansion section, and the humidity at the nozzle outlet depended on the diameter of the nozzle outlet.

4.4 Effect of cone angle of nozzle expansion section on spontaneous condensation

The condensation process of water vapor in natural gas in supersonic cyclone separator mainly occurred in the expansion section of supersonic nozzle. When the conical curve was adopted in the nozzle expansion section, the effect of the conical angle of the nozzle expansion section on the condensation liquefaction process of water vapor was studied by changing the conical angle of the expansion section with keeping the other structures consistent.

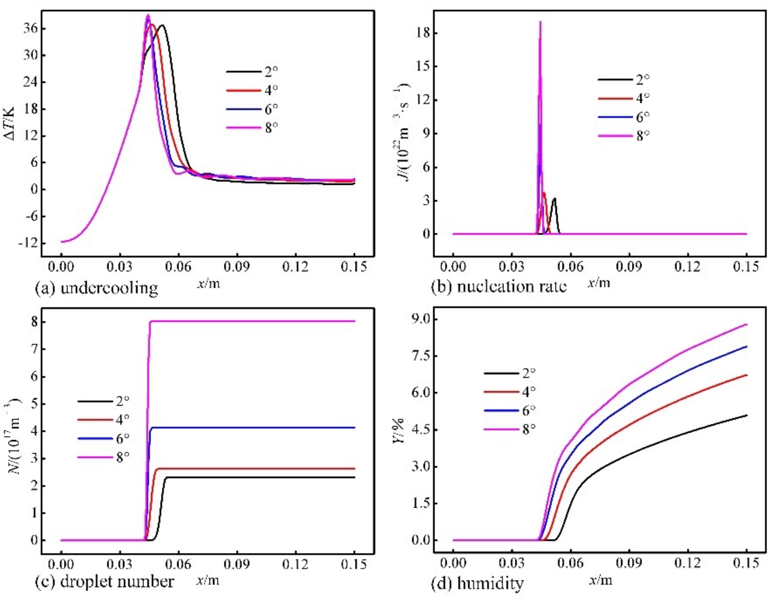

Figure 5: Effects of cone angle of expansion section on condensation liquefaction parameters

Figure 5 showed the distribution of undercooling, nucleation rate, droplet number and humidity at the central axis of the nozzle in the cone angle range of 2°~8°, respectively. According to the theory of aerodynamics, when the inlet parameters of supersonic nozzle were the same and there was no shock wave in the nozzle, the larger the cone angle of the expansion section was, the greater the gas velocity was, and the greater the change intensity of pressure and temperature was at the same position. The analyses of the numerical results showed that the rapid change of gas temperature and pressure would make the undercooling increase faster when the cone angle was enlarged, so that the water vapor reached the Wilson point earlier, as shown in Figure 5(b)~Figure 5(d). When the peak value of undercooling of water vapor increased, the maximum condensation nucleation rate, the droplet number and outlet humidity of water vapor increased. When the cone angle increased from 2° to 8°, the peak value of nucleation rate increased 493.15 %, the maximum droplet number increased 246.12 %, the outlet humidity of nozzle increased 73.37 %, which greatly increased the liquefaction rate of water vapor. The above analyses indicated that the liquefaction rate of steam could be increased by increasing the cone angle of expansion section. With the increase of cone angle of nozzle expansion section, the temperature drop and pressure drop in supersonic nozzle with the same length of expansion section also increased. The excessive temperature drop and pressure drop could make the temperature and pressure of water vapor lower than the three-phase point and be in a state of non-liquefaction, which would limit the condensation liquefaction process of water vapor in supersonic nozzle (Wen et al., 2015). In the design of supersonic nozzle for supersonic cyclone separator, it was necessary to choose the appropriate cone angle to improve the liquefaction rate of water vapor under the condition of ensuring water vapor liquefaction.

5. Conclusions

The wet steam model was introduced into the numerical calculation of wet steam liquefaction in supersonic nozzle, and the numerical model was verified and analyzed on the basis of relevant literature. The numerical result was in good agreement with the experimental data of the relevant literature, which proved the feasibility and accuracy of the wet steam model applied to the liquefaction of supersonic nozzle.

In the case of the same structure of the expansion section of the supersonic nozzle, the Witozinsky curve was selected for the contraction section of the supersonic nozzle, comparing with the nozzle employed by bicubic curve, the nucleation rate of droplets in the nozzle increased by 21.97 % and the droplet number increased by 32.16 %, which was helpful to the liquefaction of water vapor in the supersonic nozzle. When the contraction curve of the supersonic nozzle was the same and the expansion curve of the supersonic nozzle was Foelsch curve, the nucleation rate and droplet number of water vapor in the nozzle were greatly increased. The distribution of nozzle humidity had nothing to do with the line type of contraction section, but with the line type of expansion section. The humidity at nozzle outlet depended on the diameter of nozzle outlet.

With the same nozzle structure, the cone angle of the expansion section increased from 2° to 8°, the peak nucleation rate increased by 493.15 %, the maximum droplet number increased by 246.12 %, and the outlet humidity of the nozzle increased by 73.37 %, which greatly improved the liquefaction rate of water vapor. In industrial applications, under the condition of ensuring water vapor liquefaction, increasing the cone angle of expansion section was beneficial to water vapor liquefaction.

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