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NUMERICAL AND EXPERIMENTAL INVESTIGATION ON LEAK DISCHARGE-PRESSURE RELATIONSHIP FOR LINEAR ELASTIC DEFORMING PIPES

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Abstract

Large amount of research investigated the flow rate from an individual leak as a function of the internal pressure, but few of them managed to separate the effect of pipe deformation and that of leak hydraulics. In this study, experiments were carried out simultaneously measuring leak area, flow rate and pressure head so that the discharge coefficient can be experimentally determined. The experiments under both free and submerged condition were conducted. A few anomalies were found. For example, the leakage flow rate of submerged discharge was significantly greater than that of free discharge under full turbulence regime. Meanwhile, for submerged discharge, the discharge coefficient was not constant, but increased first and then decreased. Through CFD simulation, this study provided preliminary expansions of the two anomalies. The less leak flow rate of free discharge may be caused by the friction of water flow and air, and the abnormal decrease of the discharge coefficient of submerged discharge may due to cavitation phenomenon. The phenomena observed in this study could offer more information for researchers about leak hydraulics.

Keywords
Leakage Management; Free Discharge; Submerged Discharge; Pressure Management; Water Distribution System

1 INTRODUCTION [FIRST ORDER HEADING, CAMBRIA 12-POINT, BOLD, LEFT JUSTIFIED, CAPITALIZED, 12PT LINE SPACING BEFORE AND AFTER]

Leakage is the main component of non-revenue water (NRW) and an important index of water loss in water distribution system (WDS). The relationship between the leakage flow rate of a certain leak and the internal pressure of the pipe plays an important role in leakage management. The orifice equation, which was derived based on the Torricelli's law, was often used to calculate leakage flow rate in WDS:

$$Q = C_d A\sqrt{2gh} \tag{1}$$

where Q is the leakage flow rate; C_d is the discharge coefficient; A is the leak area, and h is the pressure drop. However, since the 1990s, numerous field tests and experiments have concluded that the leak flow rate was much more sensitive than the relationship predicted by the orifice equation[1-2], spanning from 0.5 to 2.79, with an average value of 1.15. a power equation was introduced and recommended by the Water Losses Task Force of the International Water Association(IWA):

$$Q = Ch^N \tag{2}$$

where C denotes the leakage coefficient and N denotes the leakage exponent. IWA's power equation was simple and easy to use, however, it can't reflect the real physical phenomenon. May [3] proposed a model assuming that the leak area increases linearly with increasing pressure:

$$Q = C_d(A_0 + mh)\sqrt{2gh} \tag{3}$$

where A_0 is the initial leak area under zero pressure conditions and m is the head-area slope.

Numerous researches were conducted to investigate the leak flow-pressure relationship under the effect of pipes' defamation [4-7]. However, due to the effect of leak discharge, few researches managed to measure leak area directly. Thus, the relationship between C_d and pressure can't be experimentally investigated.

In this study, through image analysis methods [7], leak area was measured experimentally together with leak flow rate and pressure. To provide more information for researchers about leak hydraulics, computational fluid dynamics (CFD) simulations were carried out.

2 METHOD AND MATERIALS

2.1 Laboratory Setup

A schematic of the experimental apparatus used in this study is illustrated in Fig. 1. The experiments were conducted in the Pipe Leakage Test Laboratory in Harbin Institute of Technology, China, composed by adjustable pipes and hydraulic pumping systems controlled by variable frequency drivers.

The pump could supply water at a speed of 7 L/s and a head of 75 m. An air vessel was installed downstream of the pipe to stabilize the upstream pressure. Two air valves were installed both upstream and downstream of the test section to remove the air from the pipe. Two electromagnetic meters with ±0.5% accuracy was used to measure and record the flow rate. The leakage flow rate was determined by calculating the difference between the upstream and downstream flowmeter readings. The leak flow discharge from the test tank was collected in a bucket with a capacity of 17 L. The leakage flow rate data were calibrated by simultaneously measuring the leaked water weight and the time through a weight sensor with 20 Kg full scale (FS) and 0.05% FS accuracy. Two series of manometers with 1.0 MPa and 0.10 MPa FS were utilized to measure the pressure the test section. The accuracy of the manometers was 0.2% FS. The manometers with 0.10 MPa FS was used to measure the pressure at low-pressure conditions with higher accuracy. The data collected by the weight sensor, flow meter, and manometers were recorded simultaneously by a computer at a frequency of 1 Hz.

