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Research Paper

The Effect of the Design Parameters on Mass Flow Measurement and Control in an Orifice Plate Flow Rig

Ekong, Godwin I.

Department of Mechanical Engineering Akwa Ibom State University (AKSU) and A former Researcher, Rolls-Royce supported University Research Centre for Aero-Thermal Systems and Thermo-Fluid Mechanics Research Centre, University of Sussex, Brighton, BN1 9QT, UK,

ABSTRACT: *This paper documents the effect of the design parameters on mass flow measurement and control in an orifice plate flow rig. An orifice is an opening in a vessel, through which the liquid flows out as long as the level of on the upstream side is above the orifice. Therefore, an orifice is used in the measurement of discharge, hence the measurement and control of flow. An orifice plate is a device used for measuring mass flow rate, for reducing the pressure or for restricting flow, thereby controlling the flow. The orifice flow rig of interest in the present study has a pipe diameter of 50 mm, orifice diameter 25 mm, diameter ratios β is 0.5 and the fluid used in this investigation is a compressed air. Several analyses concerning the study of orifice flow have been done with orifice having diameter ratios β in the range of 0.1 to 0.8 and aspect ratio of (l/d) less than 1 in accordance with ISO 5167 standard. This procedure uses an Excel spreadsheet program to provide an automated analysis and enable alternative geometric configurations to be evaluated. The result indicates that an increase in the upstream pressure brings about an increase in the differential pressure, thereby increasing the mass flow rate. Furthermore, an increase in the orifice diameter will increase the orifice area, diameter ratio, hence, an increased in the mass flow rate. This study was carried to assist in the calibration of orifice plates for mass flow measurement and control.*

KEYWORDS: *Mass flow, Measurement, Control, Orifice, Diameter ratios, Pressure.*

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I. INTRODUCTION

Mass flow measurement and control is an important aspect in industries like aerospace, oil, natural gas, chemicals, processing, steam and the power plant industry. There has been a continuous attempt to accurately measure and control the mass flow rate of fluid because of its strategic importance in these industries. Therefore accuracy and repeatability of flow measuring devices are of great importance to these industries since accuracy of a flow measurement indicate whether the measured quantity is the true value, while repeatability compares the various value of measurement produces by the same method, using the same measuring device, at the same place at a given time. A typical flow measurement device is the orifice plate. In addition to measurement, an orifice plate can be used in a pipe to restrict the flow rate, thereby, providing a means to control the amount of fluid used in, say, cooling of a critical component. These industrial needs, informed the creation of a test cell installed in Thermo Fluid Mechanics Research Centre (T.F.M.R.C) at the University of Sussex, capable of calibrating orifice plates for mass flow measurement and control. The flow rate is determined by measuring the pressure drop across the orifice plate.

Mass flow rate is the measure of mass of a fluid passing a point in the system per unit time. It is a function of the density of the fluid, its velocity and the cross-sectional area of flow. It is also a function of density and volume flow rate.

$$\dot{m} = \rho . V . A \qquad 1.1$$

$$\dot{m} = \rho . Q \qquad 1.2$$

where:
$\dot{m}$ = mass flow rate
ρ = density

V = velocity
A = area
Q = volume flow rate

In aerospace and other industrial applications, the mass flow of compressed air through conduits can be measured and controlled using orifice plates of various sizes and shapes depending upon where it is used for the efficient performance of the system. The study addresses the problem relating flow rate to pressure drop across chamfer-edged orifice over a wide range of orifice geometries and operating conditions.

The orifice of interest for the present study has a pipe diameter of 50 mm, orifice diameter 25 mm, diameter ratios β is 0.5 and the fluid used in this investigation is compressed air. Several analyses concerning the study of orifice flow have been done with orifice having diameter ratios β in the range of 0.1 to 0.8 and aspect ratio of (l/d) less than 1 in accordance with ISO 5167 standard.

In the aerospace industry, mass flow measurement is desirable since air is continuously needed in a jet engine for cooling of the turbine, cooling discs and pressurising bearing chambers [1]. During the design stage of a gas turbine engine, there is a need to ensure that certain parts of the engine do not operate at excessive temperature to such an extent that the safe operation of the part concerned is in danger therefore affecting the overall performance of the engine.

