Study on Energy Consumption Characteristics of Sewage Pipe under Different Conditions

Chao Jiang¹, *, Leng Qing²

¹ Nanjing Hydraulic Research Institute, Stake Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering Science, Nanjing 210029, China
² Hohai University, Nanjing, Nanjing 210098, China

*Corresponding author e-mail: wuteng@hhu.edu.cn

Abstract. It can optimize the design of sewage pipe network system and select the design conditions of pipe network to obtain the best hydraulic characteristics and the most economical design plan by studying the hydraulic characteristics of sewage pipe network under different conditions. In this paper, k-ε turbulence model is used to calculate the change of energy consumption characteristics in sewage pipe network under different working conditions. The results show that the pipe diameter is too small and the pressure on the pipe wall increases, which is not conducive to flood discharge. If the inlet velocity is too small, the negative slope of the pipe would lead to the reduction of the overall flow rate, which is easy to cause siltation of the sewage pipe network. Proper pipe diameter, inlet velocity and reasonable slope can help the pipe drain water. Increasing the diameter of the main pipe can improve the stability of the fluid, which is more conducive to sewage discharge.

1. Introduction

With the continuous development of the national economy and the continuous advancement of urban municipal projects, the design of sewage pipe network is also constantly updated and perfected. For sewage pipe network design, some intelligent algorithms and simulation software can be used to more intuitively analyze the internal hydraulic characteristics and provide theoretical basis for optimizing the design. The design is of great significance to save social resources, reduce energy consumption and improve economic benefits. Yuan Xiaoming [1] used fluent software to simulate the laminar and turbulent flow in a 3D circular tube, and analyzed the velocity distribution and pressure distribution. Wangtong [2] discussed the hydraulic characteristics of uniform flow in unpressurized circular pipes. Xu Zishun [3] analyzed the distribution of speed and pressure during sudden expansion and reflux of pipes, and summarized the variation law of resistance coefficient of sudden expansion of pipes. The simulation results can well reflect the basic characteristics of sudden expansion of pipes and provide theoretical basis for improvement of related products in production. Zhao Yanlin [4] carried out numerical simulation analysis on the effluent flow and working pressure of the simplified type of each round irrigation group in the pipe network, and simulated the pipe network pressure and flow with and without the pressure regulating tank according to the arrangement requirements of the pressure regulating tank. Liang Zhixi et al. used Fluent software to simulate the moving flow field in the elbow pipe, explore the changes of the flow field in the elbow pipe, and design the used pipe flow sharing
structure, which can effectively alleviate a series of problems caused by the existence of the elbow pipe [5]. In this paper, the hydraulic characteristics of water flow in sewage pipe network under different conditions are studied by numerical simulation, and the hydraulic characteristics of pipes under different pipe diameters, different inlet velocities, different pipe placement slopes and branch pipes are analyzed, which provides reference for the design of sewage pipe network.

2. Model Establishment

2.1. Control equation

Continuity equation. According to the law of conservation of mass, the sum of the net mass of fluid flowing out of the control body per unit time should be equal to the mass reduced by density change in the control body at the same time interval, thus the differential form of the fluid flow continuity equation can be derived as follows [6-8]:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} + \frac{\partial (\rho u_z)}{\partial z} = 0
\]

(1)

Where: \( u_x, u_y, \) and \( u_z \) are the velocity components in \( x, y \) and \( z \) directions respectively, m/s; \( t \) is time, s; \( \rho \) is the density of the liquid, kg/m\(^3\).

Momentum equation. For a given fluid micro-element, the rate of change of momentum versus time is equal to the sum of various forces acting on the micro-element. According to this law, the momentum equation is derived as follows [6-8]:

\[
\frac{\partial (\rho u_x)}{\partial t} + \nabla \cdot (\rho u_x u_x) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho f_x
\]

(2)

\[
\frac{\partial (\rho u_y)}{\partial t} + \nabla \cdot (\rho u_y u_y) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{yy}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \rho f_y
\]

(3)

\[
\frac{\partial (\rho u_z)}{\partial t} + \nabla \cdot (\rho u_z u_z) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{zz}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z
\]

(4)

Where \( p \) is the pressure on the fluid micro-element, Pa; \( \tau_{xx}, \tau_{yy}, \tau_{zz} \), etc. are the components of viscous stress \( \tau \) on the surface of the micro-element, Pa; \( f_x, f_y, \) and \( f_z \) are the unit mass force in three directions, m/s\(^2\).

2.2. Model parameter selection

In practical application, there are three material states near the sewage pipe network, namely solid, gas and liquid. The calculation of the mathematical model in this paper is only a qualitative analysis of the flow field change law of the water body near the sewage pipe network. Therefore, in order to simplify the analysis, the calculation domain materials used in the mathematical model in this paper are all water, and the specific material properties are shown in Table 1.

| Table 1. Material Properties |
|-----------------------------|
| Material Category | Material Name | Density (kg/m\(^3\)) |
| Fluid | Water | 998.2 |

In this paper, three types of boundary conditions are set, namely wall, pressure-outlet and velocity-inlet. The roughness thickness value \( k_s \) of pipe wall is 0.1 mm, and the roughness constant \( c_s \) is 0.5. The velocity-inlet is used to give the inlet velocity and various scalar values required, and is suitable for incompressible fluid problems.
Convergence can be considered when the residual error of each variable in the calculation of the mathematical model in this paper is less than 0.001. 3D single-precision solver is used to solve the problem: uncoupled implicit algorithm is selected to solve the problem. Under different working conditions, the turbulent energy distribution and turbulent energy dissipation of the model are analyzed.

