Design of outlet pipeline diameter and flow rate of the variable head water flow standard facility based on CFD method

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Abstract. This paper introduces a method of designing the diameter and flow rate of the outlet pipeline of variable head water flow standard facility based on CFD method. And the procedures of geometric model design, mesh generation, parameter setting and numerical calculation are illustrated. Then it is concluded that the instability of the gas-liquid interface will not occur in the facility in the process of water falling, under the condition of the maximum design flow rate of 25000m³/h and the outlet pipeline of 3.0m diameter. Then it is also found that there is possibility of further expanding the diameter and flow rate of the standard facility. The numerical result has practical significance for the design and flow field analysis of the variable head water flow standard facility with diameter-change section in the main water tower.

1. Introduction
The variable head water flow standard facility is a kind of flow standard facility based on the principle of volumetric method, which is mainly used for the calibration of various large-diameter liquid flowmeters. This kind of facility overcomes the disadvantages of traditional flow standard facility such as large energy consumption, more uncertainty components for parallel use of multiple standard flowmeters. In recent years, it has been widely used by flowmeter manufacturers in East China due to its advantages of low energy consumption, less uncertainty components and convenient facility calibration [1, 2].

Because of no constant water pressure support, there may be vortex, fluctuation, secondary flow on the gas-liquid interface in the water tower of the variable head water flow standard facility during the process of water level falling, of which was not suitable for the flowmeter calibration. Therefore, at the beginning of the design and construction of the flow standard facility, the diameter and flow rate of the horizontal outlet pipeline (flowmeter calibration pipeline) should be reasonably designed to maintain the flow stability in the water tower. In order to save the design cost, this paper uses CFD numerical calculation method to study the stability of the gas-liquid interface, the generation position of vortex and fluctuation and other issues of the same water tower with different diameter and flow rate of the outlet pipeline [3]. Obviously, this work has practical significance for the design and construction of the actual variable head water flow standard facility.
2. **Numerical calculation model and boundary condition setting**

2.1. *Numerical calculation model*

In order to reduce the difficulty of calculation, a simplified three-dimensional geometric model of variable head water flow standard facility is used, which include two parts of the water tower and the horizontal outlet pipeline. The 3-D model of the water tower is as follows: the bottom diameter is 4400 mm, the top diameter is 5800 mm, and the height is 27500 mm. And there is a 2000mm long diameter-change section nearly beginning at 17500mm of the water tower. Then it is planned to design the horizontal outlet pipeline with 63180mm length and 3.0m diameter of which the flow rate can be regulated by the valve. In addition, it is also planned to design the outlet pipeline with 2.0m and 0.8m diameter to adapt the diameter change of the flowmeter being calibrated, and the outlet pipeline with 3.8m diameter used as the comparison of design margin. The geometric model of the variable head water flow standard facility is shown in Figure 1.

![Figure 1. The geometric model of the variable head water flow standard facility (the outlet pipeline with 3.0m diameter)](image)

2.2. *Turbulence model and boundary conditions*

As the water level of the water tower decreases continuously during the flowmeter calibration process, this part of the space is filled with air immediately. Therefore, there will be an obvious gas-liquid interface in the water tower, which means that the CFD numerical calculation involves the field of two-phase flow of gas and liquid. In this paper, VOF model was used to capture the change of gas-liquid interface [4-5], and its surface tension was set to be 0.072N/m. The pressure based transient equations and the Reynolds averaged (RANS) steady turbulence model were used in the solver. The inlet boundary of the calculation domain was the top of the water tower with the condition of pressure inlet; while the outlet boundary was the outlet of the horizontal straight pipeline with the condition of mass flow rate outlet (the outlet flow rate was respectively set as 175000m$^3$/h, 100000 m$^3$/h, 50000 m$^3$/h and 25000 m$^3$/h as required).

3. **Numerical study on the variation of diameter and flow rate of outlet pipeline**

In this chapter, by changing the diameter of the outlet pipeline and the outlet flow rate, the flow field of the whole flow standard facility in the process of water level falling was studied. The instability position and vortex of gas-liquid interface in the water tower under different outlet pipeline diameters and outlet flow rates of the variable head water flow standard facility are investigated. Then the rationality of the designed maximum flow rate of 25000m$^3$/h ($Q_{\text{max}}$) was inspected.

The previous work of this paper has studied the change of flow field in the whole process of water level falling under the condition of the designed maximum outlet flow rate of 25000 m$^3$/h based on the above model of water flow standard facility. Considering the overall situation, the water level of the flow field in the water tower was stable, and there was no large vortex and instability in the interface, as shown in Figure 2.
Figure 2. The water level contours of the standard facility and gas-liquid interface at the time of 18.0s with the 25000 m$^3$/h outlet flow rate.

