Hydraulic characteristics and pump selection of distributed pressure drainage system

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Abstract. In order to explore the hydraulic characteristics of pumps in pressure drainage system under different working conditions, Flowmaster, a one-dimensional system simulation software, was used to analyze the flow head and pipeline velocity changes of pressure drainage system within 100 seconds of pump start-up and shutdown, and to further verify the rationality of the model of pressure drainage system pumps, providing a theoretical basis for similar engineering design.

1. Introduction

In 1954, the study of pressure flow drainage system was first put forward in the United States. In the 1970s, more than 50 households were renovated with practical pressure flow drainage pipes, which were then extended to more than 200 villas and houses. In the mid-1980s, the former Federal Republic of Germany, Japan, the Netherlands and other countries began to study the pressure flow drainage system. In Japan, in December 1985, seven research institutes related to pressure-flow drainage system initiated the establishment of the Pressure-flow Drainage System Research Association. In 1994, there were 55 pressure-flow sewage systems in Japan and the Vacuum and Pressure-type sewers were included in the revised "Sewerage Planning and Design Guidelines" by the Waterway Association. The design of drainage canal system should be based on gravity flow, with no or less lifting pumping stations. When gravity flow cannot be used or gravity flow is not economical, pressure flow can be used[1]. In recent years, with the development of economy and the improvement of environmental protection requirements, pressure drainage pipeline network has the advantages of easy leakage detection and easy maintenance, which can effectively protect the regional groundwater environment and prevent groundwater heavy metal pollution. Pressure flow drainage pipeline also has the advantages of fewer subsidiary structures, shallow buried depth, small diameter, convenient reconstruction and expansion in the later stage, strong scouring effect and inappropriate pipeline blockage, etc[2]. So pressure drainage system occupies an increasing proportion in the drainage system. A. Chen [3] built a simulation model based on InfoWorks CS and took the actual pressure drainage project as an example. The flow and pressure in the pressure drainage pipeline were analyzed by using the model. The results show that the installation of flake valves in the riser trunk pipe is helpful to maintain the water flow in the pipeline in a pressurized state. Freudenthal, Nielsen, Tanaka, Hvitved-Jacobsen, Shypanski [4]-[7] and others have studied the changes of organic and inorganic components in the pressurized drainage pipe during transportation. However, little research has been done to simulate the hydraulic characteristics of the pressurized drainage pipeline.
2. Flowmaster overview
Flowmaster is a software for fluid design and simulation developed by the British Association for Fluid Dynamics Research. It has been adopted by many well-known research institutes around the world for its efficient calculation efficiency, accurate solution ability, convenient and fast modeling method. It can inspect the steady or transient flow performance of fluid systems, solve flow and pressure distribution parameters, and predict and analyze system engineers. At present, the software is widely used in aerospace, automobiles, gas turbines, energy power, oil and gas, fluid pipeline network and other fields of internal flow design. In the field of water supply and drainage, steady and transient analysis of the flow and pressure of pipeline network, pump selection and design, water hammer analysis can be carried out.

3. Analysis of research projects
The maximum flow rate when confluence, long-distance transportation pipeline section mainly considers the loss along the way, local head loss can be neglected, along the head loss calculation formula:

\[ h_f = 10.293 \times L \times \frac{(n \times Q)^2}{D^{3.333}} \]  \hspace{1cm} (1)

In the formula, \( h_f \) is head loss along the way, m; \( Q \) is design flow rate at maximum pipe section, \( m^3/s \); \( D \) is calculation pipe diameter, m; \( L \) is calculation length, m; \( n \) is roughness, the pressure pipe value is 0.0120. The formula for calculating the lift required by enterprise pumps is as follows:

\[ H = h_0 + h_f + h_{\text{Safety}} \]  \hspace{1cm} (2)

In the formula, \( h_0 \) is the static head between the end of the pipe network and the enterprise suction tank, m; \( h_f \) is head loss along the pipeline, m; \( h_{\text{Safety}} \) is the outlet head of the pressure release well at the end of the pipe network is 1 m; the diameter of the pipe is determined by selecting the flow rate, and calculated according to the following formula:

\[ d = 18.8(\frac{Q}{v})^{0.52} \]  \hspace{1cm} (3)

