Effect of Expansion Taper Angle on Velocity and Temperature Distribution of Laval Nozzle

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***Abstract*—With the development of gas industry, the production safety and production efficiency of natural gas is crucial, Laval nozzle is the core component of natural gas supersonic dehydration technology, and the study of its structure is helpful to improve the efficiency of dehydration. Based on the finite volume method, the numerical calculation model of Laval nozzle is established, and its flow field is analyzed by the Fluent. Then, the taper angle is changed to analyze the velocity and temperature of Laval nozzle. The results show that the flow field conforms to the characteristics of Laval nozzle, the outlet velocity decreases with taper angle increases, and the maximum velocity increases with taper angle increases. The outlet temperature increases with taper angle increases and the minimum temperature decreases with taper angle increases. With the increasing of expansion taper angle, the velocity field and the temperature field are compressed to the laryngeal and the shock wave closes to the laryngeal gradually. Those results can provide a reference for the choice of Laval nozzle.**

***Index Terms*—Laval nozzle; natural gas dehydration; expansion; numerical modeling; CFD**

I. INTRODUCTION

The natural gas contains lots of saturated steam, the water vapor condenses to liquid water easily in the process of natural gas gathering and processing. Liquid water is easy to combine with natural gas to generate natural gas hydrate, which will cause the blocking of pipelines, throttles, all kinds of valves and instruments, reduce the production of natural gas and pipeline capacity, increase the power consumption, affect the normal production seriously and even cause production accidents. Natural gas supersonic dehydration technology was introduced in the field of natural gas in 2000 by the Shell as a new type of dehydration technology, which uses the phenomenon that steam in natural gas condenses in the condition of supersonic to dehydrate, and it is signally different to the traditional natural gas dehydration method on the thermodynamic principle and the system structure. Natural gas supersonic dehydration technology concentrates the function of expansion machines, segregators and compressor in a pipe, which greatly simplifying the dehydration system, improves the reliability of the system and reduces the investment of dehydration system, operation cost and environmental pollution. The research and application of natural gas supersonic technology can follow foreign technology front of natural gas dehydration and completely change the insufficient in the traditional natural gas dehydration technology, such as complex system, large volume, complex operation, severe pollution and high operating cost[1].

As the core component of natural gas supersonic dehydration technology, Laval nozzle is widely used in the power equipment of aerospace, automobile engine, steel industry and jet pump. Therefore, the study of the relationship between its structure parameters and working condition will be better to improve the its work efficiency. This paper mainly analyzes the effect of expansion taper angle on velocity and temperature distribution of Laval nozzle.

II. WORKING PRINCIPLE

Laval nozzle mainly consists of two parts, the contraction and expansion section[2], as shown in Figure 1. The contraction section is from large to small, which contract to narrow throat in the middle traditionally known as the laryngeal, and the diameter of pipe change from small to big began with the narrow throat, this is the expansion section. The gas flow into the contraction of Laval nozzle, then it crosses the narrow throat, and it finally drains out after through the expansion of Laval nozzle. The working principle of Laval nozzle: the gas comes into the contraction of Laval nozzle under certain pressure firstly, the motion of gas follows the law of motion that the velocity of gas is inversely proportional to the cross section area of pipe in this stage, so the velocity of gas is accelerated; the velocity of gas will be close to or reach the speed of sound when gas reach the laryngeal, and the velocity of gas is directly proportional to the cross section area of pipe when it is supersonic in the pipe. So, the velocity of gas will further increase in the expansion of Laval nozzle. The Laval nozzle plays a role as a “velocity gain amplifier” in the whole process of flow. If the velocity of gas isn’t reach or near the speed of sound in the laryngeal, it will be decelerated instead of being accelerated. If the velocity of gas is accelerated, it must be close to or reach the speed of sound in the laryngeal[3]. At the same time, the temperature and pressure of gas will be sharp decreased.