3.1. Study on flow field of standard facility with 3.0m outlet pipe diameter

This chapter first calculated the flow process when the outlet pipeline diameter is 3.0m and the valve is fully opened, then the maximum flow rate of the facility under the above situation was found out. Then the instability of the gas-liquid interface in the process of water level falling under this condition was studied. Also the flow field of outlet pipeline with flow rate of 7Qmax, 4Qmax and 2Qmax were calculated, and the rationality of the maximum design flow rate of 25000 m$^3$/h of the standard facility was inspected to analyze whether a large margin was left under the condition that the flow stability of the facility meet the calibration requirements.

3.1.1. Flow field of the facility with the fully opened valve. The following figure shows the velocity contours of the standard facility when the water level fell to different height under the condition of fully opened value.

Figure 3. The water level contours of the standard facility when the water level fell to 18.62.0m, 18.24m, 17.89m, 17.77m, 17.69m and 17.61m under the condition of fully opened value.

Through the analysis of the above velocity contours, it was concluded that under the condition of 3.0m outlet diameter and fully opened value, the flow velocity continued to increase and many irregular
small scale vortices appeared on the gas-liquid interface when the water flew through the diameter-change section. At the same time, due to the acceleration along the direction of gravity, it developed continuously, which eventually led to the instability of the gas-liquid interface. At the height of 18.62.0 m, a concave surface appeared, and the vortex developed to a visible degree. With the continuous contraction of the diameter-change section, the vortex developed continuously, and the difference of concave surface became larger and larger. At last, at the height of 17.61 m, the degree of vortex reached the peak, and the flowmeter calibration could not be carried out.

Under the condition of fully opened valve of the outlet pipeline, the flow rate at different time was obtained by numerical calculation. Through analysis, the outlet flow rate reached the maximum at 3.2 s, which was 376253.68 m³/h, as shown in figure 4. At this time, the flow rate was 15.05 times of the maximum design flow rate $Q_{\text{max}}$. After 3.2 s, due to the falling of water level height, the flow rate of the outlet pipeline became smaller and smaller. The acquisition of the maximum flow rate under 3.0 m outlet diameter can provide convenience for adding new flow rate points in the follow-up study and reasonably different test outlet flow points can be set as 175000 m³/h (7$Q_{\text{max}}$), 100000 m³/h (4$Q_{\text{max}}$) and 50000 m³/h (2$Q_{\text{max}}$).

![Figure 4](image1)

**Figure 4.** The time-flow rate curve of the outlet pipeline with 3.0 outlet diameter and fully opened value.

3.1.2. **Flow field of the facility with different outlet flow rates.** Changing the opening degree of the outlet pipeline valve to set the outlet flow rate as 175000 m³/h, 100000 m³/h, 50000 m³/h and 25000 m³/h respectively, the position of water level instability would fall and the vortex degree would gradually decrease correspondingly. The water level contours of the standard facility at different time under the condition of 10000 m³/h outlet flow rate were shown in Figure 5.

![Figure 5](image2)

**Figure 5.** The water level contours of the standard facility when the water level fell to 17.71 m, 17.25 m, and 15.41 m under the condition of 10000 m³/h outlet flow rate.
Through the analysis of water level contour it was found that under the condition of 3.0m outlet
diameter and 4 Qmax of the outlet flow rate, the same to fully opened value situation, due to the existence
of diameter-change section in the water tower, the flow velocity continued to increase and many
irregular small-scale vortices appeared inside, which eventually led to the instability of the gas-liquid
interface.

At the height of 17.71m, a concave surface appeared, and the vortex developed to a visible degree.
With the continuous contraction of the diameter-change section, the vortex developed continuously, and
the difference of concave surface became larger and larger. At the height of 17.25m, the degree of vortex
reaches the peak, and the flowmeter calibration could not be carried out. After this position, although,
with the continuous contraction of the diameter-change section, gas-liquid interface had been still in a
state of instability, the vortex strength was obviously weakened. While, compared to the condition of
fully opened value, the degree of vortex and instability of the water level were relatively mild, and the
height of vortex beginning to appear was falling to 17.71m, which was closer to the diameter-change
section (17.50m). After a while, the concave interface sloshing disappeared in the diameter-change
section. However the convex interface began to appear, which was in obvious contrast with the outlet
of large flow rate.

In order to save the length of this paper, this section omits the water level contours of 3.0m outlet
diameter under 7 Qmax, 2 Qmax and Qmax (which has been analyzed in the previous study) outlet flow
rates. Whether there was instability of gas-liquid interface under the above flow rates and the beginning
height of instability were listed in Table 1.

**Table 1.** The instability of gas-liquid interface under different flow rates.

| Flow rate of outlet                  | Existence of instability of gas-liquid interface or not | Beginning height of instability |
|-------------------------------------|--------------------------------------------------------|--------------------------------|
| Fully opened value (15 Qmax)        | yes                                                    | 18.62                          |
| 7Qmax                               | yes                                                    | 18.02                          |
| 4Qmax                               | yes                                                    | 17.71                          |
| 2Qmax                               | no                                                     | /                              |
| Qmax                                | no                                                     | /                              |

It can be concluded from the table that the maximum design flow rate of 25000 m³/h of the standard
device with outlet diameter of 3.0m still exits much margin. And considering the flow field stability of
the outlet pipeline and the gas-liquid interface in the water tower, the maximum design flow rate of the
standard facility can be 38000m³/h.
3.2. Study on flow field of standard facility with different outlet pipeline diameters

This chapter changed the diameter of the outlet pipeline and also the outlet flow rate of these pipelines, in order to analyze the most suitable calibration flow rate points and the effective height of the water tower of the standard facility under these different diameter pipelines.

