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# EFFECT OF ORIFICE HYDRAULIC AND GEOMETRIC CHARACTERISTICS ON LEAKAGE IN WATER DISTRIBUTION SYSTEMS

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**ABSTRACT:** Leakage from water distribution systems have significant economic and environmental impacts. Reducing leakage from distribution systems has favorable effects on the environment and energy consumption. This paper aims to understand the implications of orifice hydraulic and geometric characteristics on leakage flow. An experimental model was thus designed and built to simulate leaking water pipes with different defects. Various parameters were considered, including the size and shape of the orifice, Reynolds number ($Re$), and cavitation development in the orifice. During the tests, water was allowed to flow through the defects at controlled pressures while observing leak behavior. The results showed that the discharge coefficient ($C_d$) exhibited an extensive range (0.35–0.88) depending on the size and shape of the orifice and the flow conditions. The impact of cavitation can be so significant that it leads to variations in the discharge coefficient that are larger than those occurring with $Re$. A model is then presented to predict leakage rates at different flow conditions (i.e., cavitating and non-cavitating flow). Comparing the results shows a good fit between projected and measured flow values.

*Keywords: Discharge Coefficient, Hydraulics, Orifice Flow, Pipeline Leakage, Water Distribution Systems.*

## 1. INTRODUCTION

Water loss from water-distribution systems (WDSs) is a global problem amounting to some 126 billion cubic meters per annum (expressed as non-revenue water) [1]. Up to 30% of treated water is estimated to be lost through leakage from distribution systems [2]. In some countries, the leakage rate represents 40%–50% of water supplied. Leakage from WDSs is wasted water, lost revenue, and energy losses because of the energy required to treat and transport water that does not reach the customer. Leaks can also cause serious environmental, health, and safety issues [3]. The leaking flow can damage the foundations of buildings and roads or be contaminated by pollutants. Therefore, managing leakages in WDSs is important for water supply and safety management.

In practice, pressure management is already used as a leakage control strategy in WDSs [4,5]. Several models have been proposed to model and assess leakage rates from WDSs. Many of these attempts model leakages using the orifice flow equation (Eq. 1), where a leak is generally compared to an orifice [6-8].

$$q = C_d A_o \sqrt{2gh} \quad (1)$$

Here, $q$ is the flow rate (m³/s), $A_o$ is the orifice area (area of the leak) (m²), $g$ is the gravitational acceleration (m/s²), $h$ is the pressure head (m), and $C_d$ is the discharge coefficient—an empirical term added to account for energy loss due to friction and contraction of the water jet relative to the hole. The $C_d$ is typically 0.61 for circular, thin-walled, and square-edged orifices [9].

The orifice equation describes the relationship between the pressure head in a pipe and the leakage rate. It suggests that leaks vary in proportion to the square root of the pressure head in the pipe (i.e., having a leakage exponent of 0.5). Al-Khomairi (2005) [7] showed experimentally that the orifice equation gave a good prediction of an unsteady leakage rate for typical leak openings; however, it produced a significant error in leakage rate computations for long leak openings.

Multiple studies have shown that leakages vary with pressure to a more outstanding power exponent than 0.5 of the orifice flow equation (e.g., varying between 0.36 and 2.95 [4,10]. Several factors have been suggested to explain the range of leakage exponents found in the literature, including pipe material behavior (with leak area changing with pressure), leak hydraulics, soil hydraulics, and water demand [11], but these are not yet fully understood.

The variation of the orifice area $A_o$ with pressure has been discussed by many researchers [10,12-14]. In contrast to the assumption of the orifice equation, the areas of leak openings are not constant but rather vary with the differing water pressure induced by stress variations in internal pipe walls [10,12-16]. Ashcroft & Taylor (1983) [12] performed laboratory tests on artificially-induced leaks in plastic pipes. The tests were performed on polythene pipes with slits of 10 mm and 20 mm in length, where the pressure head was varied from 10 m to 100 m. They observed that the shapes of the slits changed as the pressure was increased. The resulting leakage exponents varied between 1.23 and 1.97—this is greater than the 0.5 suggested by the orifice flow equation. May (1994) [13] suggested the possibility of fixed area and variable area discharges (FAVAD) and used it to prove that systems react differently to pressure. Ultimately, May (1994) [13] concluded that an individual leakage path in a distribution system could be considered either 'fixed' with a leakage exponent of 0.5 or 'expanding' with a leakage exponent of 1.5.