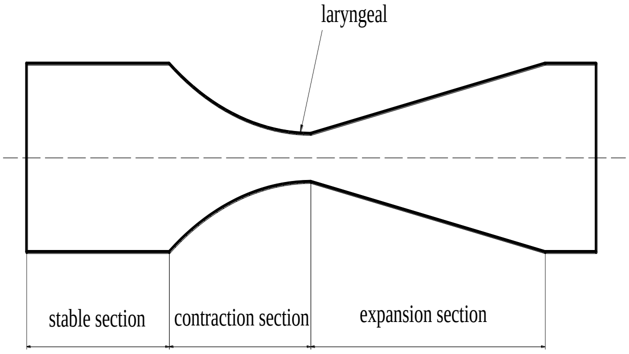

Figure 1 Section shape of Laval nozzle

The process of flow can be considered as heat insulation for the time of it is short, and the friction between gas and the

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inner wall of pipe can be ignored for the inner wall of it is smooth generally, so it is an adiabatic and isentropic ideal process that gas flow in the Laval nozzle. When the gas flows through the Laval nozzle in an adiabatic and isentropic ideal process and swells, the decrease of pressure will lead to the increase of velocity, and the outlet velocity mainly depends on the total temperature of gas and the pressure ratio between inlet pressure and outlet pressure, it's also related to the kinds of gas. In a word, the outlet velocity of Laval nozzle increases with the total temperature increases or the pressure ratio decreases[4].

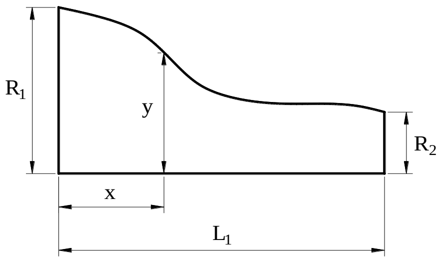
III. NUMERICAL CALCULATION MODEL

Reasonable Laval nozzle should be able to make outlet gas uniform, its turbulence should be small, and it has no shock wave. Laval nozzle can be decomposed into subsonic contraction section, laryngeal and expansion section. This paper adopts the design method: the design method of subsonic contraction section is the Vito Shinseki method, the laryngeal is a circular arc, and the supersonic expansion section is a cone[5].

The subsonic contraction section is designed from the Vito Shinseki curve, and the Formula 1 shows a radius in the contraction section.

$$y = \frac{R_2}{\sqrt{1-\left[1-\left(R_2/R_1\right)^2\right]\left(1-x^2/L_1^2\right)^2 / \left[1+x^2/\left(\sqrt{3}L_1\right)^2\right]^3}} \qquad (1)$$

As shown in Figure 2, R1 is the inlet radius of contraction section; R2 is the outlet radius of contraction section, y is the radius of cross section of any x point and L1 is the length of contraction section in the Formula 1.



As shown in figure 3, the laryngeal of Laval nozzle is a circular arc, the expansion section is a cone, the inlet diameter and outlet diameter are 40mm, the total length is 230mm, the length of inlet stable section is 40mm, and the length of contraction is 40mm. Then, the taper angle is changed to analyze the variation of velocity and temperature. Considering about the feature of model and the efficiency of solving, the model is generated by hexahedral grid, as shown in Figure 4.