3.2.1. Flow field of standard facility with 0.8m outlet diameter and the fully opened valve. This chapter calculated the flow process of the facility with 0.8m outlet diameter and the fully opened valve and the water level contours at different time were shown in Figure 7.

![Figure 7](image.png)

Figure 7. The water level contours of the standard facility when the water level fell to 18.61m, 17.50m and 15.60m under the condition of 0.8m diameter outlet pipeline and fully opened value.

Through the analysis of the contours, it is found that under the condition of 0.8m diameter outlet pipeline and fully opened value, because of the small diameter pipeline and small outlet flow rate, the diameter-change section had little influence on the water flow velocity and would neither lead to instability of the gas-liquid interface nor the concave or convex interface in the water falling process. So, the small diameter outlet pipeline is more suitable for low flow rate flowmeter calibration.

Besides the above situations, this paper also studied the situations of 4Q\text{max} and 7Q\text{max} outlet flow rate under 3.8m outlet pipeline diameter and 4Q\text{max} outlet flow rate under 2.0m outlet pipeline diameter and so on. In order to save the length of this paper, the specific water level contours of flow field was not listed in detail, but made table 2 to show whether there was instability of gas-liquid interface under the above flow rate and the beginning height of instability.

### Table 2. The instability of gas-liquid interface under different flow rates of different diameters.

| Diameter  | 3.0m | 3.8m | 2.0m | 0.8m |
|-----------|------|------|------|------|
| Instability | value opened | 7Q\text{max} | 4Q\text{max} | 2Q\text{max} | value opened | 4Q\text{max} | value opened |
| 18.62 | 18.02 | 17.71 | / | 18.02 | 17.87 | / | 18.49 | 17.78 | / |

It can be seen from the table that the gas-liquid interface instability will not occur in the process of water falling, under the condition that the maximum design flow rate is 25000 m\text{3}/h and the maximum outlet pipeline diameter is 3.0m. This is because that in the working flow range of the standard facility although the flow field in the tower has large-scale flow nonuniformity, especially the large fluctuation of velocity in the direction of gravity, and the velocity profile has obvious pulsation due to the existence of diameter-change section in the water tower, which leads to small-scale fluctuation of the gas-liquid interface, but this kind of fluctuation is relatively small compared to the characteristic scale of transverse flow (tower diameter). So it has little influence on the fluctuation of the gas-liquid interface in the water tower and outlet flow rate of the outlet pipeline. In addition, when the diameter of the outlet pipeline continues to increase to 3.8m and the outlet flow rate is still the design maximum 25000 m\text{3}/h, the
instability of the gas-liquid interface still will not appear in the whole process of water level falling. Therefore, the larger diameter flow meter can be calibrated based on the designed water tower compared to the flow meter of 3.0m diameter. On the other hand, the maximum design flow rate of the standard facility is 25000m3/h, which there is still much margin, under the condition of 3.0 m outlet pipeline diameter.

However, when the flow rate is much higher than the maximum design flow rate of the flow standard facility (Q ≥ 4Qmax), the change of the flow velocity in diameter-change section and the development of small-scale irregular vortex will both lead to different degrees of gas-liquid surface instability and flow fluctuation of the flow facility. The concave and convex surface will appear near the variable diameter section especially when the valve is fully opened. In this case, the standard facility will not suitable for flow meter calibration. The flow field of variable water head flow standard facility is also affected by the diameter of outlet pipeline. Under the same flow rate point, the flow field instability of large pipeline diameter (3.8m, 3.0m) is more obvious than that of small pipeline diameter (2.0m, 0.8m), and the concave and convex surface is prominent, which is also not suitable for flow meter calibration.

4. Conclusion

By the example of the variable head water flow standard facility planned to be built by a flow meter manufacturer, this paper studies the relationship between the internal flow field stability and the outlet pipeline diameter and outlet flow rate of the standard facility. It is concluded that the gas-liquid interface instability will not occur in the process of water falling, under the condition that the maximum design flow rate is 25000m3/h and the maximum outlet pipeline diameter is 3.0m. And there is possibility of further expanding the diameter and flow rate of the standard facility. In addition, at the same flow rate point, the smaller the outlet diameter is, the more advantageous to the flow field stability is. In the above process, this paper has finished the work of 3D geometric model design, mesh generation, parameter setting and numerical calculation. The numerical result has practical significance for the design and flow field analysis of the variable head water flow standard facility with diameter-change section in the main water tower.

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