A replaceable test pipe section with an artificial crack was installed in a tank with 0.5 m^3 capacity. As depicted in Fig. 1b, one side of this tank was transparent in order to facilitate the leak area measurements. The length of the test pipe section between two flange was 1m. The parameters of the test sections were summarized in Table.1. On the other side of the tank, a 0.6-m-high overflow weir was installed. The test pipe section was installed horizontally, facing the transparent side of the tank. The average height of the leak on the test section with respect to the bottom of the test tank was 0.1 m, so that the external water pressure head could be stabilized at 0.5 m.

Table 1. Parameters of test sections

Number of test sections	Geometry of test sections	Diameter/Length of the leak (mm)	Initial Area (mm^2)	Pipe material	Nominal Diameter (mm)	Pipe Thickness (mm)
1	Longitudinal crack	21.05	26.59	HDPE	50	4.3
2	Longitudinal crack	20	20	Steel	50	3.5
3	Round hole	5	19.64	Steel	50	3.5
4	Circumferential crack	20	20	Steel	50	3.5

Similar to the procedure reported by van Zyl and Malde [8], the pressure of the test section was increased and decreased in a stepwise manner. Each test step lasted about 30 s, and was proved to be long enough for the flow and pressure data to be stabilized. To eliminate the effect of viscoelastic behaviour of pipes, after each test step the pump would turn off for 1 minute to provide enough time for pipe material recovery. Once the total time of an experiment run exceeded 2700s, the experiment would be terminated and restarted after at least 4 hours.

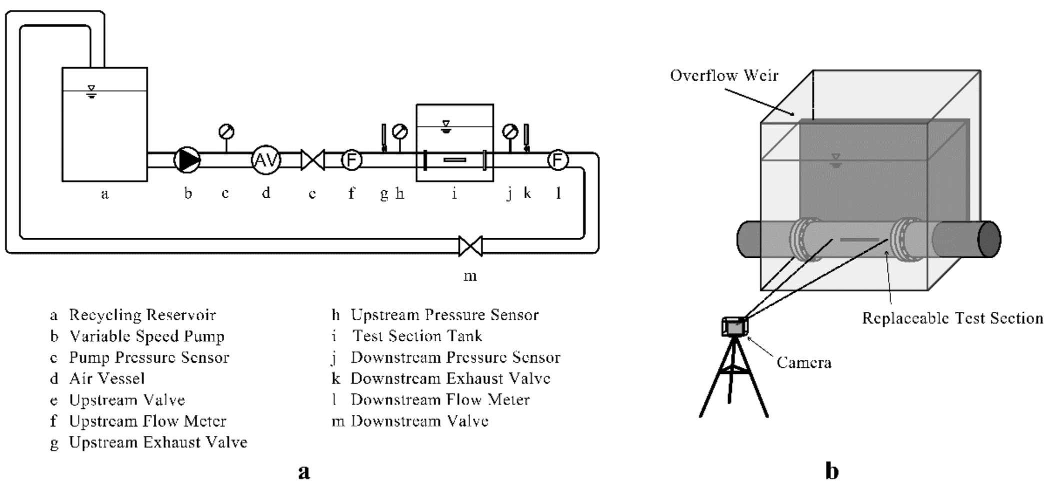


Figure 1. Layout of experimental setup.

