Transient numerical simulation of gas-liquid two-phase flow in long distance water supply pipeline

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Abstract. To reveal the gas-liquid two-phase flow characteristics in water supply pipeline due to the rugged terrain, flow pattern, pressure, velocity, turbulent kinetic energy and turbulent energy dissipation rate of 6 key sections and 4 profiles were simulated and analysed on the conditions of with and without exhaust valve. The results showed that water cannot flow smoothly without exhaust valves at sections 1-1, 2-2 and 3-3, while that flows smoothly at sections 4-4, 5-5 and 6-6. For sections 1-1, 2-2 and 3-3, water can only cover less than 50% of the pipeline cross section when the exhaust valves were not set, and various backflow zones can be observed in these sections, which can increase the resistance of the water flow. The turbulent kinetic energy of the cross sections 1-1, 2-2 and 3-3 were 0.87, 1.02 and 0.09 m²/s², which can decrease to 0.0018, 0.0017 and 0.0017 m²/s², respectively, after the exhaust valves were set. Meanwhile, the pressure in different cross sections reduced by 1 to 10 kPa and the streamline were nearly uniform and straight for the main flow in the pipe with the exhaust valves. The reverse vortex disappeared and the velocity distribution of the main flow was more uniform in these sections.

1. Introduction

Water supply is closely linked with urban development and is one of the most important factors affecting the rapid development of cities. With the economic development and social progress, people have higher requirements for water quality, quantity and stability, which made the contradiction between water use and water supply become an increasingly serious problem [1]. A large number of practices have proved that long-distance water supply project is an effective method to solve the contradiction between the increasing domestic and production water consumption and urban water resources shortage [2]. However, in long-distance water transportation projects, the pipelines disposition wind ups and down since the rugged terrain, the pressure fluctuated dramatically and the water flow was very unstable in the pipeline, usually resulting in gas blockage and non-uniform outflow, which may lead to great accidents such as pipeline explosion in serious cases [3]. Therefore, how to improve the safety and reliability of water supply by reasonable technical methods is an important issue in the design of long-distance water supply system, which attracts more and more attention on the research of flow characteristics in the pipeline [4].

In the water supply network, the pipeline needs to be filled with water for the first time put into use or after a shutdown of water supply for some reason [5]. However, in the process of filling water, there are water column separation phenomenon and gas blockage problem caused by rapid filling water
process can be observed, which is one of the reasons for gas-liquid two-phase flow existed in the water supply pipeline network [6]. The presence of gas in the pipeline is not only one of the main factors inducing water hammer to cause pipeline explosion [7], but also increases the power consumption and affects the stability of water supply. The pipeline disposition of long-distance water delivery system is complex, and how to set up the exhaust system reasonably and reduce the instability of water supply are very important, a best method is monitor and analyze the flow characteristics of key sections in the pipeline and then adopt some technical method to improve the stability of the whole water delivery system. At present, most of the relevant research focused on the simulation of the transient process in the pipeline, especially on the phenomenon of water hammer and its prevention measures [8-11], while little attention was paid on the flow characteristics of the water in the pipeline during the water filling process, and few consideration was given to the energy waste and unstable transportation caused by the flow separation.

Based on aforementioned, a length of 2.90 km pipeline with a 97.38 m elevation change in disposition was selected to analyze the flow characteristics by numerical simulation. The pipeline was taken from a practical water supply engineering named Yellow River to Linxia Hui Autonomous Prefecture Water Supply Project (YRLP) in Gansu Province. The pipeline is the one from the second pump station to the head tank, along the pipeline 6 cross sections and 4 profiles were selected to simulate the dynamic flow state, pressure, velocity, turbulent kinetic energy and turbulent energy dissipation rate in the pipeline before and after the exhaust valves were set under the actual flux (0.539 m³/s). The research can give some help and basic experience to the design and operation water supply pipeline system, improve the stability, safety and energy-saving of the project.

2. Project Overview and Pipeline Model

2.1. Project Overview
YRLP is a key water conservancy poverty alleviation project in Linxia Hui Autonomous Prefecture, Gansu Province. Its primary purpose is to solve the problem of water shortage for living, industry and breeding of urban and rural residents in Linxia city and nearby destitute areas. The water is taken from Lianhua Wharf on the South Bank of Liujiaxia reservoir, lifted to the head tank through two-stage pump station, and then flowed to two water plants by gravitational water flow, the location and disposition of the pipeline can be seen in Figure 1. The total length of the pipeline of YRLP is 40.5 km, and the total pump station head is 252 m. According to the definition of long-distance water transfer, YRLP belongs to long-distance water supply project.

