
Determination of Orifice Coefficients for Flow Through Circular and Rectangular Orifices

By

Nicholas. Akhaze Musa and Bobai, Santos Bityong

Mechanical Engineering Department,
Federal University of Technology, Minna, Niger State, Nigeria
Email; Madonick1@yahoo.com

ABSTRACT

Circular and rectangular orifices are among the types of orifices being classified according to geometrical shapes. They are among others widely used as flow meters. Knowledge about the orifice coefficients and discharges through circular and rectangular orifice is very important, when selection for use is based on the requirement of low or high discharges as well as high or low orifice coefficients. So, this research work experimentally determined the orifice coefficients and discharges through circular and rectangular orifices having the same area of 0.00015m^2 under a constant head of water of 0.9m . The experimental results revealed that under a constant head of water of 0.9m , circular orifice has average coefficient of discharge, coefficient of velocity, coefficient of contraction, theoretical and actual discharges as 0.62 , 0.94 , 0.66 , $5.52 \times 10^{-4}\text{m}^3/\text{s}$ and $3.42 \times 10^{-4}\text{m}^3/\text{s}$ respectively. More so, that rectangular orifice under the same constant head of water of 0.9m , has average coefficient of discharge, coefficient of velocity, coefficient of contraction, theoretical and actual discharge as 0.66 , 0.96 , 0.69 , $5.53 \times 10^{-4}\text{m}^3/\text{s}$ and $3.65 \times 10^{-4}\text{m}^3/\text{s}$ respectively.

Keywords: Orifice, circular orifice, rectangular orifice, coefficient of discharge, coefficient of velocity, coefficient of contraction

INTRODUCTION

An orifice is an aperture through which fluid flows. It can be classified according to shape such as circular, rectangular, square and triangular orifices. Orifices are also known as head loss flow meters or differential pressure producing devices and can be characterized by orifice edge geometry, β ratio which is the ratio of orifice bore diameter (d) to pipe diameter (D), orifice thickness (t) to bore diameter (d) (Ntamba,2011). According to Derasari(1993),The orifice flow rate is a function of the liquid head, hole diameter, plate thickness, punch direction, whether or not the surface is deburred, etc. Orifices are

used for various engineering applications such as cooling holes, fuel lines, hydraulic systems, air conditioning and water pipe systems (ESDU,2007) stated by Ntamba (2011). According Swamee and Swamee (2010). Orifices are also used as an emptying device for tanks.

An orifice for flow measurement is usually in plate called orifice plate and according to Reader-Harris (2015), an orifice plate is fundamentally a plate with a hole which may be of any shape, machined through it which is inserted into a pipe. As flow passes through the hole it produces a pressure difference across the hole (some of which is recovered). The pressure difference

is proportional to the square of the flowrate (mass or volume). According to Peter and Chinedu (2016), an orifice plate is a thin plate with a hole in the middle. It is usually placed in a pipe in which fluid flows. When the fluid reaches the orifice plate, with the hole in the middle, the fluid is forced to converge to go through the small hole; the point of maximum convergence actually occurs shortly downstream of the physical orifice, at the so-called vena contracta point. It should be noted that the orifice plate can as well be fitted to wall of a tank for fluid flow measurement. Accurate measurement of fluid flow is an essential task for many industries. If we see today's scenario, there are number of flow measuring devices available in market. Still orifice meter has broad application areas for flow measurement of fluids like chemical, oil, gas, etc. due to simple construction, low cost and easy operation (Sanghani et al, 2016). According to Yang (2015) in many industrial plants like oil and gas refineries, power generation plants or chemical plants, oil transport pipelines, restriction orifices such as the single-hole orifice, the multi-perforated orifice, and the cone type orifice are widely used to restrict the flow and measure the flow rate within many such systems.

Orifice meters are the most common instruments used for fluid flow measurement because of its ruggedness, simple mechanical construction and other known advantages. According to Abou El-Azem Aly et al. (2010), the advantages of using these orifice flow meters, are that they have simple geometry, no moving part, no lubrication or maintenance, low cost of manufacturing which does not increase significantly with the pipe size, easy installation or

replacement and the ability to select a proper calibration on the basis of the measurement of the geometry.