Cassa et al. (2010) [14] numerically studied the behavior of various forms of leak openings (circular orifice and rectangular and circumferential slots) on pressurized pipes for various pipe materials (uPVC, steel, cast iron, and asbestos cement). They found that the areas of leak orifices increased linearly with pressure, with the circular orifices showing the smallest expansion with pressure, followed by circumferential slots and rectangular slots. The effect of pressure on a leak opening increased exponentially with increases in orifice diameter or slot length.

For orifice hydraulics, Alsaydalani (2017) [17] experimentally studied the impact of the cavitation phenomenon on the hydraulic behavior of leakage from WDSs. The results showed that cavitation could develop in leaking orifices with drastic effects on the pressure-flow relationship. Its inception depends on the size of the leak opening and flow rate.

More recently, Shao et al. (2019) [18] experimentally studied the impact of pipe flow velocity on leakage through a crack in the pipe wall and found that its impact can be significant on the orifice outflow. In another study, Yu et al. (2019) [19] considered the effect of the orifice-to-pipe diameter ratio on the leakage rate for different flow conditions. Their results showed that the orifice-to-pipe diameter ratio affected the outflow. The value of the coefficient of discharge decreased from about 12% to 3% as the orifice-to-pipe diameter ratio decreased.

The controversy around the relationship between $C_d$ and head persists. In most earlier studies, $C_d$ was considered to be constant and dependent on the form of the leak hole [20,21]. The flow regime of the leak is almost turbulent; thus, researchers believe that the change of $C_d$ may be disregarded. Nonetheless, Sadr-Al-Sadati and Ghazizadeh (2019) [22] found that $C_d$ was related to $Re$ even in the presence of turbulent conditions. While several previous studies have focused on the pressure-leakage relationship to improve understanding of leakage from WDSs, the leakage mechanism remains unclear and requires further study.

## 2. RESEARCH SIGNIFICANCE

The assessment and management of leakage from WDSs require an accurate estimation of the leakage rate from a single leak as a function of the pressure head. This paper aims to investigate the influence of orifice hydraulic and geometric characteristics on leakage flow in water distribution systems, particularly emphasizing the factors influencing the discharge coefficient and the corresponding mechanisms. Understanding the mechanisms of leakage from water pipes and the controlling factors on leakage flow is essential for assessing the leakage rate, detecting leaks, and developing further leakage reduction programs.

## 3. EXPERIMENTAL DESCRIPTION

The main objective of this study is to investigate the effect of orifice hydraulic and geometric characteristics on leakage flow in WDSs. Previous research showed that the orifice geometric parameters, liquid property, and the corresponding kinematic conditions affected the coefficient of discharge $C_d$ [11,19,22,23]. Orifice parameters are size $d$ (m) and shape of the orifice $z$. The liquid property includes density $\rho$ (kg/m$^3$) and dynamic viscosity $\mu$ (N.s/m$^2$). The kinematic conditions include pressure head $h$ (m) and flow velocity $V$ through the orifice (m/s). The parameters ($\rho Vd/\mu$) represent the Reynolds number $Re$ that can be controlled easily by controlling velocity $V$ (m/s) or leakage rate $q$ (m$^3$/s) without changing liquid properties (density $\rho$ and viscosity $\mu$). Liquid properties $\rho$ and $\mu$ are constant under lab conditions. Therefore, the parameters that will be controlled during the experiments include the size of the orifice (the diameter $d$ for circular orifice or width $w$ for rectangular slot orifice), shape of the orifice $z$, Reynolds number $Re$, pressure upstream of the orifice $P$ (kPa), and leakage rate $q$ (m$^3$/s).

To achieve the objective of this study, a special experimental model was designed and built to simulate leaking water pipes with different orifice sizes and shapes and flow conditions. The experimental model is shown schematically in Figure 1. It consists of the following components: a test section (engineered leak orifice), water tank, pump, valves to control pressure and leakage rate, a flow meter, and pressure indicators to measure pressure upstream and downstream of the leak.