In the formula \( d \) is pipe diameter, mm; \( Q \) is volume flow, \( m^3/h \); \( v \) is velocity and take 0.8m/s. The hydraulic calculation table of the whole pressure pipeline system is as follows:

| No. | Q1 (m³/h) | D (mm) | L (m) | Q2 (m³/h) | hf (m) | h0 (m) | he (m) | h chauffe (m) | H (m) |
|-----|------------|--------|-------|------------|--------|--------|--------|--------------|------|
| 1   | 26.64      | 150    | 695   | 26.64      | 1.40   | 6.43   | 33.57   | 60.93        | 18.1 |
| 2   | 15.02      | 150    | 165   | 41.66      | 0.81   | 6.75   | 33.25   | 59.62        | 17.02|
| 3   | 22.48      | 200    | 643   | 64.14      | 1.62   | 6.58   | 33.42   | 58.77        | 16.04|
| 4   | 12.82      | 200    | 30    | 76.96      | 0.11   | 5.16   | 34.84   | 55.06        | 13   |
| 5   | 33         | 250    | 1437  | 109.96     | 3.23   | 4.23   | 35.77   | 54.77        | 11.96|
| 6   | 44.4       | 300    | 166   | 154.36     | 0.28   | 7.38   | 32.62   | 47.82        | 11.88|
| 7   | 18.01      | 300    | 269   | 172.37     | 0.56   | 8.14   | 31.86   | 46.74        | 12.36|
| 8   | 29.99      | 300    | 934   | 201.36     | 2.66   | 8.66   | 31.34   | 44.44        | 12.31|
| End of pipe | 40 | 41 | 1 |

Note: In the table \( Q_1 \) is maximum sewage flow rate in the enterprise, \( m^3/h \); \( D \) is Pipe diameter, mm; \( L \) is Pipe length, m; \( Q_2 \) is Pipeline maximum flow rate, \( m^3/h \); \( h_f \) is Water head loss along the way, \( m \); \( h_0 \) is Elevation difference between the end of the pipe network and the corporate sink, \( m \); \( h_e \) is elevation of the enterprise, m; \( h_{chauffe} \) is hydraulic elevation of pump node, \( m \); \( H \) is pump head, \( m \).
According to the pressure pipe hydraulic calculation table, the maximum flow rate of the enterprise and the free water head are selected for each enterprise. The pump type and parameters are shown in Table 2 below:

### Table 2. Pump model parameters selected by the enterprise

| Corresponding company | Pump model parameters | Q(m³/h) | H (m) | N(r/min) | P(kw) |
|-----------------------|-----------------------|---------|-------|----------|-------|
| No. 1                 | 100QW30-22-5.5        | 30      | 22    | 1440     | 5.5   |
| No. 2                 | 50QW15-22-2.2         | 15      | 22    | 2840     | 2.2   |
| No. 3                 | 50QW24-20-4           | 24      | 20    | 1440     | 4     |
| No. 4                 | 50QW18-15-1.5         | 18      | 15    | 2840     | 1.5   |
| No. 5                 | 50QW40-15-4           | 40      | 15    | 1440     | 4     |
| No. 6                 | 100QW60-13-4          | 60      | 13    | 1440     | 4     |
| No. 7                 | 50QW18-15-1.5         | 18      | 15    | 2840     | 1.5   |
| No. 8                 | 50QW40-15-4           | 40      | 15    | 1440     | 4     |

### 4. Establishment of simulation system

This paper studies the interaction between water pumps within 100s of the start and stop of the pump during normal operation of the pressure pipeline and the relationship between the end flow velocity and pressure of the pipeline network. The diagram of the simulation model is shown in figure 1:

![Figure 1. Schematic diagram of simulation model](image)

There are six pipeline models in Flowmaster: Cylindrical/Rectangular/ Hexagon/Prismatic/Rotating tube/Internal pipe. Pressure pipe against pressure High requirements, comprehensive hydraulic conditions, and finally the Cylindrical Rigid pipe model. In the pipeline model, the input can be simulated to the corresponding pipe length, diameter and absolute roughness. There are three models for calculating the resistance along the pipeline.