A lot of work has been done on the use of orifice meter for measuring discharge of fluid through vessels, notable among them are reported as follows: Sanghani et al, (2016) analysed fluid flow through orifice plate having different geometries using Computational Fluid Dynamics (CFD) technique. They used ANSYS CFX 15.0 software, to study various geometries of orifice in terms of pressure drop. Their simulation results revealed that under the same condition of diameter ratio and thickness, square-edged with 45° back-cut orifice plate has the highest-pressure loss and stream line approach orifice plate has minimum pressure loss. The researchers however remarked that their results can be used to select the most suitable geometry of orifice plate in practical applications. Spencer (2013) embarked on an unsteady experimental study with a view to identifying a transition region between partially full weir flow and fully developed orifice flow for a circular sharp-edged orifice. Three orifices of different diameter were tested by the researcher. He found that true orifice behaviour was achieved in the experiments and correspondingly, based on the head exponent, no evidence was obtained to support the existence of different flow behaviour within the transition. Hashiehbaf and Romano (2014) carried out an experimental study using Particle Image Velocimetry (PIV) on synthetic jets issuing from different non-circular nozzle shape at a peak Reynolds number equal to 10000. Rectangular, square, elliptical and triangular jets were employed and results of axial velocity decay rate, streamwise and crosswise

rms velocities as well as turbulence intensity ratio were compared to those of circular one to investigate the effect of asymmetry on turbulence properties of synthetic jets by the researchers. Their attention was focused in the near field of the jet ($0 < X/D < 7$) and they carried out measurements on two orthogonal planes to capture average three dimensional features of non-circular jets, where X is the axial distance from the nozzle exit and D is the nozzle diameter. Their results showed *vena contracta* and *axis switching* effects also for synthetic jets and mixing enhancement in comparison to continuous jets was also proved by the enhanced turbulence intensity in the near field. Self-similarity was found for $X/D > 5$ especially in triangular, square, minor side of rectangular and circular nozzles by the researchers.

In the same vein, Tardi et al (2015), characterized a commercial variable orificemeters (VOMs) intended for application in respiratory monitoring. Firstly, two nominally identical VOMs were calibrated within $\pm 10 \text{ L}\cdot\text{min}^{-1}$, to assess their metrological properties by the researchers. Furthermore, they performed experiments by humidifying air, to evaluate the influence of vapor condensation on sensor's performances. Their results revealed that the two VOMs' responses were linear and their response was comparable (sensitivity difference of 1.4%, RMSE of 1.50 Pa); their discrimination threshold was $< 0.5 \text{ L}\cdot\text{min}^{-1}$, and the settling time was about 66ms. The researchers remarked that the condensation within the VOM causes a negligible change in sensor sensitivity and a very slight deterioration of precision. Moreso, the good static and dynamic properties and the low influence of condensation on sensor's

response make this VOM suitable for applications in respiratory function monitoring. Shah et-al (2012) used Computational Fluid Dynamics (CFD) simulation to predict the orifice flow with better accuracy. They performed CFD simulations using OpenFOAM-1.6 solver and validated with the published experimental data of Nail (1991) and Morrison et al. (1993). The researchers proposed a new scheme to track *vena-contracta* with the help of CFD and with a suitable provision in the hardware of orifice meter. They remarked that the new scheme maintains the existing advantages of orifice meters and provides better accuracy and sensitivity. Prohaska (2008) examined the discharge coefficient as it pertained to flow through a circular orifice cut into a thin-walled vertical riser pipe. He therefore investigated several factors that may affect the value of the discharge coefficient. His findings revealed that the discharge coefficient decreased as the height above the floor was increased, up to a certain point. The discharge coefficient decreases as the orifice diameter to riser diameter ratio is increased.

Moreso, Abou El-Azm Aly et al. (2010) investigated the pressure drop through fractal-shaped orifices by measuring the pressure recovery at different stations downstream of the orifice. They compared pressure drop measured across fractal-shaped orifices with the pressure drop obtained after regular circular orifices with the same flow area. The researchers found that fractal shaped orifices had a remarkable effect on the pressure drop. They concluded that the pressure drop across fractal-shaped orifices was lower than that from regular circular orifices of the same flow area because the fractal orifices developed

additional smaller velocity scales when compared to circular orifice. The researchers remarked that it is possible to use the fractal-shaped orifices as flow meters as they can sense the low pressure drop across them accurately than the regular circular-shaped orifices. Washio et-al (1996) stated that an experimental study had been carried out on periodically changing hydraulic oil flows through an orifice. When inspected in detail, however, a net pressure loss across an orifice in a periodical flow was delayed against a change of the flow rate. The resulting relation between the pressure loss and the flow rate described a loop with a counter-clockwise hysteresis and a nonlinear twist along the steady-state one. Pressure recovery in a pulsating orifice flow varied with the flow rate almost along the steady-state relation, which was confirmed when the change was not fast.

