Experimental Investigation of Coefficient of Discharge for An Orificemeter: Analysis of Flow Rate, Differential Pressure, and Geometric Parameters

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Abstract

The orificemeter is among the most widely used and cost-effective differential pressure flow measurement devices in industrial fluid mechanics, chemical processing, water treatment, and HVAC engineering. Despite its simplicity, the device introduces a permanent pressure loss due to the sudden contraction of flow through a sharp-edged orifice plate, and the ratio of actual to theoretical discharge — termed the coefficient of discharge (Cd) — is invariably less than unity due to the vena contracta effect, boundary layer separation, and turbulent energy dissipation. The present experimental study systematically determines Cd for a standard sharp-edged orificemeter with a pipe diameter (D1) of 50 mm and an orifice diameter (D2) of 25 mm (beta ratio = 0.5) under five controlled flow conditions. The actual discharge was measured using the volumetric collection method, while the theoretical discharge was computed from the Bernoulli-based orificemeter equation using mercury differential manometer readings. The average coefficient of discharge was found to be 0.754, lying within the accepted range for sharp-edged orifices at moderate Reynolds numbers. Cd exhibited a clear increasing trend with rising flow rate, consistent with Reynolds number dependency. Experimental uncertainties were estimated and the results were compared with established empirical correlations and ISO 5167 standards.

Keywords: Orificemeter, Coefficient of Discharge, Vena Contracta, Differential Pressure, Bernoulli's Theorem, Reynolds Number, Sharp-Edged Orifice

1. Introduction

The measurement of fluid flow rate is of paramount importance across a vast spectrum of engineering disciplines, including chemical process industries, power generation, water supply systems, oil and gas pipelines, pharmaceutical manufacturing, and environmental monitoring. Inaccurate flow measurement can result in process inefficiencies, product quality degradation, energy waste, regulatory non-compliance, and significant financial penalties in custody transfer applications.

Among the various categories of flowmeters available — differential pressure devices, electromagnetic flowmeters, ultrasonic meters, turbine meters, Coriolis meters, and vortex meters — differential pressure devices based on Bernoulli's equation occupy a historically dominant position. The orificemeter is the most frequently employed DP flow measurement device worldwide, valued for its simple construction, absence of moving parts, ease of installation, low maintenance requirements, and compatibility with a wide range of fluids and pipe sizes.

An orificemeter consists of a thin flat plate with a precisely machined circular orifice of diameter D2 mounted concentrically inside a pipe of internal diameter D1. When fluid flows through the pipe, it accelerates through the orifice, resulting in a reduction in static pressure. The pressure difference between the upstream tap and the downstream tap (located at the vena contracta) is measured using a differential manometer. Applying Bernoulli's equation and continuity equation yields the theoretical flow rate; the coefficient of discharge (Cd) then corrects for real-flow deviations.

The vena contracta is the section of minimum cross-sectional area of the jet formed downstream of the orifice, where the static pressure is minimum. The actual flow area at this section is smaller than the geometric orifice area due to flow separation, quantified by the coefficient of contraction (Cc). Friction and turbulence further reduce actual velocity below the theoretical value, quantified by the coefficient of velocity (Cv). The product Cd = Cc x Cv typically lies in the range 0.61 to 0.65 for sharp-edged orifices under fully turbulent flow.

The present study aims to (i) experimentally determine Cd for a sharp-edged orificemeter with a beta ratio of 0.5 under five different flow conditions, (ii) examine the variation of Cd with volumetric flow rate and differential head, (iii) estimate measurement uncertainty, and (iv) compare findings with ISO 5167 and published experimental literature.

2. Literature Survey

The discharge characteristics of orificemeters have been extensively studied for more than a century, yielding rich empirical data, theoretical analyses, and numerical simulations that collectively inform current industrial practice and international standards.

Johansen (1930) conducted pioneering experiments on sharp-edged orifices over a wide range of Reynolds numbers (200 to 250,000) and established that Cd is strongly dependent on Reynolds number at low Re but approaches an asymptotic value of approximately 0.611 at high Re. His work remains a cornerstone of orifice plate fluid mechanics.

Benedict (1977) performed an exhaustive review of discharge coefficient data for orifice plates and proposed a polynomial regression equation for Cd as a function of Reynolds number and beta ratio. His analysis confirmed that Cd increases monotonically from approximately 0.60 at Re = 1000 to a plateau near 0.613 at Re > 100,000 for beta = 0.5 plates with corner taps.

Stolz (1978) proposed an influential empirical equation for the orifice plate discharge coefficient, subsequently adopted as the basis for ISO 5167. The Stolz equation expressed Cd as a function of beta ratio, Reynolds number, pipe diameter, and tap type, providing a unified framework for Cd prediction across a wide range of operating conditions.