### Table 3. Pipeline resistance model along the line

| Resistance model      | Laminar flow state Re ≤ 2000 | Transition area 2000 < Re ≤ 4000 | Turbulent state Re > 4000 |
|-----------------------|-------------------------------|-----------------------------------|---------------------------|
| Colebrook-White       | \( f = f_l = \frac{64}{Re} \) | \( f = xft + (1-x)f_t \) | \( f = f_l = \frac{0.25}{\log \left( \frac{k}{3.76} - \frac{5.74}{Re^{0.85}} \right)} \) |
| Hazen-Williams        | \( f = f_l = \frac{64}{Re} \) | \( f = xft + (1-x)f_t \) | \( f = f_l = \frac{1014.2Re^{0.148}}{C_{HW}^{1.852}D^{0.0184}} \) |
| Fixed                 | \( f \)                       | \( f \)                           | \( f \)                    |

Note: In the table, \( \frac{Re-2000}{2000} \); \( f \) is the frictional resistance factor of water and the inner wall of the pipeline; \( f_l \) is the frictional resistance factor of laminar flow; \( f_t \) is the frictional resistance factor of turbulent flow; \( k \) is the absolute roughness of the pipeline; \( C_{HW} \) is the roughness factor; D For the pipe diameter; Re is the Reynolds number.
This project is in the field of industrial drainage. According to the applicable conditions of the resistance model, the Hazen-Williams model is selected.

5. Result analysis
After the establishment of the system model, assuming that the drainage is incompressible fluid, the simulation type is chosen as the transient model Incompressible transient in Flowmaster, the time step in simulation date is set to 1 s, the simulation time is 100 s, and then the simulation operation is carried out under different conditions. Considering the most disadvantageous situation, two pumps with larger flow rate of 3 # and 6 # are selected to start and stop within 15 seconds. Flowmaster is used to analyze the influence of pump start-stop on other pumps and flow rate and pressure at the end of pipe network under different working conditions. The results are as follows:

![Flow and lift conditions when the two pumps stop](image1)

![Flow and lift conditions when the two pumps start](image2)

It can be seen from the figure that the fluctuation of flow and head caused by two pumps starting at the same time to other pumps is more severe than that caused by one pump. The fluctuation of flow and head of the system when starting pump is larger than that when stopping pump. From Figure 4 and Figure 5, it is concluded that the flow fluctuation of the system is small when a single pump stops, and tends to be stable at 30s when two pumps stop at the same time.

In the pressure drainage system, opening and stopping pumps are fluctuations of the flow and pressure of the whole system, which seriously affect the stable operation of the system. In order to make the system more stable, DN200 air valves are designed at the entrance of drainage pressure pipelines in various enterprises, simulation models are established, and the flow fluctuations of each...
pump after the design of air valves are analyzed when two pumps start at the same time. As can be seen from Fig. 8, the flow fluctuations of each pump after the design of air valves are after the air valve is counted, when two pumps start at the same time, the flow of other pumps will return to normal at 20s.

![Flow and lift conditions when two pumps open after air valve design](image)

Fig. 4 Flow and lift conditions when two pumps open after air valve design

From Figure 5, it can be seen that the velocity of pipes at the starting end is about 0.5m/s, and that of 8# is about 0.9m/s, which meets the design requirements of the velocity of pressure pipes. The velocity of pressure sewage pipes is between 0.5 and 2.0m/s. The minimum diameter of pressure pipes is 100mm, so as to prevent the occurrence of water hammer.

![Pipeline flow rate when the two pumps stop and start](image)

Fig. 5 Pipeline flow rate when the two pumps stop and start

6. Conclusions
The over-process of shutdown and start-up conditions in pressurized drainage system directly affects the safe and stable operation of the whole system. Based on Flowmaster software, the simulation results of different conditions in pressurized drainage system are as follows:

1) The interaction between pumps in different enterprises under the condition of start-up and shutdown of pumps in pressurized drainage system. The fluctuation of flow and pressure of the system is more severe when the pump is opened than when the pump is shut down. The fluctuation of flow and pressure of two pumps is larger when the pump is opened or shut down than that of single pump. Setting air valves in various enterprises can reduce the fluctuation of system flow and effectively ensure the stable operation of the system;

2) The velocity and pressure of the most disadvantageous point in the pressurized drainage system are proportional to the flow rate. At the end of the pipeline network, a large negative pressure may
occur at the moment when the pump starts, which may cause cavitation in the pipeline, seriously affecting the operation of the pressurized pump and the pressurized drainage pipeline. After the selection of the pump, the pressure flow rate and the flow rate of the most disadvantageous point are further verified by the simulation results of Flowmaster. Rationality of pump selection;

(3) The pressure drainage pipe is intermittent flow, the start and stop of the pump is inevitable. When the sewage pool reaches the warning level, the pump starts to work, and when the water level of the sewage pool drops to the safe level, it stops working. This paper only studies the most disadvantageous situation, that is, the starting and stopping conditions of one and two pumps with larger flow rate. In practical projects, many pumps may start and stop simultaneously, which will have more severe impact on the pressure and flow rate of the whole pressure network, and needs further study.

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