3. Calculation Conditions

According to the analysis requirements of the water flow field near the 3D circular pipe, by changing the pipe diameter D, outlet flow rate v and pipe placement slope $\alpha$ of the sewage pipe network, as well as the diameter D of different main pipes under the condition of branch pipes, the specific test groups are shown in Table 2.

| Plan | Group | Inlet velocity $V$ (m/s) | Pipe Diameter $D$ (mm) | Pipe Length $L$ (m) | Slope $\alpha$ (°) | Branch Pipe Diameter (mm) |
|------|-------|--------------------------|------------------------|---------------------|-------------------|-----------------------------|
| 1    | 1     | 0.5                      | 300                    | 5                   | 0                 | /                           |
| 1    | 2     | 0.5                      | 400                    | 5                   | 0                 | /                           |
| 1    | 3     | 0.5                      | 500                    | 5                   | 0                 | /                           |
| 2    | 2     | 0.5                      | 300                    | 5                   | 0                 | /                           |
| 2    | 3     | 0.7                      | 300                    | 5                   | 0                 | /                           |
| 2    | 1     | 0.5                      | 500                    | 5                   | 0                 | /                           |
| 3    | 2     | 0.5                      | 500                    | 5                   | $+5^\circ$         | /                           |
| 3    | 3     | 0.5                      | 500                    | 5                   | $-5^\circ$         | /                           |
| 3    | 1     | 0.2                      | 400                    | 10                  | 0                 | 300                         |
| 4    | 2     | 0.2                      | 500                    | 10                  | 0                 | 300                         |
| 4    | 3     | 0.2                      | 600                    | 10                  | 0                 | 300                         |

4. Characteristics of Pressure and Energy Consumption of Sewage Pipe under Different Conditions

4.1. Different pipe diameter conditions

The conditions set in Plan 1. The length of the pipe is 5m, the average speed of the outlet and inlet of the whole pipe is set to 0.5m/s, and the diameters of the three groups of pipes are set to 300mm, 400mm and 500mm respectively. The results are shown in Figure 1 and Figure 2. At the same inlet flow rate, when the diameter of the pipe gradually increases, the pressure at the inlet gradually increases and reaches the maximum value at the inlet. The smaller the diameter of the pipe, the greater the pressure value. With the direction of water flow, the pressure value at the outlet slowly decreases. The turbulent kinetic energy is mainly distributed at the inlet, and the maximum value appears at the inlet section. For pipes with large diameter, the overall value of turbulent kinetic energy will slightly increase, but the values are all small. The distribution of turbulent dissipation rate and turbulent kinetic energy are generally similar. Compared with small diameter pipes, the turbulent dissipation rate of large diameter pipes is larger, but the overall numerical value changes little.

![Figure 1. Pressure characteristics](image)
4.2. Different inlet flow rate conditions
The calculation conditions of Plan 2 are as follows: the length of the pipe is 5m, the water is discharged from the whole pipe, and the inlet velocities are set at 0.1m/s, 0.5m/s and 0.7m/s respectively for the pipe diameter is 300mm. Quantitatively analyze the influence of inlet velocity change on the hydraulic characteristics of the pipe, and the results are shown in Figure 3. Under the condition that the diameter of the sewage pipe is unchanged, it is generally concentrated at the inlet of the pipe, then gradually becomes uniform, and the distribution range also extends to the outlet. Turbulent dissipation is consistent with energy distribution.

4.3. Different slope conditions of the pipe
The calculation conditions of Plan 3 are as follows: the length of the pipe is 5m, the water is discharged from the whole pipe, and the diameter of the pipe is 500mm, the speed is 0.5 m/s, and the slope is changed to 0° flat slope, 5° positive slope, 5° negative slope, and 5° positive slope, i.e. the inlet is 5° higher than the outlet. The negative slope is 5, that is, the outlet is 5 higher than the inlet. For pressure distribution, compared with flat slopes, the pressure distribution of negative slope and positive slope changes greatly. Negative slope is mainly at the inlet pressure value is larger, and the bottom edge of the pipe reaches the maximum. From the pressure distribution at the entrance, it can be seen that on any section of the circular pipe, the pressure distribution is not uniform and there is also a delamination...
phenomenon. The pressure gradually decreases in the vertical direction, and the pressure value of the positive slope changes opposite to that of the negative slope. Therefore, it can be seen that the slope setting of the sewage pipe has a great influence on the pressure distribution and is the key factor in designing the pipe network. When the slope is flat, the energy is relatively large at the inlet, and then gradually decreases to reach uniform distribution, which is very small in value. The turbulent energy on the positive slope and negative slope changes slightly near the pipe wall. As there is no water on the upper edge of the pipe wall at the outlet, air swirl occurs, so the energy increases at the outlet and the distribution is uneven. Turbulent dissipation is roughly consistent with energy distribution in Figure 4.