The objective of the experiment was to simultaneously acquire data concerning the leak area-pressure head (A-h) and leak flow rate-pressure (Q-h). Image analysis methods, similar to those used in (Fox et al., 2016b), were adopted to measure the area under the effect of leakage flow. Images of the cracks were recorded using a camera with a resolution of 48 MP. The external surface around the crack was painted with waterproof red paint to provide a clear distinction line between the red pipe surface and the black leak area under the effect of leak discharge. Subsequently, an image processing procedure was followed to separate the leak area from the pipe edges based on the RGB value of the pixels. The initial length and average width of the crack on each test section were measured using a vernier caliper with an accuracy of 0.1 mm. Before each experiment, a ruler with known length and width was installed and photographed with the camera, in order to calibrate the ratio between pixel size and actual size. Under each pressure level, three images were recorded and the leak area value was the average of the three measurements. Due to the complex procedures involved in the image analysis methods adopted in this study, the leak area was recorded every 5 mH2O.

Furthermore, the wetted perimeter of the crack outlet section (χ) was measured through the image analysis method. By combining the measured leak area and flow rate, the Reynolds number of the crack outlet section under different pressures can be determined.

The experiments of this study were carried out under both submerged and free condition. When taking photos to record the leakage area, the pipe was submerged. To collect the data for free discharge, a submersible pump was installed at the bottom of the tank to discharge the leaked water from the tank. In this study, it was assumed that only the internal pressure had an impact on the leakage area, and the effect of surrounding media can be ignored. The discharge coefficient under free condition was calculated using the area measured under submerged condition.

2.2 Settings of CFD simulations

In order to obtain more information about the relationship between pressure and discharge coefficient, interaction of leak discharge and surrounding media near the leakage was investigated by finite element simulations. Model development and analyses were conducted in ANSYS Workbench (ANSYS, 2021).

Fig. 2 illustrates the 3D geometrical models of the fluid domain, which was composed of fluid field in the pipe, in the leak and in the water tank around the pipe. The geometry of computational domain of the finite element simulation were the same as those of the experimental device, and boundary conditions were the same as the experimental conditions. The height of the fluid domain in tank was set as 0.5m and the pressure of its outlet was set as 99500 Pa, which was the local atmosphere pressure in Harbin.

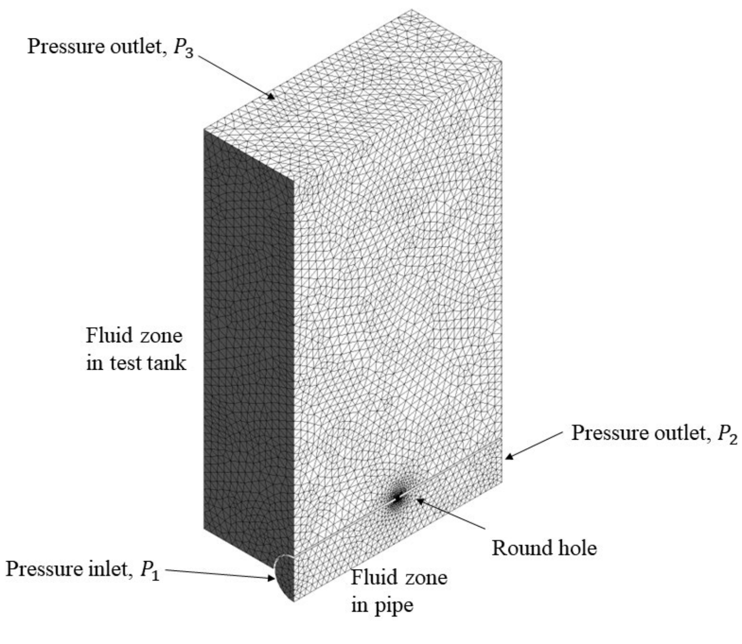


Figure 2. Standardized mesh distribution for finite-element analysis for a 5 mm round hole (test 3).

In order to avoid the influence of the side wall of the water tank on the calculation results, the direction of the leakage is set to be vertically upward. Experiments was conducted and proved that the orientation of the leakage has no effect on the leakage flow rate.

A plane of symmetry was used to reduce the model size and consequently increase calculation efficiency. Full and half fluid domain models were run and compared in order to confirm that this had a negligible impact on the leakage flow rate. The mesh near the leak is encrypted. A mesh invariance analysis was conducted and showed that increasing the resolution of the developed mesh did not significantly alter the simulation solution.

