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Analysis of Elbow Effect on the High Pressure Gas Pipe

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Analysis of Elbow Effect on the High Pressure Gas Pipe

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Abstract. For the problem of the pressure drop loss and the equivalent length calculation of elbows in submarine high pressure pipelines, the flow processes of ultra-high pressure gas in 90° elbows were numerically simulated by the way of CFD. The inner flow area was meshed with structured hexahedral grid, and by means of the numerical solution to deal with the RANS equations closed by RNG k-ε turbulence model, the flow field characteristics inside the pipe was studied, and the pressure distribution was obtained. The calculated results are consistent with the numerical simulation and model experiment results carried out by other scholars. Simulation results show that the total pressure loss of the pipe will be increased greatly due to the partial pressure loss caused by elbows. Besides, the feasibility and availability of simulating the flow characteristics of the ultra-high pressure gas inside the elbows by RNG k-ε turbulence model were verified.

1. Introduction

Pipeline is widely used in industry, especially in the shipbuilding industry, such as hydraulic system, water delivery system, high-pressure gas system and emergency blowdown system on submarines. As its working nodes are all over the cabin, pipeline, as its main component, plays an important role in connecting the main station of the system with each target node. However, due to the narrow space inside the submarine and the numerous equipment, a large number of bent pipes with different deflection angles and bending radii must be adopted in each system pipeline in order to meet the requirements of equipment installation and overall layout.

The bend pipe solves the problem of system connection and space layout well, but it also brings many disadvantages. For example, because of the bending degree of the bend, the Mach number of fluid flow and the direction of fluid movement, the flow field in the bend presents very complex flow characteristics. The separation zone will be formed near the pipe wall, especially the secondary flow generated on the cross section of the elbow will cause the loss of total fluid pressure and energy [1], thus affect the work efficiency of the system to some extent. When the submarine's high-pressure gas is emergency blown out of the main ballast tank, the high-pressure gas is rapidly fed into the tank from the cylinder channel. Compared with liquid media such as oil and water, the local pressure drop caused by high-speed flowing gas passing through the bend pipe is more significant. Therefore, it is necessary to consider the effect of bend effect on the pressure loss along the pipe when studying the working efficiency of the submarine high-pressure gas emergency blowout system and establishing the mathematical model.

Based on the existing research conclusion [2], this article adopted RNG k-ε turbulence model based on the renormalization group method to close the RANS equation of the internal flow field of the pipe bending, and by directly numerically solving the equation, the characteristics of the internal flow field of 90 ° elbow are simulated, and the calculation method of the equivalent length of 90 ° elbow under high pressure condition is given. In addition, the pressure distribution in the elbow are emphatically analyzed.

2. Turbulence Model

The author adopts the RNG k-ε turbulence model [3] proposed by Yakhot and Orzag in 1986 to close the Reynolds averaged Navier-Stokes equation, and the generating term in the model is not only related to the flow, but also a function of space coordinates, so that the flow at high strain rate or with a large degree of bending streamline can be better dealt with. The transport equation of this model is [4]:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\alpha_\varepsilon \mu_{eff}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}^{*}\rho\frac{\varepsilon^2}{k} \tag{2}$$

In this formula:

$$C_{2\varepsilon}^{*}=C_{2\varepsilon}+\frac{C_\mu \rho\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3},$$

$$\eta\equiv\frac{Sk}{\varepsilon}=\sqrt{2S_{ij}\cdot S_{ij}}\,\frac{k}{\varepsilon},$$

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right),$$

$C_{1\varepsilon}$=1.42, $C_{2\varepsilon}$=1.68, C_μ=0.0845, η_0=4.377, β=0.012.

3. Experimental Scheme

The simulation experimental model is established as shown in Figure 1. The total length of a pipe is set as 10 m, the number of elbows are set as 0, 2, 4, 6 and 8 respectively, the bending radius of all the elbows is set as 50 mm, the length of the straight tube upstream elbow is set as 1000 mm, the origin O is located in the rotary center of the bending curvature, θ is defined as the polar angle, and the θ on the entrance section of the elbow is 0°, the θ on the exit section of the elbow is 90°.

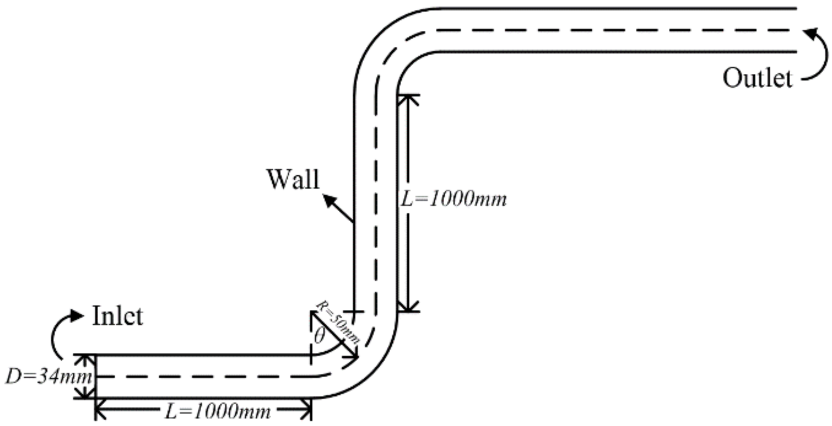

Figure 1. Dimensions of the pipe and elbow

4. Numerical Method

4.1. Boundary Conditions
In the computation, two kinds of boundary conditions were applied to the simulation: the inlet and the outlet of the primary flow use the pressure boundary condition, and the static pressure are respectively 20 MPa and 1 MPa. The pipe wall uses the no-slip wall condition, and the no-slip condition is u=v=w=0.

