Structural design and application analysis of Laval nozzle

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Abstract. The purpose of this project is to apply the principle of Laval nozzle to reconstruct the gas stove, improve the combustion efficiency of the gas stove, transform its tail gas products, and reduce the tail gas pollution of the gas stove. In this paper, ANSYS software is used to simulate the Laval nozzle of micro modular liquefied gas micro propulsion system, and the relationship between the size factors of the nozzle and the flow effect of liquefied gas is obtained.

1. Introduction

As one of the most important fuels for domestic gas stoves in China, the consumption of natural gas increases rapidly with the improvement of the living standard of residents. However, the combustion efficiency of most gas stoves is not satisfactory. Up to now, only about 10% of the gas stoves on the market have reached the level 1 energy efficiency requirements (combustion efficiency ≥ 63%), while the proportion of gas stoves that fail to reach the lowest level 3 energy efficiency threshold (combustion efficiency ≥ 55%) and are facing elimination will exceed 15%;

In this work, starting from the disadvantages of low combustion efficiency and high emission of the existing burners, the fuel premixing process is reformed by using the structure of Laval nozzle. By controlling the air flow rate and incident direction, the premixing effect of the fuel is enhanced, so as to achieve the use effect of more full fuel combustion and less waste.

In this paper, ANSYS simulation, inventor modeling and other software simulation methods are used to simulate and calculate the parameters of Laval nozzle in this project, and the parameters are more efficient in product work.

2. Structure principle of Laval nozzle

The bottom of the work adopts the design of the imitation Laval nozzle, which is in the form of expanding at both ends and closing at the middle. The Bernoulli equation is used:

\[ P + \frac{1}{2} \rho v^2 = \text{constant} \]

It can be concluded that when the methane gas flows from the flaring inlet to the middle closing part, the air flow speed is accelerated, and the pressure in the flowing area is reduced, so that the external air is sucked into the pipe to achieve the preliminary premixing effect, and then enters the multi jet tangential mixer of the next part.
3. Structural design of Laval nozzle

The jet pipe based on Laval nozzle structure consists of flared inlet, middle throat, outlet and entrainment chamber. Natural gas enters the jet pipe at a speed of 3 M/s to form turbulent jet. In the process of natural gas flowing forward, the speed is accelerated, and a certain negative pressure is formed through the closing area, which makes the outside air continuously sucked into the jet pipe, and mixed with natural gas into the next part of the multi jet tangential mixer.

The speed of the ejected air entering the Laval tube:

$$w_0^2 = \frac{2g\kappa_0 p_0}{\kappa_0 - 1 \rho_0} \left[ 1 - \left( \frac{p_2}{p_0} \right)^{\frac{\kappa_0 - 1}{\kappa_0}} \right]$$

Where:
- $\varepsilon$ - local resistance coefficient, $\varepsilon = 0.15$
- $w_0$ - velocity of the ejected gas entering Laval tube, M/S;
- $g$ - acceleration of gravity, M/S²;
- $p_2$ - inlet pressure of mixing chamber, MPa;
- $\kappa_0$ - adiabatic index of the injected gas, air $\kappa_1 = 1.40$;
- $p_0$ - pressure of the injected gas, MPa; (20)
- $\rho_0$ - density of the injected gas, kg/m³;

When $W_0 = 5$ m/s, the inlet pressure of Laval nozzle should be $P_2 = 0.354pa$.

Known initial conditions:
- Domestic natural gas pipeline pressure 2000Pa;
- The density of natural gas $\rho$ is about 0.025kg/cm³;
- Natural gas pressure at the inlet $P_0 = 0.354$mpa;
- The temperature is room temperature $t_0 = 20 \degree C + 273 = 293k$;
- Density $\rho_0 = P * 10 * 0.66kg/m³$;
- Volume flow $QV = 1.1l/s$;

The length of the contraction section of Laval tube is generally short, and the gas velocity is very high. It can be considered that there is no heat exchange between the gas and the outside, which is considered as an adiabatic process. Therefore, the isentropic adiabatic flow process can be used to deal with the gas flow in the contraction section. Let the parameters at the throat of Laval pipe be respectively: pressure $P$, density $\rho$, velocity $u$ and area $A$. The energy loss in the process of pipeline flow is not included. Since the gas flow rate of the gas source is small, the gas energy equation at the throat of the jet pipe is as follows:

$$\frac{k}{k-1} \frac{P_0}{\rho_0} = \frac{k}{k-1} \frac{P}{\rho} + \frac{u^2}{2}$$ (1)
From equation (2-1), it is found that:

\[ u = \sqrt{\frac{2k p_0}{k-1 \rho_0} \left(1 - \frac{p}{p_0} \frac{\rho}{\rho_0}\right)} \]  

(2)

From the relationship between pressure and density in isentropic process:

\[ \frac{p}{p^k} = \frac{p_0}{p_0^k} \]  

(3)

Where \( k \) is the thermal insulation coefficient, in the experiment, it is domestic natural gas, and its thermal insulation index is \( k = 1.3 \).