2.2. Pipeline Physical Model
In order to study the hydraulic characteristics of the water flow in the pipeline, the pipe from second pump station to head tank was modeled, 6 cross sections and 4 profiles were selected to monitor the flow field character, and the specific locations of which is shown in Figure 2. According to the pre experimental results, the flow was more complex and unstable in the area far away from the second...
pump station, thus the monitor section is relatively dense here, near the head tank, which are 1-1, 2-2 and 3-3 cross sections.

Figure 2. The cross sections and profiles of the modeled pipeline.

3. Computational Method

3.1. Control equation

The flow field of the incompressibility fluid in the pipe is obtained by numerically solving the incompressible Reynolds Average Equation (RANS), and the continuity equation and momentum equation are:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad (3.1)
\]

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_j u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}^{eff}}{\partial x_j} \quad (3.2)
\]

Where, \(u_i\) is the velocity component in the direction of \(x_i\), \(i,j=1,2,3\); \(t\) is time, s; \(\rho\) is the density of the fluid, kg\(\cdot\)m\(^{-3}\); \(p\) is pressure, N\(\cdot\)m\(^{-2}\); \(\mu\) is the dynamic viscosity coefficient, kg\(\cdot\)(m\(\cdot\)s\(^{-1}\)); \(\mu_t\) is the eddy viscosity coefficient, kg\(\cdot\)(m\(\cdot\)s\(^{-1}\)).

3.2. Turbulence model and VOF multiphase flow model

The standard \(k-\varepsilon\) model, first proposed by Lauder and Spalding, is one of the most widely used turbulence models [12]. The dynamic characteristics of turbulence need to be considered when the turbulence generation and dissipation imbalanced caused by the effect of convection and diffusion. Based on the \(k\) equation of turbulent kinetic energy, a \(\varepsilon\) equation of turbulent energy dissipation rate was introduced to form a standard two equation \(k-\varepsilon\) model [13], which is the realizable \(k-\varepsilon\) model. To reveal the liquid-gas two phase characteristics of the flow in the long distance pipeline, VOF model was adopted in present study, for VOF model was mainly used in calculation the free water surface, stratified flow, the movement of large suspended bubbles in liquid and dam break flow, which can capture the free surface better and is a good choice in the calculation of gas-liquid two phase flow.

3.3. Computational mesh

The length of simulated pipeline is 2.9 km, and the diameter of the pipe is 1.1 m. In order to improve the calculation accuracy, a typical O-type hexahedral structured mesh, is shown in Figure 3, is adopted in this study. The total grid element number is about 589456, and the number of nodes is 656084.
3.4. Simulation setup

Proper boundary conditions are very important in obtaining more accurate and reliable results. In this study, in order to get a calculation results that can guide the practical engineering application, the flow, pressure, parameters and upper pool water level used as the inlet boundary conditions were obtained from actual measurement. The mass flow, 0.539 m³/s of single pipeline on March 14, 2019 was taken as the inlet boundary condition. Pressure outlet and slip wall boundary conditions were used, the pressure is the atmospheric pressure and its value is zero. Non-equilibrium wall function method was used for near wall calculation.

The incompressible Reynolds-averaged Navier-Stokes equations were numerically solved by the commercial CFD software ANSYS FLUENT 17.0 [15]. Segregated solver and PISO algorithm were adopted for coupling the mass, momentum and pressure equations, improved QUICK scheme was chosen for spatial discretization because of its good stability, high accuracy and low diffusion error. PISO algorithm is an approximate relationship algorithm based on correcting pressure and velocity [16]. The details of solver setup can be inferred the software ANSYS [15].

4. Results and Analysis

4.1. Flow characteristics

It can be seen from Figure 4 that the pipeline was full of gas at the beginning of water filling, however, when the filling time went to t=8 min, a clear liquid-gas interface can be observed at the left and right sides of the pipeline. With the water flow continuously, the water near the bottom of the pipeline flow faster than the upper layer water, and a long-distance air flow area appeared in the upper layer of the pipeline when the water filled about 16 minutes. When the water filling time went to is t=24 min, the gas-liquid stratification of the upper and lower section of the pipeline is more obvious. After the water filled about 32 minutes, a group of bubbles with a length about 206 m appeared at the upper layer of the pipeline, which have severe influence on the water flow and velocity inside the pipeline, also a great challenge to the operation safety of water supply system, sometimes even can cause bursting accident of the pipeline. When the filling time went to t=40 min, the water flow at the right side of the pipeline began to flow continuously, but the bubbles were still existed on the upper layer of the pipeline. After 60 minutes, the water reached to the head tank, however, a phenomenon should be noted that only less than 50% of the water covered the cross section of the pipeline, which seriously decreased the flow capacity, water flow and velocity of the pipeline, and finally affect the efficient operation of the water supply system.
Figure 4. Flow characteristics of the pipeline at different sections along with water filling time.

