Simulation research on the flow field performance of the supersonic separator for natural gas

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Abstract. The separation of natural gas dehydration and de-heavy-hydrocarbons is an important part of natural gas treatment, the main purpose of which is to prevent liquid water in the later processing, transportation and storage of natural gas, and to prevent acidic gas dissolving in free water which will cause the corrosion of pipelines and equipment. This paper introduces a new type of natural gas separation technology—supersonic gas-liquid separation technology. Based on the working principle of supersonic gas liquid separator, using relevant theories such as fluid mechanics, gas dynamics and thermodynamics, the structure of Laval nozzle was mainly optimized and the flow field of the separator was simulated through ANSYS software, the distribution of the characteristic parameters such as pressure, velocity, temperature of shrink segment, throat, expansion segment of the supersonic cyclone separator nozzle were studied in this paper. The results show that the design of the nozzle structure meets the needs of low temperature, can make the water vapor in natural gas condense into small droplets and separate out, so as to achieve the goal of natural gas dehydration. Then, comparing the different design methods of Laval nozzle, the most reasonable design scheme is selected to improve the separation efficiency of the separator.

1. Introduction
The main components of natural gas extracted from the well site are methane, which also contains a certain amount of water, heavy hydrocarbons, acidic gases, etc., which can cause serious harm to natural gas transportation. Condensation of water and heavy hydrocarbons increases the resistance of pipeline flow and increases the energy consumption of transportation, as well as the risk of hydrates clogging pipes; the dissolution of acidic gases such as hydrogen sulfide and carbon dioxide in liquid water can cause corrosion of pipes and shorten pipe life. In order to ensure the safe storage and transportation of natural gas, it is required to separate the water, heavy hydrocarbons, acidic gases and other parts of natural gas.

In the late 1990s, supersonic separation technology for dehydration of natural gas was successfully developed abroad. Supersonic cyclone separator is a major technological innovation in natural gas processing industry. Compared with conventional natural gas treatment technology, it has the advantages of less investment, high efficiency, low energy consumption, no pollution and small size, which greatly simplifies the process of natural gas dehydration. Currently, there are two broad categories of supersonic natural gas separation technology: first expansion and then rotary flow (Twister I type) and first spinr and then expansion (Twister II type). The dew point of natural gas treated by this device can be reduced to less than -10 degrees C, which can meet the requirements of natural gas export in many areas. Lower pressure reduction, as low as 25%-33%,is attained and liquid separation efficiency can be more than 90%[1]. The design of key components of this separator in
China also depends on experience, lack of complete theoretical calculation method. The design of
dewatering device efficiency can not achieve the desired effect due to the uncertainty of empirical
design. It is particularly necessary to optimize the structure on the basis of known theoretical analysis,
and quantitatively study the internal detailed flow field of the device. Using numerical simulation
method, this paper studies the flow field characteristics of the shrinkage segment and the expansion
segment of the Laval nozzle, the key component of the first expansion gas supersonic separator, and
then compares the different design methods of the Laval nozzle to select the most reasonable design
scheme and improve the separation efficiency of the separator.

2. Principle and design of structure
The supersonic separator consists of a Laval nozzle segment, a rectifier separation segment (which
contains a rotary wing) and an expansion pipe segment (also known as a backpressurized segment).
The gas flow accelerates from the subsonic velocity of the indented segment to the outlet
supersonic velocity of the edification segment, while the gas pressure and temperature drop sharply
within the Laval nozzle, and the condensate vapor condenses into small droplets in the air flow; The
rectified tube in front of the rotary wing causes the outlet air flow of the nozzle to reduce the
turbulence, and the rotary wing causes the gas flow to produce a whirlwind, causing the liquid to be
thrown to the wall of the pipe and flowing out of the drain pipe under the action of large centrifugal
force, separating water and coagulate from natural gas; the pressure expansion tube achieves dry gas
flow boost and velocity reduction, so the pressure is restored to 70% to 80% of the initial pressure.
According to the field inlet pressure 11 MPa, temperature 278K, yield 30×10^4 m^3/d of the operating
conditions, using the BWRS actual gas state equation to calculate the throat size, the design of the
geometry of the nozzle is: Laval nozzle shrink segment 187mm, throat length 5mm, expansion section
52 mm, steady segment 110mm, expansion section 80mm, inlet diameter 100mm, throat diameter
13.84mm, nozzle outlet diameter 17.7mm.