A stainless-steel pipe section (0.5 m length, 25.4 mm inside diameter $D$, and 1.2 mm wall thickness) with an orifice was fitted into the system to simulate a leak in a defective pipe.

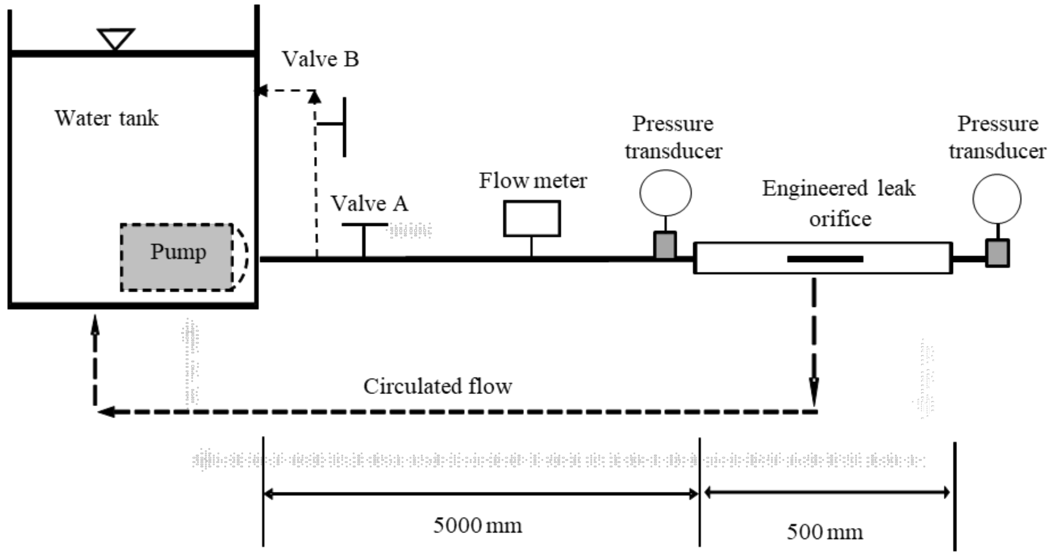


Fig. 1 Schematic diagram of the experimental setup.

Three pipe sections were made with different orifice sizes (1.6 mm, 3.6 mm, and 6.0 mm orifice diameters) to simulate leaking pipes with different hole sizes. Another set of three sections was manufactured to model different leak shapes (Fig. 2):

(a) a rectangular slot (7.4 mm length, 1.4 mm width) simulating a longitudinal defect in a pipe wall,

(b) a rectangular slot with the same dimensions simulating a circumferential defect, and

(c) a circular hole (3.6 mm diameter) simulating a pinhole leak.

These all had the same opening area (10.36 mm²). An additional test section with very small orifice sizes (i.e., a fraction of a millimeter slot orifices) was used for the test (d). This section was constructed from boxes measuring 100 × 100 × 100 mm and having narrow slot orifices running the full width of the boxes to simulate fractured water distribution pipes. The slot sizes were adjusted using flat feeler gags measuring between 0.33 mm and 0.61 mm. The form of the slots remained unchanged, with square-edged orifices 10 mm thick and 132 mm long (see Figure 2 (d)). All engineered leak orifices were manufactured using laser machines with high-precision dimensions.

### 3.1 Water Supply and Control Systems

The water supply and control systems consist of a water tank, pump, control valves, and piping systems. The water tank was filled with water that was then pumped into the piping system. The pump used in this research was a multistage submersible pump manufactured by Pedrollo (model NKm 4/3) capable of delivering a pressure head of 50 m of water at its maximum flow rate of 3200 l/h.

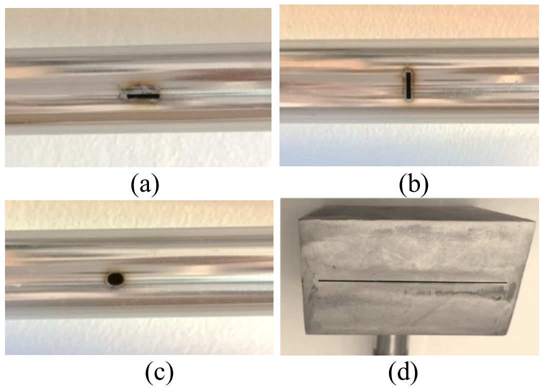


Fig. 2 Photos of the leak orifices: (a) longitudinal slot orifice, (b) circumferential slot orifice, (c) circular orifice, and (d) a fraction of a millimeter slot orifice.