To simulate the submerged discharge, the material of fluid domain in tank was set as water. It was set as air when simulating free discharge. The turbulence model was set as realizable k-ϵ model, and the multiple flow model is set as mixture model. The measured leak flow rate and pressure data was used to calibrate the simulation results.

3 RESULTS AND DISSCUSSION

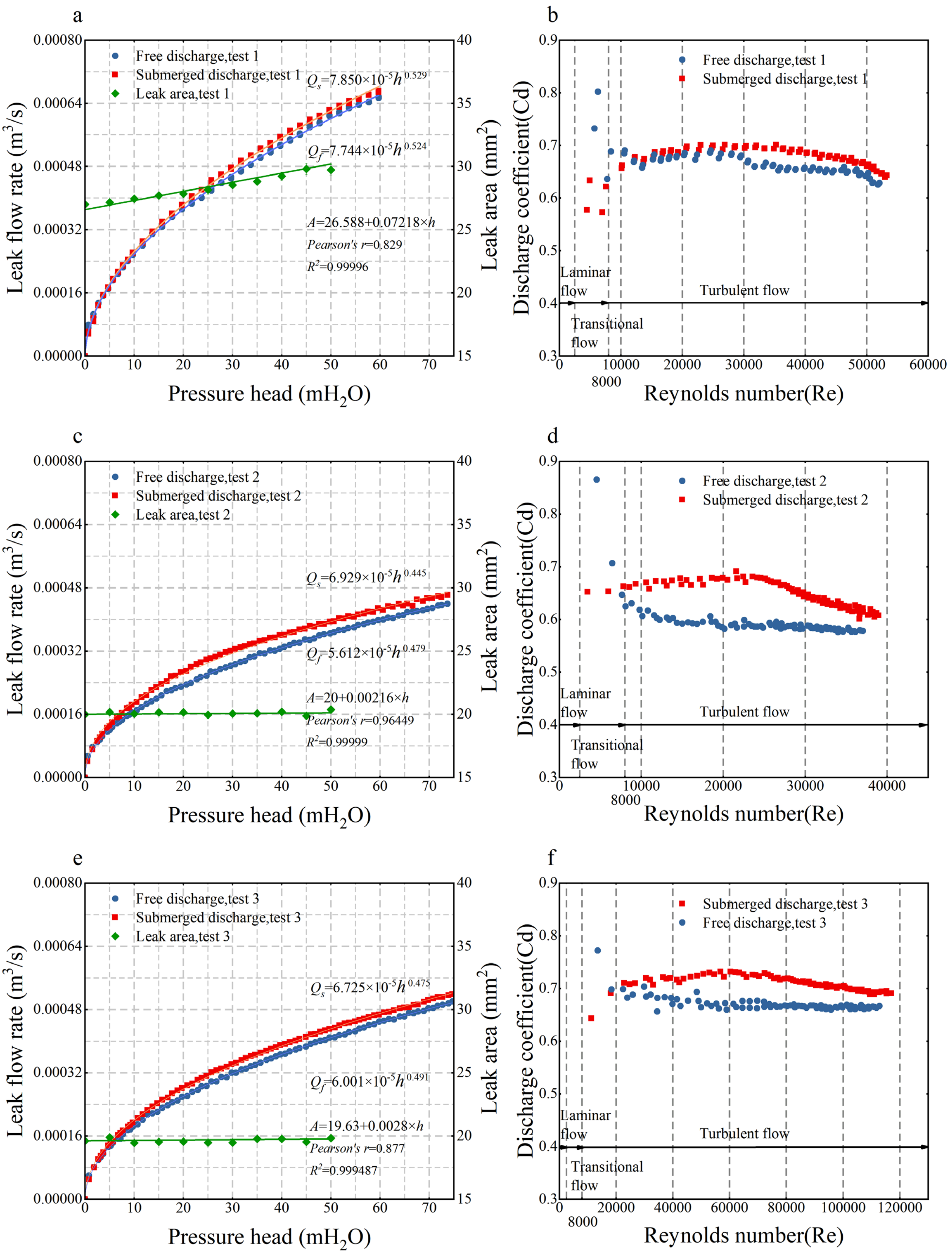
Variation of the measured leak area and flow rate with internal pressure and corresponding variation of discharge coefficient with Reynolds number for the experimental test 1~4 under the conditions of free discharge and submerged discharge are shown in Fig. 3.