Eghbalzadeh et-al (2016) used three artificial neural network models including feed forward back propagation, radial basis function, and Generalized Regression neural networks as well as a multiple non-linear regression method to predict the discharge coefficient for flow through both square and circular shapes of sharp-crested side orifices. The researchers modeled discharge coefficient as a function of five input non-dimensional variables resulted from five dimensional variables, which were the type of orifice shape, the diameter or width of the orifice, crest height, depth and velocity of approach flow. The results obtained in their study indicated that all of the neural network models could successfully predict the discharge coefficient with adequate accuracy.

Sharma and Fang, (2014) conducted experimental investigations into

the flow behaviour of low-pressure water jets emanating from orifices with non-circular geometries, including rectangular, square, and triangular shapes and draws a comparison with the flow behavior of circular jets. Their investigations revealed that the non-circular geometric jets demonstrated enhanced instability as compared to the circular jets. Watson et al (2003) investigated into the effect of both the number of orifices and the geometry of these orifices on the fluid structures exiting from a synthetic jet actuator. Their results indicated that the use of two small orifices can perhaps produce two coherent vortex rings with a total circulation greater than that found in the ring produced by a large, single orifice of equivalent area. Moreso, their results showed that a rectangular orifice of a given exit plane area is more likely to produce a turbulent ring than the equivalent circular orifice due to a 'smoothing' process which endeavours to create an axisymmetric ring from a non-axisymmetric slug of fluid. Mi et al (2007) carried out an experimental investigation of the near-field mixing characteristics of a turbulent jet issuing from a notched – rectangular orifice plate. The researchers used Planar particle image velocimetry(PIV) to measure the velocity field with exit Reynold = 72,000. They made comparison of the results for the jet and its circular counterpart obtained under the identical conditions and found that notched jet has an overall superior mixing capability over the circular jet.

Dhumal,et al(2017) remarked that compare to single-hole orifices (SOs), multi-hole orifices (MOs) have smaller orifice sizes and various patterns of orifice distribution. The geometric description of MOs is more complex, increasing the difficulty of MO

structural design. They found the discharge variations of single hole, 4-hole, 5 holes and 7-hole Orifice by designing and experimenting on them and concluded that 5-hole orifice gave best results as expected. Jan and Nguyen (2010) studied discharge coefficients for water flow through a vertical, circular orifice at the bottom of a conical hopper experimentally. Experiments were carried out under different orifice diameters and water heads in a conical hopper which consisted of a cylindrical hopper of inside diameter of 48 cm and a bottom cone of side slope of 45° . The dependence of the discharge coefficient on the orifice diameter and water head was analyzed, and then an empirical relation was developed by using a dimensional analysis and a regression analysis by the researchers. Their results showed that the larger orifice diameter or higher water head had a smaller discharge coefficient and the orifice diameter played more significant influence on the discharge coefficient than the water head did. The discharge coefficient of water flow through a bottom orifice was larger than that through a sidewall orifice under the similar conditions of the water head, orifice diameter, and hopper size. Ntamba (2011) conducted wide-ranging experimental studies of the flow in orifice plates and derived a correlation which can predict pressure loss coefficient from laminar to turbulent flow regime. The researcher made a direct comparison between circular orifice and triangular orifices plates tested. His findings revealed that the differences in pressure loss and discharge coefficients between circular and triangular orifice plate with sharp apex were -6% and 2.1% respectively and -0.5% and 1.5% respectively for the triangular orifice plate with round apex. Adam et-al (2017)

embarked on a study which focused on the influence on the contraction ratio β and the orifice shape on the head losses and the influence zone produced by the orifice in a surge tank, during the refurbishment of a high head power plant. two types of shape orifice were tested, i.e. sharp-edged and rounded orifices, by allowing the tests to produce the same amount of head losses in the sharp flow approach by the researchers. Their findings revealed that for the contracted flow approach, the rounded orifices produced less head losses than the sharp-edged orifices. Furthermore, the head losses in the sharp flow approach (AB) agreed well with existing formula. For the gradual flow approach (BA), head losses were 40% lower for the sharp orifices and 65% lower for the rounded orifices.