![Figure 4. Influence of Slope on Pipe Energy Consumption](image)

4.4. Influence of branch pipes

The calculation conditions of Plan 4 are as follows: the diameter of the main pipe is 400mm, 500mm and 600mm respectively, the length is 5m, and the inlet velocity is 0.1m/s. At 2.5m, there is a pipe with a diameter of 300mm (inlet flow rate 0.2m/s) and a length of 2.5m. Quantitatively analyze the influence of setting branch pipes on energy consumption of different main pipe diameters, and the results are shown in Figure 5.

![Figure 5. Influence of branch pipes on Pipe Energy Consumption](image)

Pressure, flow rate, turbulent kinetic energy, the turbulent dissipation rate of the two pipes is relatively large at the intersection of pipes. The pressure distribution of the branch pipe is relatively uniform. The main water flow changes the direction under the high pressure of the horizontal branch pipe, causing strong bending to flow to the branch pipe, and generating a large number of whirlpools at the same time. The pressure values in the main pipe are all at large values, and the flow velocity at the junction also increases slightly. The streamlines are concentrated in the junction and diffuse from inside.
to outside. There is some energy dissipation at the intersection. It can be seen from this that the joint between the branch pipe and the main pipe is the key part in the design, which needs to be comprehensively considered in combination with the relationship between the adjacent two pipes and the flow rate. The turbulent energy is relatively large and the distribution of turbulent dissipation rate is relatively uniform. The maximum dissipation values under the three working conditions are about 0.125 m²/s³, 0.056 m²/s³ and 0.05 m²/s³ respectively. The dissipation rates are relatively large.

5. Conclusion
The numerical simulation method can better reflect the real situation of flow pressure, turbulent energy and turbulent dissipation in the sewage pipe network. When the diameter of the pipe gradually increases, the pressure at the inlet gradually increases as a whole and reaches the maximum value at the inlet. The turbulent kinetic energy and turbulent dissipation rate are mainly distributed at the inlet of the pipe. For the larger the diameter of the pipe, the overall turbulent kinetic energy value will slightly increase. Turbulent energy and turbulent dissipation are concentrated at the inlet of the pipe, then gradually become uniform, and the distribution range also extends to the outlet. For different slopes, the pressure distribution changes of negative slope and positive slope appear upper and lower stratification. The pressure value of negative slope is mainly larger at the inlet and reaches the maximum value at the lowest edge of the pipe. The pressure value changes of positive slope are just opposite to negative slope. The distribution laws of turbulent energy and turbulent dissipation of positive slope and negative slope are consistent. When there is a branch pipe, there is a certain energy dissipation at the intersection of the pipes.

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References
[1] Yuan Xiaoming, Zhu Xuan, Hou Zhenxing, Wang Chu, Luo Cheng. Simulation of Laminar Flow in Circular Tube Based on Fluent [J]. Machine Tool and Hydraulic, 2019, 47 (11): 155-158 +187. (in Chinese)
[2] Wang Tong, Zhao Jianqiang, Cai Guang. Discussion on the Hydrodynamic Characteristics of Uniform Flow in Unpressurized Circular Pipes [J]. Journal of Chang'an University (Architecture and Environmental Science Edition), 2003 (01): 9-10. (in Chinese)
[3] Xu Zishun, Xian Kai, Yu Jianfa, Zhang Guirong. Numerical Simulation of Flow Field in Low Reynolds Number Sudden Expansion Tube based on Fluent [J]. Internal Combustion Engines, 2016 (01): 27-30. (in Chinese)
[4] Zhao Yanlin, Zhang Yufeng. Numerical Simulation of Large-scale Irrigation Pipe Network System in Hilly Area based on FLUENT [J]. Journal of Water Conservancy and Construction Engineering, 2018, 16 (05): 208-212 +218. (in Chinese)
[5] Liang Zhixi, Wang Haiyue, Qi Xiangsong, Wang Jianpeng. Numerical Simulation of Flow Field in Pipe Based on Fluent Software [J]. Nanfang Agricultural Machinery, 2017, 48 (16): 111. (in Chinese)
[6] Zhu Hongjun. FLUENT 15.0 Practical Guide to Flow Field Analysis [M]. Beijing: People's Posts and Telecommunications Publishing House, 2015: 503. (in Chinese)
[7] Wu, Teng., Wu, Lingli. High-resolution scheme based on the undetermined coefficient method and its application. Journal of Engineering Science and Technology Review, 2013, 6 (1): 119-123.
[8] Wu, Teng, Li, Xiuxia. Vertical 2-D mathematical model of sediment silting in dredged channel. Journal of Hydrodynamics, 2010, 22(5): 628-632.