A flexible hose with a diameter of 25.4 mm was used for the connection between the test section and the water tank. This was long enough (about 5 m) to provide a sufficient length allowing us to connect the fittings, including valves, flow meter, and pressure transducers. A full pipe flow is required to get the optimal performance of the flow meter and pressure transducers. Therefore, locations were selected with a sufficient distance of straight pipe immediately upstream and downstream of the fittings when installing the fittings. This helps ensure that the system is always filled and would not be exposed to air bubbles at any time, which might otherwise have air bubbles in places, thus affecting measured readings (pressures and flow rates). Similarly, the leak orifice was created in the middle of a 0.5 m length pipe (test section). This gives an aspect ratio of about 10 (i.e., 5 /0.5) that was appropriate to eliminate any artifacts arising from the experimental apparatus. The pressure and flow rate in the system were regulated with two valves (A and B; Figure 1). Water was allowed to return to the water tank through circulated pipes. Circulating water into the tank avoided the issue of depressurizing the system, which could lead to the formation of air bubbles in the system, thus affecting the measured heads.

### 3.2 Measurement of Leakage Rate and Pressure

A flow meter (model Signet 2551) with a display unit was fitted into the systems to record the leakage rate. The meter includes a function to average the flow rate (i.e., setting a period of time during which the meter averages the flow signals). This function was set to 25 seconds during each test run to smooth the display on the LCD. The meter attains ± 2% accuracy based on its specifications. Pressure upstream of the engineered leak orifice was obtained using a pressure indicator (Model-DPI 261, GE Sensing, Leicester, UK) with a head range up to 351 m (3,441 kPa) and an accuracy of 0.04%.

### 3.3 Test Program and Procedure

Tests were mostly conducted at controlled flow rates. Some other tests were done at controlled pressures upstream of the orifice with pressures ranging between 1 and 250 kPa. This represents the range that might occur in WDSs. All experiments were performed at a water temperature of 20°C. During these tests, water was allowed to flow through the defects, and the behavior of the leakage flow out of the orifice was observed. The hydraulic behavior of the defects was performed by monitoring steady-state flow behavior (i.e., measuring the rate of flow through the orifice while injecting water at stationary conditions).

*3.3.1 Test Procedure*

The consideration of various aspects was required before the test started. First, the engineered leak orifice (i.e., the test section) with the required orifice size was connected to the system. The system was then primed, and the water tank was filled using a water supply hose. The pump was then turned on, allowing water to flow from the tank throughout the system and out of the leak orifice. The apparatus was ready for testing once the system was primed (i.e., purged of all air, including bubbles).

Water was then pumped through the orifice during the test. Small flow rates (i.e., 150 l/h) and thus pressures were initially applied; these were then increased until the required pressure or capacity of the apparatus was reached. Flow rates were noted at each increment of pressure after five minutes of stabilization. The pressure upstream of the leak was read from the pressure indicator while flow rates were read from the flow meter display as mentioned. The same procedure was repeated with each increase in pressure and flow rate. A minimum of three tests were performed for each case under the same conditions to validate the test results for repeatability and reproducibility.

## 4. RESULTS AND DISCUSSION

The results showed that the discharge coefficient $C_d$ exhibited a large variation (0.35–0.88). The experimental results showed that in addition to the size and shape of the orifice, Reynolds number ($Re$) cavitation development in the orifice also affects the discharge coefficient. Cavitation has the greatest effect on the coefficient of discharge $C_d$. It was responsible for the greatest reduction in the value of the coefficient of discharge $C_d$.

### 4.1 Effect of Orifice Shape

Figure 3 shows the measured discharge coefficient of three orifice shapes (circular, rectangular slot, and circumferential slot) with the same opening area (10.36 mm²) but different shapes to simulate three different leak shapes. The accuracy of the measured discharge coefficient is guaranteed because the pressure measurement precision may reach 0.04%, and the flow meter used to measure flow rate includes a function to average flow rate (i.e., setting a time during which the meter averages the flow signals) with an accuracy of ±2%. Figure 3 shows that the discharge coefficient of the rectangular slot orifice is noticeably higher than that of the circular orifice with the same section area. The longitudinal and circumferential slot orifices have a similar discharge coefficient. The measured discharge coefficient $C_d$ for the longitudinal and circumferential slot orifices is about 0.84 and 0.69 for the circular office (see Figure 3).