When a jet of fluid exits from an orifice, it gets contracted the narrowest section of the jet or stream of the fluid at the downstream side of the orifice is known as the vena-contracta. The ratio of the area of the jet or stream at vena-contracta to the area of the orifice is known as coefficient of contraction (C_c). The ratio of actual velocity of the jet or stream at vena-contracta to the theoretical or ideal velocity is known as coefficient of velocity (C_v). The ratio of actual discharge to theoretical or ideal discharge is known as coefficient of discharge (C_d). The orifice meter measures the theoretical or ideal discharge of fluid by virtue of differential pressure across the orifice in the orifice plate fitted to the pipe or the orifice in the tank. The discharge of fluid is a function of the velocity of flow as well as the area of the orifice. The values of orifice coefficients are needed to calculate the actual discharge through the pipe or tank from the measured pressure difference or

head across the orifice in the flow path. Orifice coefficients are empirical because of difficulty in accurately predicting the effects of geometrical complicity and flow separation from the wall (Shah et al,2012). The purpose of this work was to evaluate the orifice coefficients viz-a-viz coefficient of velocity, coefficient of contraction and coefficient of discharge of circular and rectangular orifices. This was done with a view to finding which among the circular and square orifices has the highest orifice coefficients and flow rate or discharge.

MATERIALS AND METHOD

Materials

The materials used in the research work comprised of

- 1, The Orifice test rig developed by Bobai (2014) whose schematic diagram is shown in Figure 1 comprises of water tank provided with
 - a. Orifice slot where orifice of different shapes is fitted.
 - b. Scale (Horizontal and vertical scale)
 - c. Measuring tank

The C_v was found by using the relation stated by (Rajput,2008) as

$$C_v = \frac{x}{\sqrt{4yH}} \tag{1}$$

Where H is the head of water.

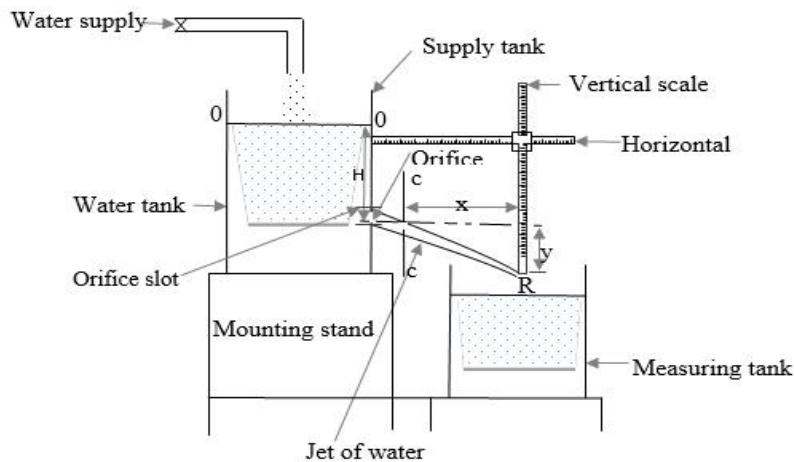


Figure 1. The Schematic diagram of the orifice test rig developed by Bobai (2014).

- d. Mounting stand
2. A circular orifice having diameter of 0.0138m and area of 0.00015m²
- 3 A rectangular orifice having length of 0.015m and width of 0.01m and area of 0.00015m²
5. Stop watch

Experimental Method

A circular orifice was fitted to orifice slot in the water tank (fluid supply tank) and the experimentation was performed using the method stated by (Rajput, 2008). So, the water tank was filled with water and allowed to flow through the orifice. A 0.9m head of water in the water tank was maintained by regulating the supply of water. The vertical scale was slide on the horizontal scale through a reasonable distance to touch the centre line of the jet of water denoted by point R. The coordinates of the point, R that is x and y in the jet shown in figure 1 were measured. The time t, taken for rise of water through a certain height in the measuring tank was noted.