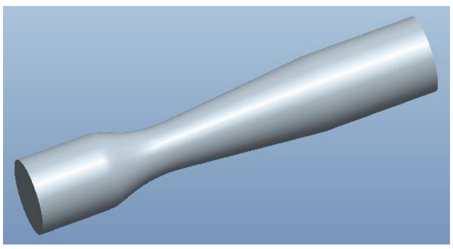


Figure 3 Geometric model

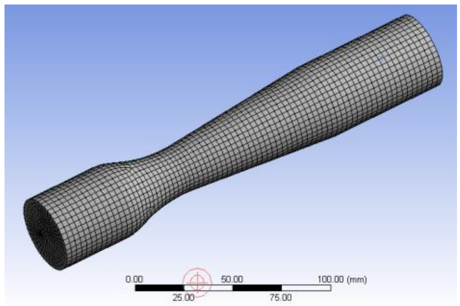


Figure 4 Calculation model

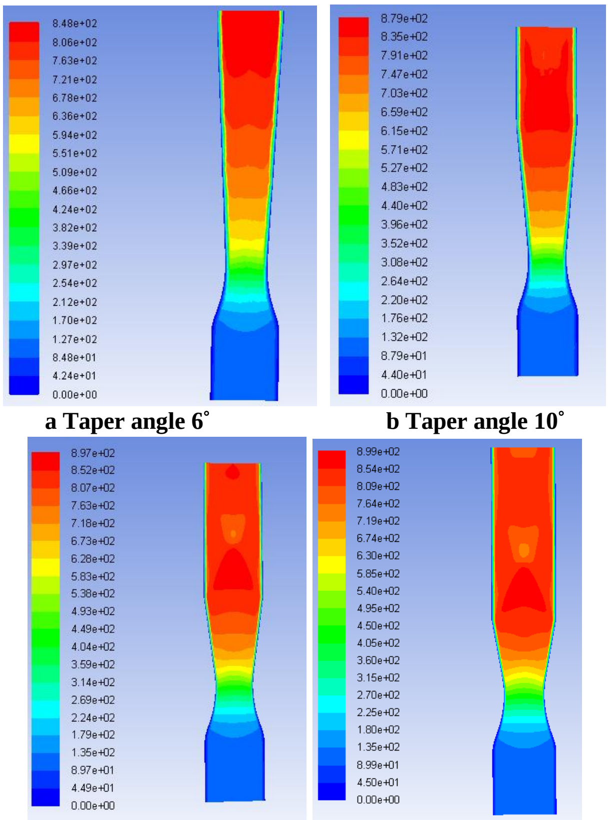
The boundary conditions all use the actual value to simulate the changes of the velocity and temperature distribution more accurately in the process of numerical simulation[6]. The inlet pressure is 0.25MPa, the inlet temperature is 350k; the outlet pressure is 0MPa, the outlet temperature is 300k; and the other boundaries are no slip adiabatic wall. The turbulence parameters of inlet and outlet are turbulent intensity and hydraulic diameter. The gas used in the simulation is methane, and the operation pressure of environment is 0MPa.

The software module of Fluent is imported in the Workbench, the turbulence mode is standard k-epsilon model, the 3D steady-state solver is choosed in the calculation, and the energy equation is opened. The Numerical method choose SIMPLE algorithm; the pressure of discrete format is QUICK format; the coupling between pressure and velocity chooses SIMPLE format; the momentum and energy all adopt the second-order windward format.

IV. ANALYSIS OF THE SIMULATE RESULTS

A. *Analysis of the velocity distribution*

The Figure 5 shows the velocity distribution when the taper angle is 6°, 10°,15°and 20°, the velocity of gas in the laryngeal near the velocity of sound, and the gas is accelerated to supersonic, which meet the characteristic of Laval nozzle. The gas is almost stationary when it near the wall due to the effect of wall, but the velocity gradient is large. When the taper angle is 6°, the velocity field is stable and has no obviously shock wave. When the taper angle is 10°, the velocity field is gradually compressed to the laryngeal and begins to occur the shock wave, and the local velocity field is not stable. When the taper angle is 15°, the velocity field is further compressed to the laryngeal and occurs obvious shock wave, the velocity decreases significantly in the center of shock wave, and the velocity field of expansion section occurs fluctuation. When the taper angle is 20°, the velocity field is further compressed to the laryngeal too and occurs several shock waves, the velocity decreases significantly in the center of shock wave, the shock wave is increased and closes to the laryngeal, and the velocity field of expansion section occurs larger fluctuation. The change of taper angle severely influences the velocity field under the laryngeal and has small effect on the stable section and contraction section up the laryngeal. With the increasing of taper angle, the velocity field under the laryngeal is compressed to the laryngeal, the velocity gradient is increased, and the shock wave is close to the laryngeal gradually.