Flow is normally controlled by adjusting such devices to a certain restricted flow, then the flow is measured and the devices are adjusted again and the measurement taken and this procedure is repeated until the desired flow measurement is obtained. The above process of adjusting and readjusting the devices for flow measurement makes the process complex, therefore giving rise to a test facility that incorporate both flow control devices and flow measurement devices that is capable of controlling the flow and at the same time measure the flow under a single operation. This test facility which is in the TMFRC University of Sussex incorporates devices like orifice plates, Rotameter, Venturi, valves and a laminar flow element.

In the test facility, pipes of varying cross-sectional area were used. But the constant flow rate in the varying cross-sectional area of the duct gives rise to the fact that the fluid velocity and pressure must be compensated accordingly on the basis of conservation of mass and energy. In view of the above, the following principles and more are employed in the analysis of this project.

Continuity equation: $\dot{m} = \rho.A.V$ 1.3

Bernoulli's equation:

$$\frac{\upsilon^2 \rho}{2} + \rho g h + p = cons\tan t \quad 1.4$$

Hagen- Poiseuille equation:

$$Q = \frac{\pi \Pr^4}{8\eta l} \quad 1.5$$

Discharge coefficient (C_d): $C_d = \dfrac{q_m \sqrt{1-\beta^4}}{\frac{\pi}{4} d^2 \sqrt{2\Delta p e_1}}$ 1.6

The objectives of this study are to use the designed test facility for measuring and controlling mass flow using orifice plates, determine the mass flow rate for a given pressure drop for different orifice plate geometries, analyse of the effect of different design parameters on mass flow rate of the fluid in the orifice flow rig.

II. REVIEW OF ORIFICE PLATES FOR MASS FLOW MEASUREMENT

Mass flow measurement is very essential in industrial process because it provides vital information about the flow and may lead to better efficiency of the process thereby reducing waste and cost of the operation. An orifice plate is a device which measures the rate of fluid flow. It is a thin plate in which a circular aperture has been machined. Orifice plates are the most common method of differential flow measurement. An orifice plate produces differential pressures, which depend on both fluid characteristics and the plate's geometry; a typical orifice plate is shown as Figure 2.1.

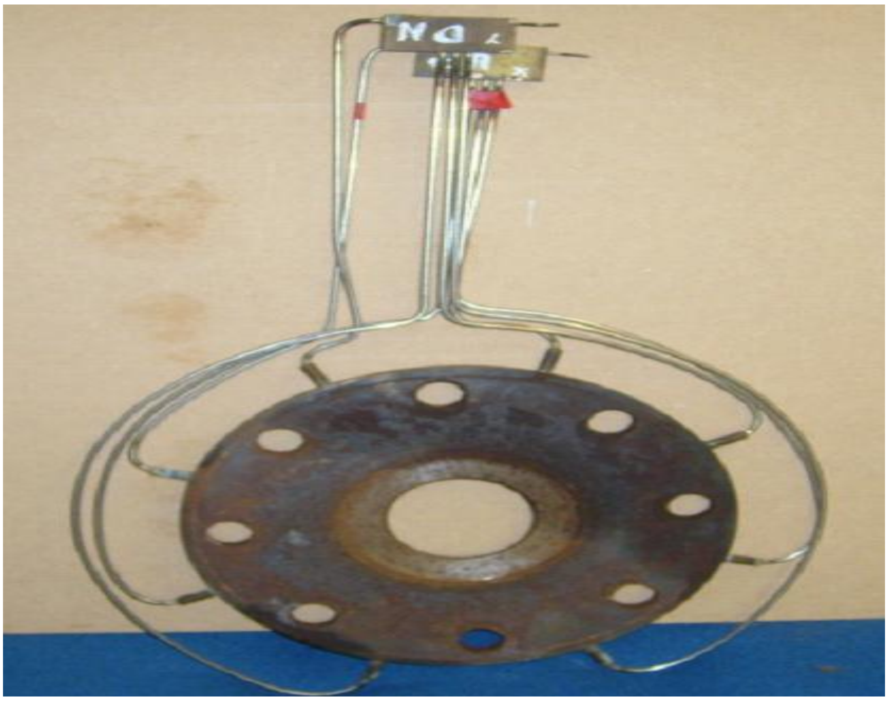


Figure 2.1: Photograph of an Orifice plate (Courtesy of T.M.F.R.C)