Note: A, B, C, D, E, F is corresponding to flow at these locations of the pipeline.

4.2. Pressure distribution
Problem frequently encountered in long-distance water supply pipeline with rugged terrain is that the
flow will become gas-liquid two-phase flow. Since the bubbles existed in the pipeline, which will cause the pressure fluctuation inside the pipe, and result in instable flow. Fig. 5 and Fig. 6 presented the pressure contours in different cross sections of the pipeline, it can be seen that when the pipeline was not equipped with exhaust valves (Figure 5), lots of bubbles deposited in the cross sections 1-1, 2-2 and 3-3, and the pressure distributed uneven with gas covered large part of the cross section of the pipeline, meanwhile, the pressure of the whole cross section were much higher than that after equipped with exhaust valves (Figure 6). It can be seen clearly from Fig. 6 that the section pressure reduced by 1 to 10 kPa in different cross sections of 1-1, 2-2 and 3-3, meanwhile, the water flow area increased in the cross-section of the pipeline, and the pressure distribution much more evenly. For the investigated cross-section 4-4, 5-5 and 6-6, the change of pressure distribution, water flow and bubbles were not obviously before and after the exhaust valves equipped, which illustrated that gas resistance had little influence on the flow at the sections of 4-4, 5-5 and 6-6, so exhaust valves are not the necessaries at these cross-sections. A preliminary analysis is that the sections 4-4, 5-5 and 6-6 are more close to the second pump station, and the elevation of the pipeline changes little, furthermore, the water flows with a great power and pressure got from the second pump station, which will overcome the influence of the air resistance pressure in the pipeline, so the air had little influence on the flow and pressure distribution at sections 4-4, 5-5 and 6-6. However, the cross-sections 1-1, 2-2 and 3-3 are far away from the pump station, the elevations of which are nearly 100 m, and the water head loss of the pipeline increased with the flow, thus the influence of the air resistance increased. Meanwhile, this influence increased with length of pipeline from the second pump station for the water head loss and elevation increase. Therefore, the influence of air resistance can be reduced effectively after the exhaust valves equipped at the cross-sections 1-1, 2-2 and 3-3.

![Figure 5. Pressure contours at different cross-sections (without exhaust valves).](image-url)
Figure 6. Pressure contours at different cross-sections (with exhaust valves).

Figure 7 presented the pressure contours at different profiles of the pipeline without and with the exhaust valves, for the above section had proved that there was little influence of air resistance on the water flow for the sections near the second pump station, so in this section the attention was paid on the profile 1 and profile 2. The location of profiles can be seen in Figure 2. It can be seen from the pressure contours of profile 1 that the bubbles were existed at the round of pipe when the pipeline had no exhaust valve, meanwhile the pressure was much higher, however, the water flow more evenly and the bubbles disappeared after the exhaust valve was equipped. Moreover, the pressure inside the pipeline decreased about 10 kPa. For the profile 2, there was no obvious difference can be observed from the pressure contour of the pipeline with and without the exhaust valve, but the value of the pressure mean decreased by 10 kPa after the exhaust valve equipped. For the air have great compressibility, and the air in the pipe can generate great pressure, sometimes this pressure can increase instant to several times or even ten times higher than the liquid pressure in the same pipe, which may cause the pipeline explosion accident. After setting the exhaust valve, the pressure in the pipeline will be reduced significantly, and there were no bubbles inside the water flow, which greatly ensures the safety of the pipeline. Therefore, it can be concluded that equipping exhaust valve is an effective way decrease the pressure inside the pipeline, make the flow more evenly and ensure a safety of water supply.
4.3. Flow velocity characteristics

Figure 8 showed the vector diagram of the cross-section 1-1 and 2-2 of the pipeline without and with exhaust valve under the actual operation conditions. It can be seen that there were different degrees of backflow at section 1-1 and 2-2 when the pipeline was not equipped with an exhaust valve, which illustrated that vortices were generated inside the pipeline. The vortices swirled and increased the frictional and local resistance of the water flow, finally greatly increased the energy consumption and operation cost of the system. After the installation of exhaust valve in the pipeline, the water flows in the central region of the cross-section were approximately uniform linear flow with similar size and basically parallel direction, which illustrated that the swirled backflow disappeared inside the pipeline and a good internal flow generated.