Substituting formula (2-3) into formula (2-2), we can get:

\[ u = \sqrt{\frac{2k p_0}{k-1 \rho_0} \left(1 - \left(\frac{p}{p_0}\right)^{\frac{k-1}{k}}\right)} \]  

(4)

If the sectional area of Laval nozzle throat is \( a \), then the mass flow through the nozzle is:

\[ q_m = p u A \]  

(2-5)

Among them, from the relation formula (2-3) of pressure and density under isentropic relation, we can get:

\[ \rho = \rho_0 \left(\frac{p}{p_0}\right)^{\frac{1}{k}} \]  

(2-6)

Substituting equation (2-6) and equation (2-4) into equation (2-5), the expression of gas mass flow rate can be obtained as follows:

\[ q_m = \rho_0 \left(\frac{p}{p_0}\right)^{\frac{1}{k}} A \left\{\frac{2k p_0}{k-1 \rho_0} \left[\left(\frac{p}{p_0}\right)^{\frac{2}{k}} - \left(\frac{p}{p_0}\right)^{\frac{k+1}{k}}\right]\right\} \]

When the initial stagnation parameter of gas is given, the mass flow through the throat section of Laval nozzle depends on the pressure change at the throat. When the pressure is in the range of \( 0 \sim P_0 \), the change of flow rate increases from zero to a maximum value \( Q_{max} \). The maximum flow rate \( Q_{max} \) can be calculated by \( \frac{dQ}{dP} = 0 \), that is:

\[ \frac{d}{dq} \left[ \left(\frac{p}{p_0}\right)^{\frac{2}{k}} - \left(\frac{p}{p_0}\right)^{\frac{k+1}{k}}\right] = 0 \]

The pressure at the throat is:

\[ p = p_0 \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = 0.354MPa \left(\frac{2}{1.3 + 1}\right)^{\frac{1.3}{1.3-1}} = 0.193MPa \]

The velocity at the throat is:

\[ u = \sqrt{\frac{2k p_0}{k+1 \rho_0}} = \sqrt{\frac{2 \times 1.3 \times 3540}{1.3 + 1 \times 6.6 \times 0.354}} = 41.3857m/s \]
For the natural gas with pressure of $P = 0.002$ mpa and temperature of $T = 20 ^\circ C$, the volume flow rate is $q = 1.1l/s$, and the mass flow rate is:

$$q_m = \rho_0 V = 6.6 \times 0.354 \text{kg/m}^3 \times 1.1 \times 10^{-3} \text{m}^3/s = 2.57 \times 10^{-3} \text{kg/s}$$

According to the continuity equation of the fluid:

$$q_m = puA$$

The throat area of Laval nozzle is:

$$A = \frac{q_m}{pu} = \frac{q_m}{\rho_0(\frac{p_e}{p_0})^{\frac{k}{k+1}}} = \frac{2.57 \times 10^{-3}}{2.3364 \times \frac{0.193}{0.354}^{\frac{1}{1.3}} \times \frac{2.6}{2.3} \times 354000 \times 2.3364}$$

$$= 5.608 \times 10^{-4} \text{m}^2 = 560.8 \text{mm}^2$$

If $a < e$ is the exit cross-sectional area of Laval nozzle, the formula for calculating the exit cross-sectional area of Laval nozzle expansion section is as follows:

$$A_e = \frac{q_m}{\sqrt{2k \rho_0[(\frac{p_e}{p_0})^{\frac{2}{k}} - (\frac{p_e}{p_0})^{\frac{k+1}{k}}]}}$$

$$= \frac{2.57 \times 10^{-3}}{\sqrt{2.6 \times 354000 \times 2.3364 \times [(0.048)^{\frac{2}{1.3}} - (0.048)^{\frac{1.3+1}{1.3}}]}}$$

$$= 1344.9 \text{mm}^2$$

The diameter of the outlet section of Laval pipe is:

$$d_e = \frac{4A_e}{\pi} = 41.391 \text{mm}$$

The diameter of the throat is:

$$d = \frac{4A}{\pi} = 26.728 \text{mm}$$

In order to ensure the smooth flow of air flow, a transition section shall be set at the throat. The diameter of the transition section is the same as that of the throat. Its function is to ensure the smooth flow of air and prevent turbulence. The length calculation formula of this section is:

$$\delta = (0.5 \sim 1) \times d$$
Where δ generally does not exceed the size of the throat diameter, it is calculated that:

\[ \delta = 17mm \]

The temperature at the throat is:

\[ T = 0.833T_0 = 244.07K \]

If the diameter of inlet end of Laval pipe is \( D_1 = 40\text{mm} \), the length of contraction section of Laval pipe is:

\[ L_c = \frac{d_1 - d}{2 \tan \frac{\alpha}{2}} \]

In the formula, the value range of \( \alpha \) method is \( \alpha = 30^\circ \sim 45^\circ \) and \( \alpha = 30^\circ \) for calculation. The length of contraction section is as follows:

\[ L_c = 24.761mm \]

The length of Laval expansion section is:

\[ L_d = \frac{d_e - d}{2 \tan \frac{\beta}{2}} \]

Take \( \beta = 8^\circ \), and the calculated length of Laval expansion section is: \( LD = 104.886\text{mm} \)

![Figure 2 Laval nozzle structure design](image)

4. Parameter verification and result analysis
Use the above parameters to use Inventor software for modeling, and use ANSYS software for fluid simulation analysis. The results are as follows:
According to the fluid analysis of ANSYS, when the gas enters the Laval pipe and flows from the flaring inlet to the middle closing part, the gas flow speed increases and the pressure in the flowing area decreases, which can achieve the effect of entraining the external air into the pipe. At the same time, by controlling the gas velocity in the inlet direction and the length in the opening direction, the gas velocity entering the next part of the multi jet tangential mixer can be determined.
5. Epilogue
Through calculation, Laval nozzle can effectively control the gas flow rate and meet the use requirements of the project.

In this paper, the simulation analysis of the Laval nozzle of micro modular liquefied gas is carried out by using ANSYS software. The relationship between the size factors of the nozzle and the flow velocity is obtained, and the final optimized size of the nozzle is given.

(1) The outlet diameter, throat diameter and length of contraction section have great influence on the velocity of fluid.

(2) The final optimized size of nozzle is: inlet diameter 40 mm, throat diameter 26.728 mm, outlet diameter 41.391 mm, contraction length 15 mm, expansion length 105 mm.

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