Orifice plate design and installation requirements are contained in national and international standards organization, documentation for example ISO 5167 and BS 1042. A standard orifice plate is described as a thin plate with a sharp square edge because the thickness of the plate is small compared with the diameter of the measuring section [2]. It is therefore a thin plate having a hole in the middle. An orifice plate usually placed in a pipe in which fluid flows for the purpose of measuring the flow rate, slowing down the flow or accelerating the flow. Figure 2.2 shows the geometry of an orifice plate with the defined parameters. The orifice plate used in this research was designed and manufactured to meet the requirement of British standard BS 1042 and International standard organization ISO 5167.

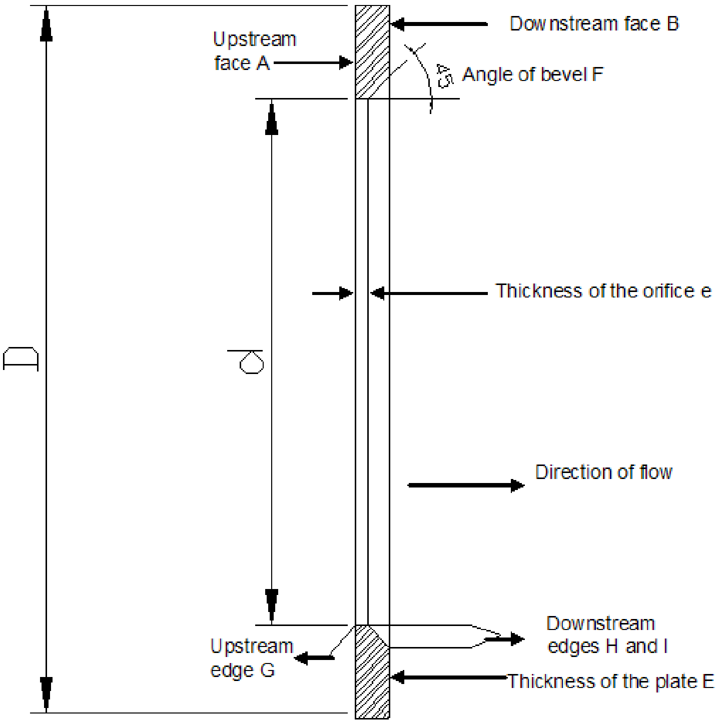


Figure 2.2: Standard orifice plate

D = Upstream pipe diameter
d = Orifice diameter
e = Orifice thickness
E = Plate thickness
F= Angle of bevel
G = Upstream edge
H and I = Downstream edges
d/D = Diameter ratio

For accurate mass flow measurement, the orifice plate is provided with a series of small dimension ports, such as holes or slots, in which pressure sensing devices can be connected to sense pressure at different points upstream and downstream. The different pressure measured at various points upstream and downstream gives the differential pressure that is used to determine the mass flow rate of the flow. Mass flow measurement using orifice plates has been studied in the past for several applications. The literature review here presents some of the previous work done on mass flow measurement and mass flow control using orifice plates; this includes Differential pressure, flow rate measurement device [3], flow measurement and Control [4], Method and apparatus for determining the mass flow of fluid [5], Orifice measuring device [6], Fluid control device [7], Flow and pressure drop of highly viscous fluid in small aperture orifices [8], Method and System for determining flow rates and/ or fluid density in single and Multiple-phase flows utilizing discharge coefficient relationships [9], Incompressible flow through orifice plates [10], Device and method for measuring fluid flow in a conduit having a gradual bend [11], Effectiveness analysis of slotted orifice plate multiphase flow meter coupled with Venturi meter and visualization study [12], Influence of the orifice shape on mass flow measurements of air–water mixture [13], Mass flow rate measurements in gas-liquid flows by means of a Venturi or orifice plate coupled to a void fraction sensor [14].