Figure 9 presented the velocity vector diagrams of profile 1 for the pipeline under the conditions of without and with exhaust valve. It can be seen that when the pipeline was not equipped with the exhaust valve, the water flow inside the pipeline was unstable due to the existence of bubbles, which may cause pipeline vibration and sometimes intense vibrations. The long-term vibration would make the connecting parts of pipeline system become loose, leaks or even break, which will reduce the service life of the pipeline and other equipment. When the exhaust valve was equipped, the back flowed velocity vector was disappeared and all the water flow in the same direction (Figure 9b), which will greatly decrease the water head loss and is conducive to the energy-saving of the project operation. Figure 10 showed the velocity vector diagrams of profile 2, 3 and 4 after the pipeline set the exhaust valve, it can be observed that all and the velocity direction of the investigated profile was nearly the same, and the water flow velocity distribution in the central area of each section was more uniform, which indicated that proper exhaust valve can effectively avoid the backflow inside the pipe and was benefit to keep a good flow state. In addition, the average velocity of the pipeline was 0.59 m/s, which was close to the design theoretical value of 0.57 m/s. The calculated velocity was a little bigger than the theoretical value may because some small ups and downs were ignored in the modeling of the numerical simulation.
4.4. Turbulent kinetic energy

Turbulence pulsation kinetic-energy is called turbulent kinetic energy (TKE), which is one of the most important variables in the analysis of turbulent flow, because it is a measure of the intensity of turbulence. It is directly related to the transport of the momentum of water, and is the factor indicating flow stability for its value determines the ability of the flow to maintain turbulence or generate turbulence. Figure 11 showed the turbulent kinetic energy contours of water in cross-section 1-1, 2-2 and 3-3 before and after the exhaust valves equipped in the pipeline, it can be seen that the TKE of water flow in the investigated sections without exhaust valves were much higher than that in sections with exhaust valves. The maximum TKE of cross-section 1-1, 2-2 and 3-3 reached 0.87 m²/s², 1.02 m²/s² and 0.09 m²/s² before, while that values decreased to 0.0018 m²/s², 0.0017 m²/s² and 0.0017 m²/s², respectively, after the exhaust valves equipped. A large TKE means an intense turbulence and higher operating cost and lower water supply efficiency. The results indicated that bubbles existed in the pipeline had a great impact on the smooth of water flow and stable operation of the project, and set exhaust valves at proper sections of the pipe is an effective way to avoid energy loss.
4.5. Turbulent dissipation rate

Turbulent dissipation rate in turbulence refers to the rate at which the mechanical energy of isotropic small-scale vortices convert into heat energy, which is the main way to consume energy of turbulent flow. A larger turbulent dissipation rate means greater energy loss of the flow. Figure 12 illustrated the turbulent dissipation rate at cross-section 1-1, 2-2 and 3-3 on the conditions of the pipeline without and with exhaust valves. On the conditions of pipeline without exhaust valves, there were bubbles and vortices existed in the pipeline and the turbulence inside the pipe was high for a strong reaction between liquid and gas. So the corresponding maximum turbulent dissipation rates were higher, that was 2.6622 m²/s³, 3.1181 m²/s³ and 0.3256 m²/s³, respectively, for the investigated cross-section 1-1, 2-2 and 3-3. However, the turbulent dissipation rates at these sections decreased to 0.0011 m²/s³, 0.0010 m²/s³ and 0.0010 m²/s³ after the exhaust valves were set, which indicated that the energy loss were greatly decreased. Meanwhile, the contours were much uniform on distribution, further confirmed that the exhaust valve was an effective method to avoid bubbles existed in water flow, decrease turbulent in water and make the flow more smoothly, finally decrease the project operation cost.
5. Conclusions
In this paper, a transient numerical simulation of gas-liquid two-phase flow during water filling inside a pipeline was studied under the conditions of without and with exhaust valves. 6 key cross sections and 4 profiles were selected and analyzed from the view of flow characteristics, pressure, velocity, turbulent kinetic energy and turbulent dissipation rate to discuss the influence of exhaust valve in the pipeline of water supply system.

(1) When the water supply system operated without exhaust valves, the liquid flow in the pipeline was unstable, and there were lots of bubbles accumulated and long air area existed in part sections of the pipeline. Meanwhile, vortices were generated and swirled inside the pipeline, which greatly influenced the flow characteristics, increased turbulent kinetic energy and turbulent dissipation rate of the water flow, and resulted in flow pressure drop and energy lost.

(2) When the exhaust valves were equipped, the pressure in the pipeline reduced by 1 kPa to 10 kPa in different sections compared with that without the exhaust valve; the water flowed smoothly in the whole pipeline and the streamline was nearly parallel, moreover, the flow was more stable and the velocity distribution at the cross-section was uniform. Meanwhile, the average velocity in each section was around 0.59 m/s close to the theoretical value of 0.57 m/s; the turbulent kinetic energy and turbulent dissipation rate were also significantly reduced, and the maximum values for all analyzed sections were 0.0018 and 0.0011 m²/s³, respectively. The results indicated that set exhaust valve in some key sections is an effective way to obtain stable uniform flow and reduce the cost of water supply system.

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