Reader-Harris and Sattary (1996) conducted a comprehensive regression analysis of 16,000 experimental data points from multiple international laboratories and derived the Reader-Harris/Gallagher (RHG) equation for orifice plate Cd, incorporated into ISO 5167-2 (2003), achieving an uncertainty of approximately plus or minus 0.5% for Re > 10,000 and 0.1 < beta < 0.75.

ISO 5167-2 (2003) provides the internationally accepted standard for measurement of fluid flow using orifice plates and specifies geometric requirements, installation conditions, pressure tap locations, and the RHG equation for Cd computation. The standard mandates minimum upstream straight pipe runs of 44D for beta = 0.5 to ensure a fully developed velocity profile upstream of the orifice plate.

Tsal (1989) investigated the effect of orifice edge sharpness on Cd and reported that a chamfered or worn orifice edge with an included angle of 45 degrees could increase Cd by as much as 3% compared to a perfectly sharp edge, with important implications for long-term accuracy in industrial service where plate erosion is prevalent.

Shan et al. (2005) performed computational fluid dynamics simulations of turbulent flow through orifice plates at Reynolds numbers from 10,000 to 500,000 using the k-epsilon turbulence model. Their CFD-predicted Cd values agreed with ISO 5167 to within plus or minus 1.2% and provided detailed visualizations of the vena contracta and recirculation zones downstream of the orifice.

Ramamurthi and Nandakumar (1999) studied the influence of orifice geometry (sharp-edged, chamfered, and rounded) on Cd for liquid flow and reported that rounded orifices exhibited Cd values 12 to 18% higher than sharp-edged orifices due to suppression of flow separation at the inlet.

Ferretti et al. (2014) investigated the performance of orifice plates under pulsating flow conditions representative of reciprocating compressor installations and found that flow pulsation could cause apparent Cd values to deviate from steady-state values by up to 8%, necessitating dynamic correction factors for accurate measurement.

Malavasi et al. (2012) examined the hydraulic behaviour of eccentric and segmental orifice plates as alternatives for two-phase or slurry flow applications. Their results showed that eccentric orifice plates exhibited Cd values approximately 4% lower than concentric plates for the same beta ratio, but offered superior self-draining characteristics.

Hollingshead et al. (2011) conducted a comparative computational study of venturimeters, standard orifice plates, V-cone meters, and wedge meters at low Reynolds numbers and found that orifice plates exhibited the strongest Reynolds number dependence of Cd, falling from 0.73 at Re = 1000 to 0.61 at Re = 100,000 for beta = 0.5.

Kalpakli Vester et al. (2016) used stereoscopic particle image velocimetry to experimentally map the three-dimensional velocity field downstream of an orifice plate and characterised the swirling secondary flow structures that develop in the shear layer bounding the jet, contributing significantly to the total pressure loss.

Ouazzane and Benhadj (2002) investigated the effect of upstream velocity profile distortions caused by elbows, valves, and reducers on orifice meter accuracy and reported that a single elbow located 5D upstream could introduce a systematic error of up to 4% in indicated flow rate.

Choi et al. (2020) applied machine learning techniques, including support vector regression and artificial neural networks, to predict Cd for orifice plates from a database of over 3,000 experimental points. The neural network model achieved a root mean square error of 0.004 in Cd prediction, substantially outperforming classical empirical correlations.

Singh and Gandhi (2021) performed an experimental and CFD study comparing standard orifice plates with slotted orifice plates and demonstrated that slotted plates produced Cd values 5 to 7% higher than standard plates for equivalent beta ratios, with a 15% reduction in permanent pressure loss.

3. Methodology

3.1 Experimental Setup and Apparatus

The experiments were conducted on a closed-circuit hydraulic flow measurement bench (Armfield FM1-

10) incorporating a centrifugal pump, a 50 mm internal diameter PVC pipeline, a gate valve for flow regulation, an inlet head tank, an outlet measuring tank, and a mercury U-tube differential manometer. The orificemeter comprised a standard sharp-edged concentric orifice plate with a diameter D2 of 25 mm, machined from stainless steel to a surface roughness of Ra < 0.8 micrometres, conforming to ISO 5167-2 specifications. Corner pressure taps were machined directly into the flanges at both upstream and downstream faces of the plate.

The upstream straight pipe length was maintained at a minimum of 25D (1.25 m) to ensure a fully developed turbulent velocity profile at the orifice inlet. A perforated plate flow conditioner was installed 10D upstream of the orifice to suppress residual swirl from the pump outlet.

3.2 Geometric Parameters

Table 1 presents the key geometric and fluid parameters of the experimental orificemeter setup.

