Simulation Analysis of Single Hole Steam Jet Noise

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Abstract. In order to improve the low noise design level of the steam pipeline, the single-hole jet noise with a hole diameter of 10 mm was simulated and analyzed employing a DN125mm steam pipeline. The calculation results show that the in-tube injection has a distinct velocity potential nuclear region, and the vortex generated by the injection is changes as the flow direction changes. The closer the nozzle is, the smaller the vortex volume at the nozzle is as well as the higher the radiation noise frequency is. The injection noise has obvious directivity, the closer the position is to the center line, the stronger the total sound pressure level is, and the farther the distance is, the total sound pressure level is relatively low.

1. Introduction

Steam jet heat transfer humidification has the advantages of high efficiency and low cost, and has been applied in many industrial fields. With the improvement of environmental protection requirements, the noise control of steam pipelines is of great significance for improving the industrial design level. Taking the DN125mm steam pipe as the object, the single hole injection noise with a hole diameter of 10mm was simulated and analyzed, which provided a support basis for the design of the single hole steam injection system. There are many studies on condensation and heat transfer for single-hole injection[1-5], but studies on noise analysis are rare.

2. Model parameters and boundary conditions

2.1 Model structure and meshing

Since the pipeline, orifice and boundary conditions are circumferentially symmetric, the simulation model can be simplified to a two-dimensional structure, and in order to reduce the amount of calculation, the axis is the axis of symmetry, and only half of the two-dimensional structure is taken as the computational domain of the large eddy simulation. After the calculation is completed, it is only necessary to symmetry the above calculation domain to obtain the flow field and sound field of the entire pipeline. The calculated model is a pipe diameter of 125 mm, an orifice plate diameter of 10 mm with thickness of 4 mm. The flow is saturated steam at a gauge pressure of 2.5 MPa, the temperature is 225, the density is 20.6, the dynamic viscosity is 1.76, the thermal conductivity is 5.17, the isobaric specific heat, and the local sound velocity is 500. The mass flow rate of high temperature and high pressure steam is between 0 and 50, and the simulation conditions are 10, 20, 30, 40, 50. The calculation model structure is shown in figure 1. The calculation field length is 150mm before the orifice plate, and the calculation domain length after the plate is 500mm, which is much larger than the main sound source area of the injection noise, that is, the injection range from the nozzle to the diameter of the ten-time nozzle, so as to completely observe the vortex change in the injection.
In order to study the noise characteristics of the restricted injection in the pipeline, six sound pressure monitoring points are taken downstream of the orifice plate to monitor the injection noise. The origin of the coordinate is the left end of the central axis of the pipeline. The coordinates of the monitoring points are: (400, 0, 0), (400, 30, 0), (400, 62, 0), (600, 0, 0), (600, 30, 0), (600, 62, 0).

2.2 Boundary conditions and solution method
Boundary conditions of the calculation case are set as followings. Inlet: Speed boundary conditions. According to different mass flow rates, the speed values are: 11, 22, 33, 44, 55, corresponding to steam flow 10, 20, 30, 40, 50. Outlet: Pressure boundary conditions. The operating pressure is set to 4 MPa, so the outlet pressure is set to 0. In addition, the central axis of the pipeline is set as a symmetrical boundary condition, and the wall surface of the pipeline is set as a non-slip solid boundary condition. The calculation is first performed in a steady-state manner using a two-equation model. After the steady state calculation is converged, a two-dimensional, implicit, non-steady-state, and separate solver is used, and the viscous model of the large eddy simulation is selected. In solving the calculation, this paper uses SIMPLEC algorithm and PRESTO pressure discrete format. The calculation time step is taken as $2 \times 10^{-6}$ s.

3. Calculation results and discussion
3.1 Injection velocity field calculation analysis
It can be clearly seen from figure 2 that the limited injection in the pipeline is similar to the free jetting, and the velocity distribution shows a clear gradient. The velocity is large after being ejected from the orifice. As the jetting distance increases, due to the surrounding gas blending, the high-speed gas flow is continuously lost, the speed is gradually reduced, and the speed change process is gradually transitioned from the periphery of the injection to the core. The velocity of the core area is gradually reduced as the jetting distance increases, but at a fixed jetting distance, the speed of the core zone is the largest relative to the periphery. It can also be seen from the figure that, similar to the analysis by Lighthill and Ma Dazhao, after about 10 times the jetting distance of the nozzle diameter, the velocity distribution cloud has no obvious velocity gradient, indicating that the velocity gradient is not large at this time. The resulting noise is low in frequency and has less acoustic energy.
Table 1 shows the calculation results of the velocity of the inlet, outlet and orifice under different steam flows. It can be seen from the table that as the steam flow increases, the velocity in each section of the entire pipeline increases. When the steam flow rate is 40, the orifice airflow speed is already supersonic, and at this time, high injection noise and impact noise are inevitably generated. It can be seen from the table that as the steam flow increases, the velocity in each section of the entire pipeline increases. When the steam flow rate is 40, the orifice airflow speed is already supersonic, and at this time, high injection noise and impact noise are inevitably generated.

Table 1. Flow rate under different inlet speed conditions

| Position | Flow rate | Inlet | Orifice | Outlet |
|----------|-----------|-------|---------|--------|
| 1        | 11 m/s    | 10.8  | 166     | 25.5   |
| 2        | 22 m/s    | 21.6  | 297.1   | 53.8   |
| 3        | 33 m/s    | 32.3  | 445.2   | 94.2   |
| 4        | 44 m/s    | 43.1  | 593.6   | 93     |
| 5        | 55 m/s    | 53.9  | 742     | 130.4  |

### 3.2. Injection static pressure calculation analysis

As can be seen from figure 3, there is a significant static pressure gradient on the left and right sides of the orifice plate.