4.2. Discrete Grid
Structured grid in the pipe is generated by using hexahedral grid cell. In order to improve the computational efficiency, and ensure the precise details of the flow in the dramatic flow area can be captured, the distribution law of compute nodes of the parts with long straight section along the primary flow direction is parabolic, and the grid of the elbow and its nearby area is refined as shown in Figure 2. The near-wall model method is adopted to solve the flow in the viscous bottom layer and the transition layer in the near-wall area. The distance between the grid nodes of the first layer and the endpoints is set as 1.5mm, and the growth ratio of the grid is 1.05, as shown in Figure 3. The total number of the mesh in the five examples is about 320,000, and the simulation results show that when the number of grid nodes in the pipeline length reaches the above set density, the numerical solution of the grid has reached the grid-independent solution.

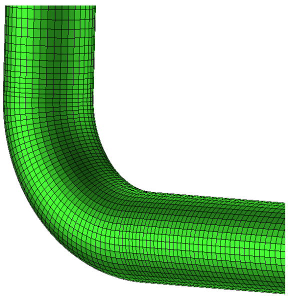

Figure 2. Mesh of the elbow

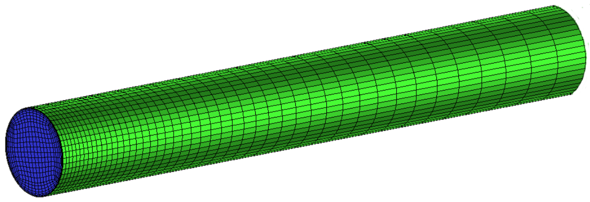

Figure 3. Mesh of the straight pipe

5. Results and Discussion
In the experiment scheme, a few pipes with different number of elbows were designed, for the purpose of studying the equivalent length of the bend conveniently. However, the effects of elbows on the definite inner flow field pattern of each pipeline have the similarity, therefore in the following simulation results analyses, just only the pipe with two elbows was taken as an example, and the inner flow field pattern of the elbow was analyzed emphatically.

Figure 4 shows the isobaric distribution on the symmetry plane of the elbow. As can be seen from the figure, the elbow has a significant effect on the pressure distribution inside the pipe. The pressure distribution on the symmetrical surface of the straight pipe section from the inlet to elbow 1 is uniform. And because of the effect of elbow 1, the pressure distribution on the symmetrical surface of the straight pipe section from the outlet of elbow 1 to the inlet of elbow 2 is non-uniform. The pressure in the region near the pipe wall is higher, while the pressure near the center of the pipe is low, and this phenomenon gradually fade away in the downstream straight pipe of the elbow 2, which means the pressure distribution change to uniform again. What's more, it can also be found that the flow along the pipe wall has a frictional head loss and secondary flow loss due to the molecular viscosity, so that the pressure at the downstream straight pipe section of the bend is less than that at the upstream straight pipe section.

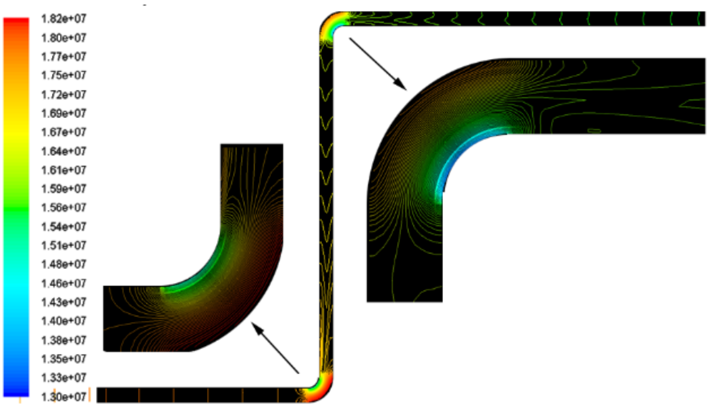

Figure 4. Isobaric distribution of the symmetry plane

In the elbow, the radial pressure gradient is very large, showing a kind of distribution pattern which is that pressure of the region near the inner wall is small, and the pressure near the outer wall region is bigger. The primary cause of this phenomenon is the bending curvature of the elbow. During the process of gas flowing, due to the centrifugal force, high pressure gas will move to the region near outside wall which has a bigger curvature radius, and result in large number of fluids jostling the lateral wall. [5]

In order to further study the law of development and change of pressure distribution at different polar angle sections of the elbow, the cloud maps of pressure distribution on five different polar angle sections of elbow 1, which is that θ=0°, θ=22.5°, θ=45°, θ=67.5° and θ=90° were extracted as shown in Figure 5. The upper part of each figure is the inner side of the elbow and the lower part is the outside of the elbow. As can be seen from the figure, the pressure on the cross section of the elbow shows a distribution trend of low inside and high outside, and before θ=45° cross section, the inside pressure gradually decreases and the outside pressure gradually increases, while after θ=45° cross section, the inside pressure gradually increases and the outside pressure gradually decreases. This is because the centrifugal force on the gas gradually increases before θ=45° section, and gradually decreases after θ=45° section, which is consistent with the theoretical and numerical research conclusions of literature [6], as shown in Figure 6.