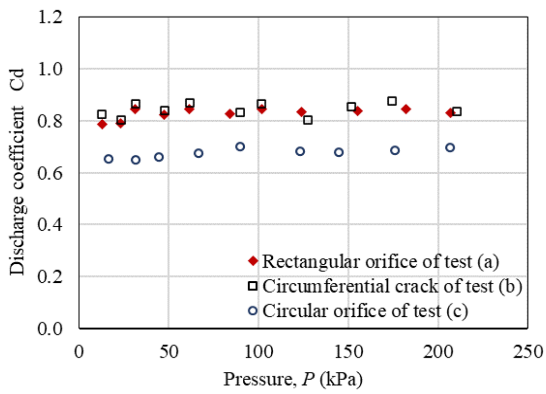


Fig. 3 Measured discharge coefficient for a circular orifice of 3.6 mm diameter and a rectangular and

circumferential slot orifice of the same area.

The leakage flow rate increased as the leakage opening changed from circular to rectangular (see Figure 4) as a result of a combination of flow contraction and viscous losses. The circular orifice causes a contraction of the jet downstream from the orifice opening. As the leakage approaches the orifice, it tends to contract due to an inability of streamlines to take a sharp turn at the opening. The narrowing at the leakage produces a flow contraction (i.e., vena contracta). A larger flow contraction leads to a lower leakage flow rate. The results show that the leakage rate is approximately 20% larger in longitudinal (rectangular) orifices than in circular orifices. This suggests that flow contraction dominates viscous effects and that the flow contraction is smaller in longitudinal than circular leakages.

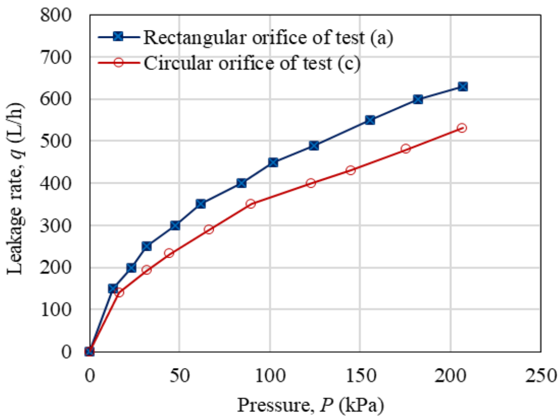


Fig. 4 The measured leakage of a circular orifice 3.6 mm diameter as well as a rectangular slot orifice of the same area.

### 4.2 Effect of Orifice Size

The impact of internal pressure on the discharge coefficient depends on the size of the orifice. Figure 5 shows the discharge coefficient for three orifice sizes (1.6 mm, 3.6 mm, and 6.0 mm diameters). A smaller orifice diameter leads to a larger discharge coefficient. For example, the $C_d$ is 0.8 for the 1.6-mm-diameter orifice and 0.6 for the 6-mm orifice. This is a reduction in the coefficient of discharge by about 25% because the orifice diameter is increased from 1.6 mm to 6 mm. The pressure drop across the orifice occurs due to losses at the orifice entry (i.e., flow contraction and viscous losses discussed above). This is proportional to the dynamic head $\rho v^2/2$. Here, ρ is fluid density (kg/m³), and v is the fluid velocity (m/s). The higher value of $C_d$ obtained for the smaller orifice is consistent with the observation of Ramamurthi & Nandakumar (1999) [23] who noted that smaller orifices produce higher discharge velocities for the same pressure drop.

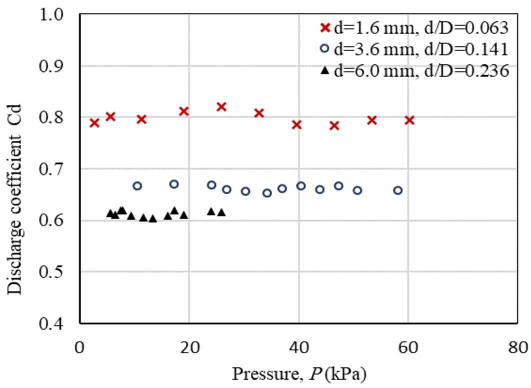


Fig. 5 Measured discharge coefficient as a function of internal pressure for different circular orifice openings of test (c).