Then actual discharge, Q through the orifice was calculated by using the relation stated by Rajput (2008) as

$$Q = \frac{\text{Area of measuring tank} \times \text{rise in water level in the measuring tank}}{\text{time}(t)} = \frac{\pi D^2 l_o}{4t} \tag{1}$$

Where D is the diameter of the measuring tank which is cylindrical in shape and lo is the rise in water level in the measuring tank.

$$Q_{th} = a \times \sqrt{2gH} \tag{2}$$

Hence
$$C_d = \frac{Q}{Q_{th}} = \frac{Q}{a \times \sqrt{2gH}} \tag{2}$$

Where a is the area of the orifice. For circular orifice, $a = \frac{\pi d^2}{4}$ (3)

Where d is the diameter of the circular orifice.

For rectangular orifice, a = Length x Width (4)

The coefficient of contraction Cc was found from the following relation as also stated by Rajput (2008), as

$$C_d = C_c \times C_v$$

$$C_c = \frac{C_d}{C_v} \tag{5}$$

After the use of circular orifice, it was dismantled from the orifice slot in the test rig and a rectangular orifice was fitted and the same procedure was repeated.

The experiments using circular orifice and rectangular orifice were each conducted five times. The average values of the coefficients of discharge, coefficients of velocity, and coefficients of contraction, theoretical and actual discharges through

Theoretical discharge, Q_{th} was calculated using the relation stated by Rajput (2008) as

the orifices were determined for the circular and rectangular orifice.

3.0 RESULTS AND DISCUSSION

The average orifice parameters viz-a- viz coefficient of discharge, coefficient of velocity, coefficient of contraction, theoretical and actual discharges are shown in Table 1.

Table 1: Average orifice coefficients and discharges through circular and rectangular orifices.

Orifice Parameters	Circular Orifice	Rectangular Orifice
Coefficient of discharge(Cd)	0.62	0.66

Coefficient of velocity(Cv)	0.94	0.96
Coefficient of contraction(Cc)	0.66	0.69
Theoretical discharge	5.52 x 10 ⁻⁴ m ³ /s	5.53 x 10 ⁻⁴ m ³ /s
Actual discharge	3.42 x 10 ⁻⁴ m ³ /s	3.65 x 10 ⁻⁴ m ³ /s

It can be seen from Table 1 that circular orifice has average coefficient of discharge, coefficient of velocity, coefficient of contraction, theoretical and actual discharges as 0.62, 0.94, 0.66, $5.52 \times 10^{-4} \text{m}^3/\text{s}$ and $3.42 \times 10^{-4} \text{m}^3/\text{s}$ respectively and the rectangular orifice has average coefficient of discharge, coefficient of velocity, coefficient of contraction, theoretical and actual discharges as 0.66, 0.96, 0.69, $5.53 \times 10^{-4} \text{m}^3/\text{s}$ and $3.65 \times 10^{-4} \text{m}^3/\text{s}$ respectively. It is very evident in Table 1 The Cd of rectangular orifice is higher than that of circular orifice and this is in line with the findings of Novák and Koza(2013) and Qing-fei et al(2014) that discharge coefficients of narrow rectangular orifice were much higher than discharge coefficients for comparable circular orifices. Moreso in line with the findings of Navaneetha et al, (2017) who found Cd for 1.32cm^2 circular orifice to be 0.602 and for 0.78cm^2 rectangular orifice to be 0.842. The Cv and Cc of rectangular orifice are higher than those of circular orifice as seen from Table 1. The variation in Cc is in line with the

finding of CODECOGS (2018) that the value of coefficient of contraction varies slightly with the shape of the orifice. It suffices to infer from Table 1 that rectangular orifice has higher orifice coefficients as well as discharges than circular orifice.

CONCLUSION

Knowledge about the orifice coefficients and discharges through circular and rectangular orifice is very important, when selection for use is based on the requirement of low or high discharges as well as high or low orifice coefficients. In this research work rectangular orifice has been found to have higher orifice coefficients as well as discharges than circular orifice. So where high flow rates are required, a rectangular orifice should be considered for use and when low flow rates are required, circular orifice should be considered for use. However, the selection should be based on the designed flow rate requirement for the system.

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