It can be seen that there was an obvious linear correlation between leakage area and pressure when viscoelastic deformation effect was eliminated. In addition to the obvious linear deformation of HDPE pipe, the linear deformation of steel pipe was almost negligible. This is consistent with the study of van Zyl and Malde [8]. Combined with the data of initial area, the relationship between leakage area and pressure can be obtained by using the least square method. The discharge coefficient can be obtained by using the orifice equation:

$$C_d = \frac{Q}{A\sqrt{2gh}} = \frac{Q}{(A_0 + mh)\sqrt{2gh}} \tag{4}$$

The IWA's power equation was used to fit the pressure-leak flow data. It can be seen that only the leakage exponent of HDPE pipe is greater than 0.5. This was consistent with the conclusions of previous researches that the expansion of the leakage area could lead to the leakage exponent greater than 0.5.

In addition, interesting phenomena can be seen by comparing the leak flow rate-pressure curves of free discharge and submerged discharge under the same conditions. Since there is an external pressure of 0.5 mH_2O under submerged condition, theoretically, the leakage flow rate of the submerged discharge should be less than that of the free discharge when the internal pressure and discharge coefficient are the same. However, the data was not consistent with this prediction: in all 4 tests, when the internal pipe pressure was less than 2 mH_2O, the leakage flow rate of free discharge was greater than that of submerged discharge; When the pressure was between 2 mH_2O and 5 mH_2O, the leakage flow of the two were roughly the same; When the pressure was greater than 5 mH_2O, the leakage flow of submerged discharge was significantly greater than that of free discharge.


a
Free discharge,test 1
Submerged discharge,test 1
Leak area,test 1
Q_s=7.850×10$^{-5}h^{0.529}$
Q_f=7.744×10$^{-5}h^{0.524}$
A=26.588+0.07218×h
Pearson's r=0.829
R^2=0.99996
Leak flow rate (m^3/s)
Leak area (mm^2)
Pressure head (mH$_2$O)
b
Free discharge,test 1
Submerged discharge,test 1
Laminar flow
Transitional flow
Turbulent flow
Discharge coefficient(Cd)
Reynolds number(Re)
c
Free discharge,test 2
Submerged discharge,test 2
Leak area,test 2
Q_s=6.929×10$^{-5}h^{0.445}$
Q_f=5.612×10$^{-5}h^{0.479}$
A=20+0.00216×h
Pearson's r=0.96449
R^2=0.99999
Leak flow rate (m^3/s)
Leak area (mm^2)
Pressure head (mH$_2$O)
d
Free discharge,test 2
Submerged discharge,test 2
Laminar flow
Transitional flow
Turbulent flow
Discharge coefficient(Cd)
Reynolds number(Re)
e
Free discharge,test 3
Submerged discharge,test 3
Leak area,test 3
Q_s=6.725×10$^{-5}h^{0.475}$
Q_f=6.001×10$^{-5}h^{0.491}$
A=19.63+0.0028×h
Pearson's r=0.877
R^2=0.999487
Leak flow rate (m^3/s)
Leak area (mm^2)
Pressure head (mH$_2$O)
f
Submerged discharge,test 3
Free discharge,test 3
Laminar flow
Transitional flow
Turbulent flow
Discharge coefficient(Cd)
Reynolds number(Re)