### 4.3 Effect of Cavitation in the orifice

The experiments were repeated using very small orifice sizes (i.e., a fraction of a millimeter slot orifices) under high water heads of 25 m (250 kPa), thus simulating the operation of real water distribution pipes that normally have supply heads in that range. Figure 6 demonstrates the relationship between the coefficient of discharge $C_d$ and the Reynolds number $Re$ for three orifice sizes (0.33 mm, 0.42 mm, and 0.61 mm). The coefficient of discharge is fairly constant in the first flow condition phase (i.e., up to a Reynolds number of about 6,000) in which an average value of $C_d$ is obtained. The $C_d$ is 0.63–0.65 for all three tested small orifice sizes in this first phase (0.33 mm, 0.42 mm, and 0.61 mm; see Figure 6). In the second flow phase (i.e., at Reynolds numbers above 6,000), the coefficients of discharge have a notable decrease (Figure 6). The $C_d$ drops from 0.65 to 0.46 when $Re$ is about 6,000 as in the case of the 0.61-mm orifice. This decrease is directly related to the collapse of the rate of discharge as a result of the cavitation phenomenon, defined as the formation and collapse of vapor bubbles in a region of high flow velocity [24]. Cavitation occurs when the local static pressure in the orifice drops because of an increase in flow velocity below the local vapor pressure of the liquid [24]. The vapor region occupies a fraction of the orifice area (A) and passes through the vena contracta ($A_c$) when cavitation occurs in the orifice. Regardless of the orifice shape, when the pressure in the orifice drops below the vapor pressure of the liquid, cavitation forms. Cavitation can be predicted by monitoring the choking flow rate and reduction in the coefficient of discharge $C_d$ [25] as observed in the current study for a fraction of a millimeter slot orifice. Previous studies in other scientific fields (i.e., fuel atomization) [25-27] observed cavitation in small orifices of different shapes, including circular and rectangular shapes.

Thus, we conclude that the impact of cavitation can be significantly large and can lead to changes in the discharge coefficient that are larger than those occurring with *Re* as observed in the results of this study. Its commencement is dependent on the size of the orifice and leakage rate.

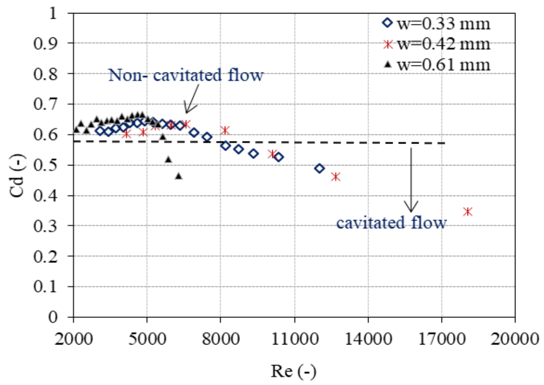


Fig. 6 Coefficient of the discharge as a function of the Reynolds number for a fraction of millimeter orifice openings of test (d).

## 4.4 Comparison between Calculated and Measured Leakage Rate

The change in discharge coefficient is a reflection of fluid energy loss through the orifice and can be affected by a number of factors, such as pipe material, orifice shape, orifice size, and the head upstream of the orifice. In practical calculations, the experience value of 0.61 is usually used as the discharge coefficient to estimate the leakage flow rate in the orifice flow equation (Eq.1). However, the effective area of the orifice changes dramatically when cavitation in the leaking orifice occurs (as observed in the results of this study) because of the development of the vapor region that occupies a fraction of the orifice area (*A*) and passes through the vena contracta ($A_c$). In this case, calculations relying on the experience value may result in larger errors. Such errors are illustrated in Figure 7, which shows the measured and calculated pressure-leakage relationship for orifice widths *w* of 0.42 mm and 0.61 mm. The calculated values were obtained using the orifice flow equation with a $C_d$ of 0.64 and 0.65 for orifice widths *w* of 0.42 mm and 0.61 mm, respectively.