3. Method of numerical simulation
3.1. Control equations and computation model
The flow of natural gas in the supersonic separation device follows the continuous equation, the
momentum conservation equation and the energy conservation equation. In addition, since internal
flow involves high-velocity expansion, it is important to select a turbulent model that accurately
describes this complex flow field. The existing turbulence model is analyzed in this paper: Because the
standard k-ε model will appear some distortion when it has a curved wall surface, and the RNGk-ε
model can better handle the high strain rate and the high degree bending of stream-line, the RNG k-ε
model suitable for high Reynolds number turbulence field is choosed in this paper.

3.2. Mesh generation calculation method
According to the structure of the supersonic separator designed, the Laval nozzle segment, the
expansion section and other parts can be used heteara-body mesh. The rotary wing and the rotary tube
are divided by non-structural tetrahedral mesh . Among them, Laval nozzle throat and gradual
expansion pipe, cyclone pipe segment needs to be properly mesh encryption treatment. The flow
equation, the turbulent energy equation and the turbulent energy dispersion equation in the turbulence
model are solved in a second-order welcome style. Due to the compressible fluid flow characteristics,
using pressure import and export boundary conditions, solid wall surface with no slip, insothermal, no
seepage conditions.

4. Optimization of the structure design of Laval nozzle
4.1. Shrink segment design
A good shrinkage can improve the stability, uniformity and reduce turbulence of the flow field. The
shrink ratio and shrink curve determine the performance of the shrink segment. If the shrink angle is 15 degrees, the length of the shrink segment is \( L_1 = \frac{D_0}{2 \tan 15^\circ} = 186.6 \text{mm} \).

The shape of the shrink curve affects the uniformity of the nozzle outlet airflow. There are many design methods of shrink segment curves, and in this paper, the three design methods of Witozinsky curve, double three curves and five curves are used to design shrink segment lines and determine the optimal scheme. The nozzle expansion segment lines in all of the figures below are designed according to the Foelsch method.

4.1.1. Pressure-position chart comparison of the three curves

![Figure 1. Vitosinski-curve pressure-position](image1)

![Figure 2. Double-triple curve pressure-position](image2)

![Figure 3 Five-time-curve pressure-position](image3)
Through Figure 1, Figure 2, Figure 3, the shrinkage segment pressure-position map of three different curves, it can be seen that for the Vitosinski-curve the pressure gradient does not change much, dropping to 4.5MPa at the throat; for the double-three-time curve before 125mm of the axial distance pressure basically does not change, after 125mm the pressure gradient becomes large, near straight down to the throat pressure 6MPa, after the throat pressure gradient change slows down; for the five-time curve before 125mm of the axial distance the pressure basically does not change, after 125mm the pressure gradient becomes larger, from 175mm to near the throat the pressure gradient changes slow down, the pressure gradient at the throat increases again, the throat pressure 5.5 MPa.

4.1.2. Temperature-position chart comparison of the three shrink segment curves

Figure 4. Vitosinski-curve temperature-position

Figure 5. Double-triple-time temperature-position

Figure 6. Five-time curve temperature-position
Through Figure 4, Figure 5, Figure 6 these temperature-position map of three different curve of shrinkage segment, we can see that the Vitosinski curve fell flat to the throat after a sharp decline; for double three-time curve before 125mm of the axial distance the temperature basically does not change, after 125mm the temperature gradient becomes large, near straight down to the throat temperature 230K-225K, after the throat temperature gradient change slows down; the temperature of five-time curves before 125mm of the axial distance is basically unchanged, after 125mm the temperature gradient becomes larger, and slows down from 175mm of the axis to near the throat, and at the throat increases again.