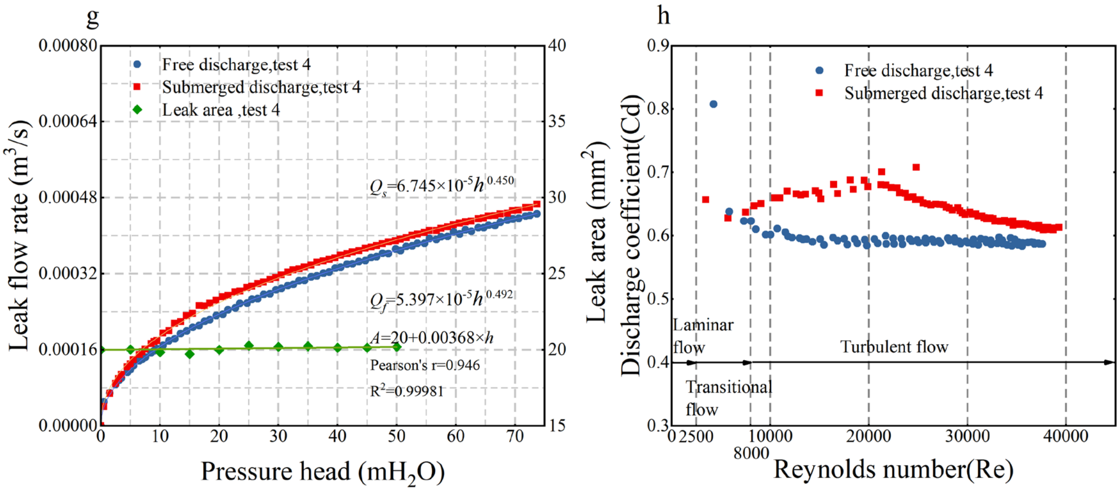


Figure 3. Variation of the measured leak area and flow rate with internal pressure and corresponding variation of discharge coefficient with Reynolds number for test 1~4

By analysing the relationship between discharge coefficient and Reynolds number, it is not difficult to see that all the flows in experiment tests were under the transition regime or fully turbulent regime. Since the normal operating pressure of the real WDS is usually greater than 10 mH_2O, it can be inferred that most of the leakage flow in real WDS is under fully turbulent regime. The leakage coefficients of free discharge and submerged discharge showed different characteristics. For free discharge, the discharge coefficient decreased monotonically with Reynolds number, while at high Reynolds number, it decreased lowlier with the increase of pressure or even remained unchanged, which is consistent with to Iderik's inverse proportional model. However, for submerged discharge, the discharge coefficient was not constant, but increased first and then decreased.

To authors' knowledge, there lacks detailed research explaining the difference between free discharge and submerged discharge. This study tried to give some explanations through the information obtained by CFD simulations. This study only simulated leak hydraulics without considering the variation of leak area caused by pressure. Therefore, this study only simulates the working conditions of test2, 3 and 4.

Under turbulence regime, taking the leakage of 5mm Round hole (test 3) under 40 mH_2O as an example, the streamline near the hole is shown in Figure 4. The lower part of the fluid domain was the water flow inside the pipe, the upper part was the media around the pipe, the middle part is fluid in the hole. Obvious vena contracta can be observed in the hole, and there was a clear eddy current near the vena contracta. The velocity of eddy in free discharge was significantly higher than that of submerged discharge, which means that the disturbance of air was greater than that of water in the orifice. In addition, by observing the volume fraction of air for free discharge near the round hole shown in Figure. 5, due to the friction between water flow and air, the water column will gradually diffuse, resulting in a much more dispersed velocity distribution of free discharge than that of submerged discharge. More sufficient mixing and friction with external media may lead to the dissipation of flow kinetic energy, so that the velocity of free discharge is less than that of submerged discharge, resulting in less flow rate.

For the flow with low Reynolds number, the impact by this friction may be less than that of external pressure, so that the leakage flow of free discharge is greater than that of submerged discharge.

in addition, one possible explanation for the abnormal decrease of the discharge coefficient of submerged discharge is that cavitation occurred when the pressure in the pipe exceeded a certain threshold. Bubbles generated by cavitation hindered the leakage flow.