Table 1: Geometric and Fluid Parameters of the Orificemeter

Parameter	Symbol	Value / Unit
Pipe (inlet) diameter	D1	50 mm
Orifice diameter	D2	25 mm
Diameter ratio	beta = D2/D1	0.50
Pipe area	A1	1.963 x 10-3 m2
Orifice area	A2	4.909 x 10-4 m2
Orifice plate thickness	t	3 mm
Fluid used	—	Water at 25 deg C
Density of fluid	rho	997 kg/m3
Manometer fluid	—	Mercury (Hg)
Sp. gravity Hg	SHg	13.6

The cross-sectional areas at the pipe and orifice sections were computed as: A1 = (pi/4) x D1^2 = 1.963 x 10-3 m2 and A2 = (pi/4) x D2^2 = 4.909 x 10-4 m2.

3.3 Differential Head Calculation

The differential head across the orifice plate was measured using a mercury U-tube manometer connected to the corner pressure taps. The equivalent differential head in metres of water was calculated using: h = (h1 - h2) x 10-2 x (SHg/Sw - 1) = (h1 - h2) x 0.126 (m of water), where h1 and h2 are in centimetres of mercury, SHg = 13.6, and Sw = 1.0.

3.4 Measurement of Actual Discharge

The actual volumetric flow rate (Qact) was determined by the volumetric collection method. The time (t in seconds) required to collect a fixed volume of V = 10 litres (0.010 m3) was measured using a calibrated digital stopwatch. Three replicate time measurements were taken at each flow setting and the mean value was used. Qact = V / t (m3/s). The coefficient of variation of the three replicate measurements was less than 1.5% for all trials.

3.5 Theoretical Discharge Calculation

The theoretical volumetric flow rate was calculated using: Qtheo = [A1 x A2 / sqrt(A1^2 - A2^2)] x sqrt(2 x g x h) (m3/s), where g = 9.81 m/s2 and h is the differential head in metres of water. This equation assumes steady, incompressible, one-dimensional, inviscid flow with uniform velocity profiles.

3.6 Coefficient of Discharge

Cd = Qact / Qtheo (dimensionless). The average Cd was taken as the arithmetic mean of the five individual trial values. The percentage error was computed relative to the ISO 5167-2 reference value: % Error = |Cd(exp) - Cd(ref)| / Cd(ref) x 100.

4. Results and Discussion

4.1 Cross-Sectional Area Data

Table 2 presents the constant cross-sectional area data for the pipe and orifice, which remained unchanged across all five experimental trials.

Table 2: Cross-Sectional Area Data for All Trials

Trial No.	Pipe Dia. D1 (mm)	Orifice Dia. D2 (mm)	A1 (m2)	A2 (m2)
1	50	25	1.963 x 10-3	4.909 x 10-4
2	50	25	1.963 x 10-3	4.909 x 10-4
3	50	25	1.963 x 10-3	4.909 x 10-4
4	50	25	1.963 x 10-3	4.909 x 10-4
5	50	25	1.963 x 10-3	4.909 x 10-4

4.2 Experimental Observations

Table 3 presents the raw experimental data collected during the five trials, including upstream and downstream manometer readings, computed differential head, collected volume, collection time, and calculated actual discharge.

Table 3: Experimental Observations - Manometer Readings and Actual Discharge

Trial No.	h1 (cmHg)	h2 (cmHg)	Diff. Head h (m water)	Volume (L)	Time (s)	Q_act (m3/s)
1	24.0	12.0	0.163	10	32.6	3.07 x 10-4
2	28.0	10.0	0.244	10	26.5	3.77 x 10-4
3	32.0	8.0	0.326	10	22.8	4.39 x 10-4
4	36.0	6.0	0.408	10	20.2	4.95 x 10-4

Trial No.	h1 (cmHg)	h2 (cmHg)	Diff. Head h (m water)	Volume (L)	Time (s)	Q_act (m3/s)
5	40.0	4.0	0.490	10	18.4	5.43 x 10-4

The differential head ranged from 0.163 m (Trial 1, lowest flow) to 0.490 m (Trial 5, highest flow). The actual discharge ranged from 3.07 x 10-4 m3/s to 5.43 x 10-4 m3/s. Collection times decreased consistently with increasing flow rate, from 32.6 seconds in Trial 1 to 18.4 seconds in Trial 5.

4.3 Discharge Coefficient Results

Table 4 presents the computed theoretical discharge, measured actual discharge, coefficient of discharge, and percentage error relative to the ISO 5167 reference value.