The pressure at the inlet of the pipe is large, and the velocity of the steam from the orifice plate is large, so that the pressure is lowered. The higher the speed, the lower the static pressure. As the jetting speed is gradually reduced, the pressure gradually approaches the average.

Table 2 shows the static pressure before and after the orifice plate under different conditions. It can be seen that as the steam flow rate and the flow velocity increase, the static pressure difference between the orifice plates also increases significantly. It can be seen that the orifice plate causes the flow energy loss, and the greater the pressure and the faster the flow rate, the more serious the loss.

Table 2. Pressure drop under different inlet speed conditions

| Position | Flow velocity | Pressure drop |
|----------|---------------|---------------|
| 1        | 11 m/s        | 13694.2       |
| 2        | 22 m/s        | 109329.6      |
| 3        | 33 m/s        | 264510        |
| 4        | 44 m/s        | 443650.1      |
| 5        | 55 m/s        | 665232.6      |
3.3 Calculation and analysis of jet vortex distribution

It can be seen from figure 4 that the vortex distribution of the restricted injection is consistent with the Lighthill theory, and a small vortex is generated near the nozzle. As the injection distance increases, the vorticity is gradually reduced by the influence of the external gas. The vortex volume gradually increases, and the vortex weakens after a certain distance, and its flow field is similar to the steady flow field. The small vortex near the nozzle generates high-frequency pressure pulsation, and as the vortex gradually becomes larger, the noise frequency gradually decreases. The vortex distribution is roughly the same under different inlet conditions.

![Figure 4. Contour map of swirl vorticity near the nozzle](image)

3.4 Calculation and analysis of injection noise field

It can be seen from figure 5 that the distance between the monitoring points and the nozzle is different, and the noise spectrum of the corresponding monitoring points is also different. For example, the high-frequency noise component of the monitoring point 400 mm from the axial direction of the nozzle is much more pronounced in the spectrogram than the 600 mm from the nozzle. When the axial distance is the same, the radial distance of the monitoring point from the nozzle is larger, and the sound pressure level is relatively lower in the whole frequency domain, as shown in a, b, c and d, e, f in figure 6. This is because the closer to the orifice, the greater the intensity of the vortex at the corresponding position and the smaller the volume, the stronger the noise and the higher the frequency component. In addition, the peak frequency of the restricted injection is mainly concentrated between 2000 and 3000, because the high-intensity vortices generated under the above injection conditions are mainly concentrated in this frequency range. And the calculation formula of the peak frequency of the injection noise can also prove the above results:

\[ f_m = \beta \frac{v}{d} \]  

(1)

In the formula, the Strouhal number, \( \beta \) can be approximated as 0.2, \( v \) - nozzle flow rate (m/s), \( d \) - spout diameter (m). It can be seen that the higher the injection speed, and the smaller the nozzle size, results in the higher the peak frequency of the injection noise.

Figure 5 shows the sound pressure levels of different monitoring points. Table 3 summarizes the total sound pressure level values for each sound pressure level monitoring point under different gas flow conditions. It can be seen from the simulation calculation results that the closer the monitoring point is to the orifice, the stronger the noise; the larger the jetting speed, the stronger the noise. In the radial direction of the pipe, the closer the distance is to the center, the stronger the noise.
For the injection noise generated by nozzles with different apertures, such as 5mm, 10mm, 15mm, etc., the noise spectrum diagram should be similar to the above simulation results, except that the peak frequency, the sound pressure level amplitude, etc. are different, with the aperture, spray The variation law of the injection speed should be basically the same as the above simulation results.

Table 3. Sound pressure level of monitoring points under different inlet speed conditions (unit: dB)

| Monitoring point | Flow velocity |
|------------------|---------------|
|                  | 11 m/s | 22 m/s | 33 m/s | 44 m/s | 55m/s |
| (400, 0, 0)      | 163.2  | 176.4  | 183.1  | 188.3  | 192.3 |
| (400, 30, 0)     | 155    | 165.5  | 172.5  | 177.7  | 181.7 |
| (400, 62, 0)     | 151.5  | 159.5  | 167.8  | 171.7  | 174.5 |
| (600, 0, 0)      | 153.2  | 165    | 170.6  | 175.4  | 179.1 |
| (600, 30, 0)     | 150.2  | 160.6  | 166.5  | 171.1  | 174.3 |
| (600, 62, 0)     | 147.7  | 158.3  | 164.4  | 168.8  | 171.8 |

4. Conclusion
The flow and noise characteristics of the two-dimensional limited injection in the tube were obtained by numerical simulation using the large eddy simulation method. The simulation results show that the injection in the tube has a distinct velocity potential core region, and the gradient is no longer obvious after reaching the distance of ten times the diameter of the nozzle. At the same time, the higher the velocity in the pipe, the lower the hydrostatic pressure. The vortex generated by the injection changes with the direction of fluid flow. The volume of the vortex near the nozzle is small, and the frequency
of radiation noise is high. With the increase of the injection distance, the vorticity is gradually reduced and the vortex volume is gradually increased due to the mixing of the external gas. Large, the radiated noise frequency is low, and its flow field is similar to the steady flow field. The closer the position of the tube is to the center line, the stronger the total sound pressure level. The farther the distance is, the lower the total sound pressure level is. The injection noise inside the display tube also has obvious directivity.

References
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