a Taper angle 6° **b Taper angle 10°**

c Taper angle 15° **d Taper angle 20°**

Figure 5 Cloud picture of velocity in different taper angle

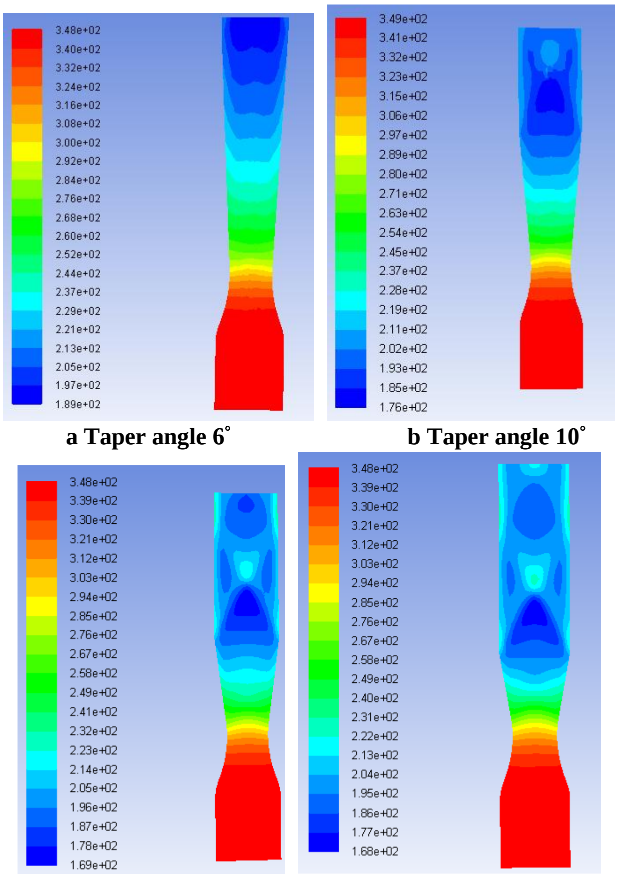
The Table 1 shows the value of velocity in different taper angle, the outlet velocity decreases with taper angle increases, the maximum velocity increases with taper angle increases, and both of them are significantly greater than the speed of sound.

Table 1 Velocity in different taper angle

Taper[°]	6	10	15	20
maximum velocity[m/s]	848	879	897	899
Outlet velocity[m/s]	821.5	815.2	801.9	796.4

B. Analysis of the temperature distribution

The Figure 6 shows the temperature distribution when the taper angle is 6°, 10°,15°and 20°, the temperature of gas decreases continually and the amplitude of variation is large, which meet the characteristic of Laval nozzle. When the taper angle is 6°, the temperature field is stable and has no obviously shock wave. When the taper angle is 10°, the temperature field is gradually compressed to the laryngeal and begins to occur the shock wave, and the local temperature field is not stable. When the taper angle is 15°, the temperature field is further compressed to the laryngeal and occurs obvious shock wave, the temperature decreases significantly in the center of shock wave, and the temperature field of expansion section occurs fluctuation. When the taper angle is 20°, the temperature field is further compressed to the laryngeal too and occurs several shock waves, the temperature decreases significantly in the center of shock wave, the shock wave is increased and closes to the laryngeal, and the temperature field of expansion section occurs larger fluctuation. The change of taper angle severely influences the temperature field under the laryngeal and has small effect on the stable section and contraction section up the laryngeal. With the increasing of taper angle, the temperature field under the laryngeal is compressed to the laryngeal, the temperature gradient is increased, and the shock wave is close to the laryngeal gradually.



a Taper angle 6° **b Taper angle 10°**

c Taper angle 15° **d Taper angle 20°**

Figure 6 Cloud picture of temperature in different taper angle

The Table 2 shows the value of temperature in different taper angle, the outlet temperature increases with taper angle increases, the minimum temperature decreases with taper angle increases, and both of them are significantly less than the inlet temperature.

Table 1 Temperature in different taper angle

Taper angle[°]	6	10	15	20
Minimum temperature[k]	189	176	169	168
Outlet temperature[k]	198.4	200.7	205.3	207.3

V. Conclusion

This paper mainly analyzes the effect of expansion taper angle on velocity and temperature distribution of Laval nozzle. The velocity of gas in the Laval nozzle is increasing, it reaches the speed of sound in the laryngeal and it is accelerated to supersonic in the expansion section, the temperature is decreasing, all of them meet the characteristic of Laval nozzle. The outlet velocity decreases with taper angle increases and the maximum velocity increases with taper angle increases. The outlet temperature increases with taper angle increases, the minimum temperature decreases with taper angle increases. With the increasing of taper angle, the velocity and temperature field is compressed to the laryngeal and the shock wave is close to the laryngeal gradually. Therefore, the suitable taper angle in the expansion section can be choosed according to the results when the Laval nozzle is used for natural gas supersonic dehydration.

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