The pressure–leakage relationship shows notable behavior (Figure 7): The leakage rate initially changes with pressure following the orifice flow equation. However, a deviation from the orifice flow equation was noticed at a certain point (i.e., at a leakage rate beyond 1250 l/h), and this deviation grows larger as the pressure and leakage rate increase. The deviation from the orifice flow equation is attributed to cavitation development in the orifice (as discussed above), which is associated with a significant drop in the coefficient of discharge $C_d$. During this mechanism, a vapor zone likely forms inside the orifice, thus reducing the effective area of the flow until a point is reached where the leakage does not continue to increase as the pressure increases (see Figure 7).

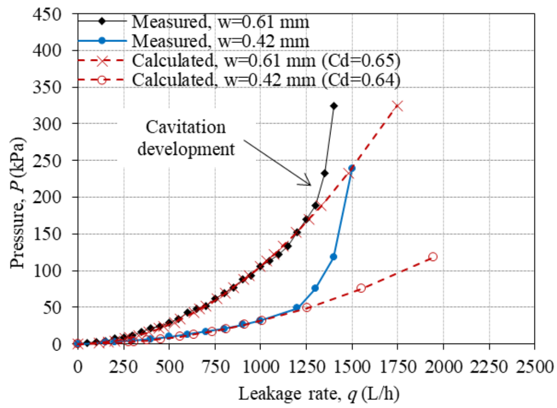


Fig. 7 Pressure-leakage rate relationship for two different orifice widths of test (d).

In the case of a cavitating orifice flow, the coefficient of discharge is affected by the cavitation number instead of the Reynolds number [25,28,29]. However, in conditions of non-cavitating flow, a constant value for the coefficient of discharge can be assumed, which is a function of the Reynolds number.

The cavitation number (*K*) can be expressed as a form of the Euler number that is influenced by pressure and velocity. These are combined with density in the cavitation number:

$$K = \frac{2\,(P_d - P_v)}{\rho V^2} \tag{2}$$

Here, $P_d$ is the pressure downstream from the orifice (kPa), $P_v$ is the saturated vapor pressure (kPa), ρ is water density (kg/m³), and *V* is the average velocity of the liquid at the orifice (m/s). Term *V* can be calculated as $Q/A_o$ where *Q* is the rate of flow (m³/s) and $A_o$ is the cross-sectional area of the orifice (m²).

Under cavitating conditions, Pearce & Lichtarowicz (1971) [28] proposed an equation that predicts the discharge coefficient as a function of a cavitation number, *K*:

$$C_d = C_c\sqrt{1+K} \tag{3}$$

Here, $C_c$ is the contraction coefficient represented by the ratio of the actual area $A_c$ at the contraction (m²) to the orifice cross-sectional area ($A_o$) (m²). Parameter *K*, the cavitation number, is given in Eq. (2).

In this case, the flow behavior through an orifice opening for both cavitating and non-cavitating flow can be predicted. A fixed value of the coefficient $C_d$ is used for non-cavitating flow, and $C_d$ is determined as a function of the cavitation number using Pearce and Lichtarowicz's equation for cavitating flow (Eq. (3)).

According to hydraulic theory, the coefficient of contraction $C_c$ for an orifice depends on the size and geometry of the orifice and can be obtained experimentally. For this experimental setup, the value of $C_c$ was determined by assuming a value for $C_c$ and then calculating the leakage rate to obtain the best fit with the measured leakage rate. A coefficient of contraction $C_c$ of 0.38 was found to give the best fit with that measured leakage rate.

Figure 8 compares predicted leakage rates using the model with those observed during the experiments for three orifice sizes: 0.33 mm, 0.42 mm, and 0.61 mm. In non-cavitating flow conditions, a constant value for the coefficient of discharge ($C_d$) of 0.65 was used (e.g., for the 0.42 mm and 0.61 mm orifices). In cavitating flow conditions, $C_d$ values that vary as a function of the cavitation number were used as calculated using Eq. (3).