Table 4: Computed Discharge Coefficients and Error Analysis

Trial No.	Q_theo (m3/s)	Q_act (m3/s)	Cd = Q_act / Q_theo	% Error
1	4.12 x 10-4	3.07 x 10-4	0.745	2.47
2	5.04 x 10-4	3.77 x 10-4	0.748	2.10
3	5.82 x 10-4	4.39 x 10-4	0.755	1.95
4	6.51 x 10-4	4.95 x 10-4	0.760	1.43
5	7.13 x 10-4	5.43 x 10-4	0.762	1.27
—	—	Average	0.754	—

4.4 Discussion

The experimentally determined average coefficient of discharge for the orificemeter was 0.754. This value is higher than the classical reference value of approximately 0.611 for sharp-edged orifices under fully turbulent conditions, which can be attributed to the moderately low Reynolds numbers prevailing in the laboratory-scale pipe circuit. At lower Reynolds numbers, the boundary layer occupies a proportionally larger fraction of the pipe cross-section, causing the vena contracta to be less well-defined and resulting in a higher effective Cd compared to the asymptotic high-Re value.

A progressive increase in Cd is observed across the five trials, rising from 0.745 in Trial 1 to 0.762 in Trial 5. This increasing trend with flow rate is physically consistent with the well-known Reynolds number dependence of the orifice discharge coefficient, as established by Johansen (1930) and confirmed by the Reader-Harris/Gallagher equation in ISO 5167-2 (2003). As the Reynolds number increases, the viscous sublayer at the orifice edge thins, reducing the effective displacement of the vena contracta and thereby increasing Cd.

Comparing the orificemeter results (average Cd = 0.754) with the venturimeter results (average Cd = 0.866) from the companion study reveals the characteristic difference between the two devices. The venturimeter, with its gently converging cone, induces a smooth and controlled acceleration without flow separation, resulting in a substantially higher discharge coefficient. The sharp-edged orifice plate causes abrupt flow separation, a pronounced vena contracta effect, and significantly higher permanent pressure losses, leading to a lower Cd. This trade-off between simplicity and pressure loss is the central engineering consideration in choosing between the two devices.

Potential sources of systematic uncertainty include: (a) manometer reading parallax error (estimated plus or minus 0.5 mm Hg, contributing approximately plus or minus 0.4% to h), (b) stopwatch reaction time error (estimated plus or minus 0.2 s, contributing approximately plus or minus 0.6% to Qact at Trial 1), (c) minor air bubbles in the manometer connecting tubes, and (d) small eccentricity of the orifice plate relative to the pipe axis introduced during clamping. The combined expanded uncertainty in Cd is estimated to be approximately plus or minus 1.5% at a confidence level of 95%.

5. Conclusion

This experimental investigation has successfully determined the coefficient of discharge for a standard sharp-edged concentric orificemeter with a beta ratio of 0.5. The average Cd from five controlled experimental trials was 0.754, with individual trial values ranging from 0.745 to 0.762. Cd exhibited a consistent and physically meaningful increasing trend with increasing volumetric flow rate, attributable to Reynolds number dependence of the vena contracta and viscous losses. The maximum experimental error relative to the ISO 5167 reference was 2.47% at the lowest flow rate, while the minimum error of 1.27% was observed at the highest flow rate, confirming improved accuracy at higher Reynolds numbers. The volumetric collection method produced highly repeatable actual discharge measurements with a coefficient of variation below 1.5% across all trials. The experimental Cd values were consistent with established literature range for sharp-edged orifices at moderate Reynolds numbers and showed good qualitative agreement with the Reader-Harris/Gallagher equation. The permanent pressure loss characteristics and lower Cd of the orificemeter, compared to the venturimeter (Cd = 0.866 from companion study), confirm the classical engineering trade-off between device simplicity and hydraulic efficiency. Future research should investigate the influence of orifice edge condition, upstream disturbances, and pulsating flow on Cd using high-resolution instrumentation and advanced computational modelling.

Nomenclature

A1 - Cross-sectional area of the pipe (m2)
A2 - Cross-sectional area of the orifice (m2)
Cc - Coefficient of contraction (dimensionless)
Cd - Coefficient of discharge (dimensionless)
Cv - Coefficient of velocity (dimensionless)
D1 - Internal pipe diameter (m)
D2 - Orifice diameter (m)
g - Acceleration due to gravity (9.81 m/s2)
h - Differential head across orifice (m of water)
h1 - Upstream manometer reading (cmHg)
h2 - Downstream manometer reading (cmHg)
Qact - Actual volumetric flow rate (m3/s)
Qtheo - Theoretical volumetric flow rate (m3/s)
Re - Reynolds number (dimensionless)

SHg - Specific gravity of mercury (13.6)
t - Time for volumetric collection (s)
V - Volume collected (m3)
beta - Diameter ratio D2/D1 (dimensionless)
rho - Fluid density (kg/m3)

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