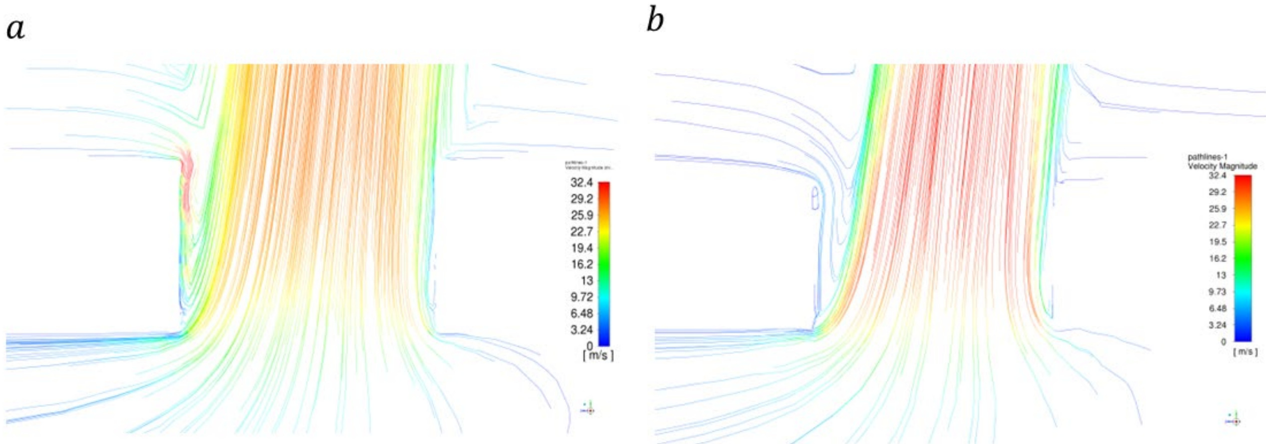


Figure 4. Streamline of leak flow near a 5mm round hole with 40mH$_2$O pipe internal pressure under (a)free and (b) submerged condition

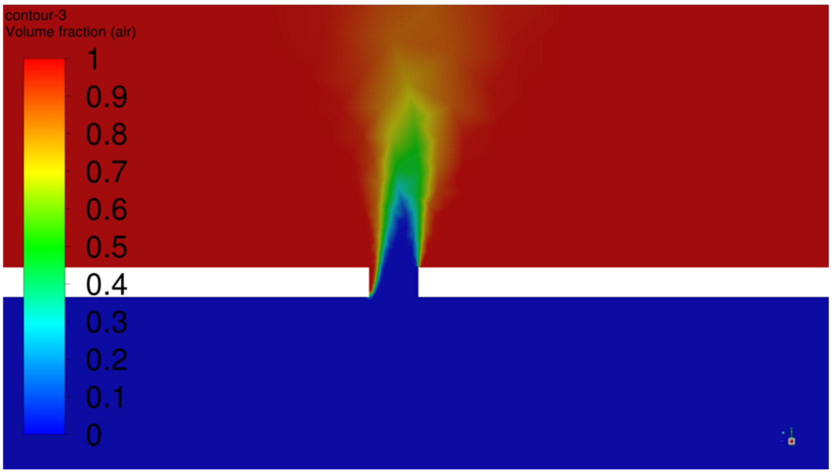


Figure 5. the volume fraction of air for free discharge near the round hole

4 CONCLUSION

For clear understanding of physical characteristics of the relationship between leakage flow rate and pipe internal pressure, experiments were carried out simultaneously measuring leak area, flow rate and pressure head so that the discharge coefficient can be experimentally determined. The experiments under both free and submerged condition were conducted. Two anomalies were observed:

1. The leakage flow rate of submerged discharge was significantly greater than that of free discharge under full turbulence regime, even the external water pressure could have negative effect on submerged discharge.

2. For submerged discharge, the discharge coefficient was not constant, but increased first and then decreased.

Through CFD simulation, this study provided premilitary expansions of the two anomalies. The less leak flow rate of free discharge may due to the friction of water flow and air, and the abnormal decrease of the discharge coefficient of submerged discharge may due to cavitation phenomenon.

The phenomena observed in this study could offer more information for researchers about leak hydraulics. In the future, more research will be carried out to investigate the effect of soil and more efforts will be made to find more reliable theoretical explanations for these anomalies.

5 ACKNOWLEDGEMENTS

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