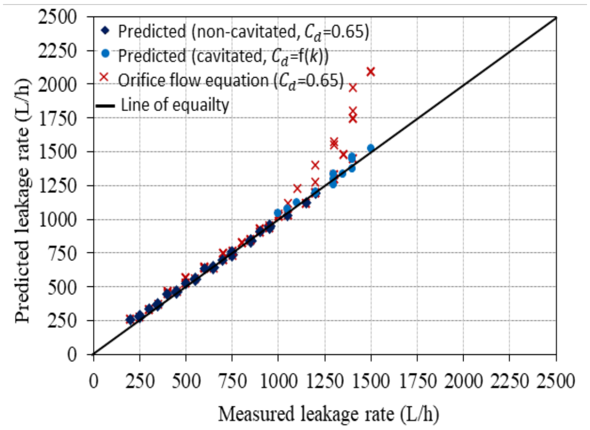


Fig. 8 Predicted leakage rates versus those observed during the experiments (d).

Figure 8 shows that the orifice flow equation prediction (assuming a steady flow) increasingly overestimates the leakage rate. The values predicted using the proposed model continue to give reliable estimates of leakage rates even at the largest leakage levels used in the tests, thus providing confidence in the method.

Based on the discussion above, we conclude that the impact of cavitation can be so large as to lead to variation in the discharge coefficient larger than that occurring with *Re*. This occurrence is based on the orifice size and leakage rate. Furthermore, a constant value for the coefficient of discharge $C_d$ can be assumed in conditions of non-cavitating flow. This is a function of the Reynolds number *Re*. However, when the flow starts to cavitate, the coefficient of discharge $C_d$ is affected by the cavitation number (*K*) and not just the Reynolds number *Re* reported by others [25,28,29].

## 5. CONCLUSIONS

This paper investigated the effect of orifice hydraulic and geometric characteristics on leakage flow in WDSs. In particular, it examined the factors influencing the discharge coefficient and the corresponding mechanism. For this purpose, a special experimental model was designed and built to simulate leaking water pipes with different orifice sizes, shapes, and flow conditions. Using this model, water was allowed to flow through the defects at controlled pressures. Some tests used controlled flow rates. We then observed the behavior of leakage flow out of the orifice.

Based on this study, the following may be concluded:

- The discharge coefficient $C_d$ exhibited a large variation (0.35–0.88), which presented a large deviation from the typical value 0.61 normally used as the discharge coefficient in practical calculations to estimate the leakage flow rate using the orifice flow equation. Thus, care is needed when using the orifice flow equation to estimate leakage from water distribution pipes.
- The results showed that, in addition to the size and shape of the orifice, Reynolds number (*Re)* cavitation development in the orifice also affects the discharge coefficient. Cavitation has the greatest effect on the coefficient of discharge $C_d$ and was responsible for the greatest reduction in the value of the coefficient of discharge $C_d$.
- The rectangular slot orifice was found to give higher discharge coefficient values than the circular orifice with the same section area. In terms of the size of the leak opening, a smaller opening implies a larger discharge coefficient.
- Regardless of the orifice shape, cavitation can develop in an orifice when the pressure drops in the orifice below the vapor pressure of the liquid. Cavitation can be predicted by monitoring the choking flow rate and reduction in the coefficient of discharge $C_d$. For water heads on the order of 20–25 m that simulate the operation of actual water distribution pipes, cavitation can occur in the case of very small orifice sizes (i.e., a fraction of a millimeter orifice). Cavitation cannot be ignored while modeling leakage from water distribution.
- A model has been presented to predict leakage flow rates for the two flow conditions: non-cavitating and cavitating. In the first phase, the coefficient of discharge is assumed to be constant because it depends on Re. In the second phase, the coefficient of discharge $C_d$ is determined as a function of the cavitation number *K*. The data show that the model gives

reliable estimates of leakage rates even at the highest leakage levels used in the tests. This underscores confidence in the model.

The model presented here is of practical importance in determining the coefficient of discharge $C_d$ for both cavitating and non-cavitating orifice flow. It is of fundamental importance in numerical models of pressurized pipe systems that are used to model the leak outflow.

The mechanism of leakage in WDSs considered here is different from that occurring in storm or sanitary sewer systems in which liquid flows partially filling the pipes and flows due to gravity with a free surface. Therefore, further studies on leakage in the storm and sanitary sewer systems are recommended.

## 6. ACKNOWLEDGMENTS

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