4.1.3. Velocity-position chart comparison of three curves

Figure 7. Vitosinski curve velocity-position

Figure 8. Double-triple-time curve velocity-position

Figure 9. five-time curve velocity-position
Through Figure 7, Figure 8, Figure 9th velocity-position charts of three different curve shrink segment, you can see: velocity at the throat can reach 1 times the velocity of sound, and in the exit of the expansion segment it reaches 2 times the velocity of sound; for Vitosinski curve from start to the near of throat the velocity gradient remains unchanged, after the throat it has a sharp rise, and then the change slows down; double three-time curve before 90mm of the axial distance the velocity basically does not change, after 90mm the velocity gradient becomes large and basically unchanged, near straight line rose to the throat to the expansion section exit. For five-time curve in the axial distance of 90mm before the velocity basically does not change, 90mm after the velocity gradient becomes larger, from 175mm of the axis distance to near the throat gradient change slows down, the velocity gradient of the throat increases again.

4.1.4. A comparative analysis of the shrink segment design method

According to the above diagrams, first of all, three design methods meet the design requirements, and the temperature at the outlet of the nozzle is between 150K and 160K, far exceeding the condensation temperature of the separated water vapor and some heavy hydrocarbons, and higher than the corresponding pressure methane condensation temperature of 110K. For the Vitosinski curve the diameter gradient at the far end of the throat is larger than of the nozzle, while radius change at the front part of the shrink segment is relatively flat. For double three-time curve and five-time curve radius gradient change is relatively flat overall, it is the most drastic in the middle part. Compared with the five-time curve, for double three-time curve radius gradient change after the exit of the throat is flat, which is conducive to improving fluid flow of the throat and expansion segment. All the above analysis shows that parameter variation curves of the double-three-time curve are smoother than that of the five-time curve and the Vitosinski curve. Based on this study, it is suggested that the design of the nozzle shrink segment of the supersonic cyclone separator should give preference to the double-triple curve.

4.2. Expansion segment performance comparison

The performance comparison of the expansion segment adopts the control variable method, and the shrink segment is designed with a double-three-time curve. The performance of the expansion segment of the Laval nozzle of Fuls's wave-eliminating design is reflected in the above figures, and the following only explains the variation of the flow parameters of the expansion segment of the conical angle design method.
4.2.1. The pressure, temperature and velocity distribution chart of the conical angle method design

Figure 11. Pressure-position of the conical angle method

Figure 12. Temperature-position of the conical angle method

Figure 13. Velocity-position of conical angle method

4.2.2. A comparative analysis of the expansion segment design method

For Fuls wave-eliminating method and conical angle design method, due to diameter of the expansion segment export is the same, and are designed according to twice Mach number, and the boundary conditions have not changed, so the pressure, velocity, temperature and other parameters are not significantly different. It is obvious from Figure 13 that the expansion segment velocity has stagnated, and from Figure 12, it can also be seen that the temperature changes in some parts of the expansion segment interface are not continuous. Therefore, the biggest difference between the two design methods is that the conical angle design can
not eliminate the expansion wave caused by the continuous increase in the diameter of the pipe wall, resulting in local variation in the expansion segment stagnation. From the above research, it can be seen that the expansion segment design should adopt the Fuls wave-eliminating method.

5. Conclusion
In this paper, the key component nozzles of supersonic separators are designed, and the flow of fluid under different nozzle structures is simulated with Ansys software, and the following conclusions are obtained through simulation results analysis:

(1) The shrinkage segment the change law of pressure, axial velocity and axial temperature of different curves are studied and the change trend of double-triple-time curve is better than that of Vitosinski curve and five-time curve. Double-triple-time curve is recommended for selecting curve of the shrink segment design

(2) The throat segment velocity increases to twice the local sound velocity, and the pressure, velocity, and temperature change the most. In order to ensure the gas flow evenly 5mm long iso-diameter tube is used.

(3) The expansion segment With the increase of pipeline cut-off area, the pressure and temperature continue to decrease, and the gradient of each flow parameter gradually becomes flat; the velocity reaches supersonic velocity and is nearly twice the velocity at the exit. The Fuls de-wave method significantly makes the expansion segment flow more uniform and the pressure loss less. It is recommended using the Fuls wave-eliminating method for designing the expansion segment.

(4) About the length The shrinkage and expansion segment of the nozzle should not be too long, too long pressure loss is too much; at the same time they cannot be too short, in order to avoid uneven fluid flow or even the possibility of separation, to avoid the condensation of the droplets too small and not conducive to the condensation of the droplets.

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