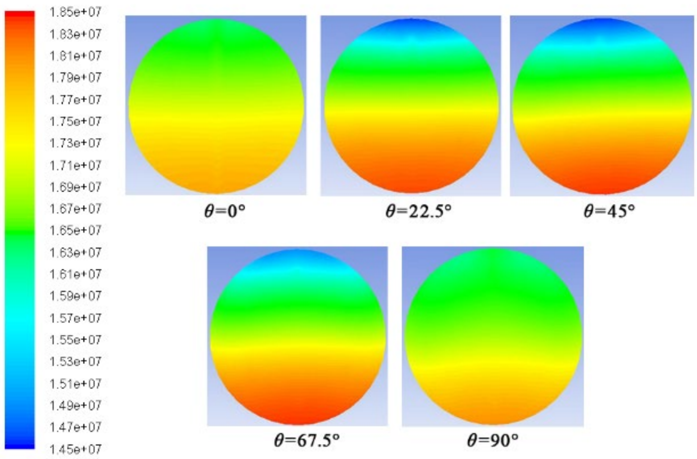

Figure 5. Pressure distribution contours of different polar-angle sections of the elbow

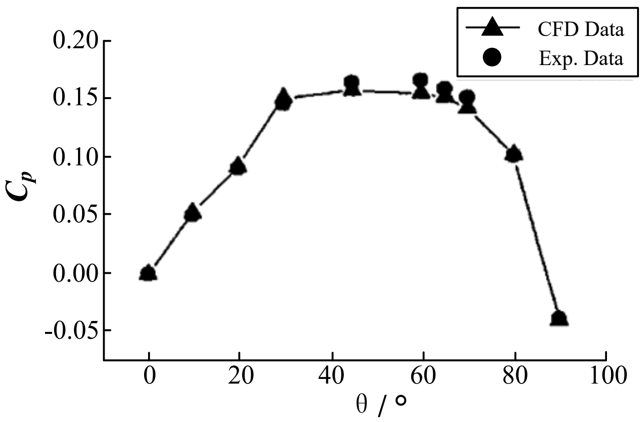

Figure 6. Pressure factor versus polar-angle on the outer wall [12]

Table 1 shows the average static pressure of the inlet section and outlet section of the pipeline and the total gas pressure loss along the pipeline when there are different numbers of elbows in the pipeline.

Table 1. Influence of different number of elbows to the pressure loss along the pipe

The number of elbows	Static pressure of inlet (MPa)	Static pressure of outlet (MPa)	Pressure drop (MPa)	Total length of equivalent pipe (m)
0	17.7	6.6	11.1	9.85m
2	17.8	6.42	11.38	10.32m
4	17.8	6.26	11.54	10.82m
6	17.9	6.12	11.78	11.25m
8	17.9	5.99	11.91	11.8

It can be known by calculating through the table that in this experimental scheme the partial pressure drop caused by 2 elbows is approximately equivalent to the friction pressure drop caused by 0.5 m straight pipe with the same diameter, and compared with the loss pressure along the pipe with no bend, 8 90° elbows can caused an additional 0.8 MPa pressure drop. With regards to submarine emergency blowing efficiency of high-pressure gas, this will cause a serious effect undoubtedly. Therefore, during the design and construction phase of the submarine, the high-pressure air pipe should be reasonably arranged, and the bending pipe, especially the bending pipe with a large deflection angle, should be used as little as possible to connect, so as to improve the high-pressure gas blowing rate of the submarine in an emergency and ensure the submarine's emergency floating ability.

6. Conclusion

By numerical solving RANS equations of compressible gas directly, the authors simulated the flow process of high pressure gas in the quarter bend on the submarine through the RNG k-ε turbulence model, and analyzed the flow pattern in the elbow and its influence on pressure drop. The availability of the numerical method adopted in this paper is verified by comparing with the experimental data of other scholars. The principal conclusions are listed below.

(1) Under the condition that the total length of the pipeline remains unchanged, the local pressure drop caused by the elbow will greatly increase the total pressure loss along the pipeline. Under the pressure conditions described in this paper, the local pressure drop caused by a quarter bend is about 0.2 MPa, and its equivalent length is about 0.25m.

(2) The pressure distribution in the elbow along the flow direction is as follows. Pressure at the inner side first decreases and then increases. On the contrary, pressure at the outer side first increases and then decreases. Even so, the pressure at the outer side is always greater than the former.

Acknowledgments
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