III. METHODOLOGY

The standard convention for relating orifice flow rate to differential pressure is given by the use of discharge coefficient C_d in equation 2.1,

$$C_d = \frac{q_m \sqrt{1-\beta^4}}{\frac{\pi}{4} d^2 \sqrt{2\Delta P \rho_1}} \qquad 2.1$$

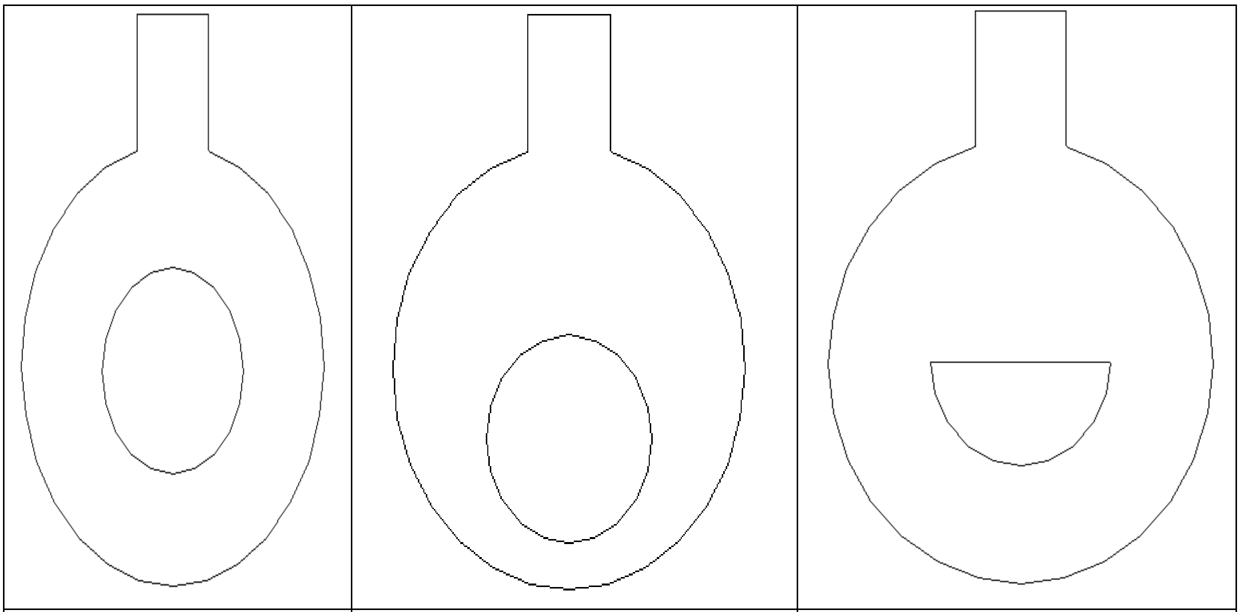
where q_m= mass flow rate in (kg/s)

β = diameter ratio
d = Diameter of orifice in (m)
ΔP = Differential pressure in (Pa)
ρ_1 = Density of the fluid in (kg/m^3)
A = Area of the orifice ($\pi d^2/4$) in (m)
ε = Expansibility factor
The mass rate of flow can be determined using the mass flow rate equation,

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \varepsilon_1 \frac{\pi}{4} d^2 \sqrt{2\Delta P \rho_1} \qquad 2.2$$

where ρ_1 is refers to the upstream conditions.

Orifice plates are classified according their shape and position of the hole or opening they contain. The different types of orifice plates in use include Concentric, Conical, Eccentric, Integral, Quadrant, and Segmental orifice plates. However, the most commonly used orifice plates are concentric, eccentric and segmental orifice plates shown in Figure 3.1.



Concentric Orifice Plate	Eccentric Orifice plate	Segmental Orifice Plate

Figure 3.1: Different types of Orifice Plates

3.1 Principle of operation of orifice plates

An orifice operates on Bernoulli's principle which state that for an ideal fluid, an increase in velocity will cause a decrease in pressure. Bernoulli's principle of equation 2.3 shows the principle of conservation of energy for a steady flow.

$$\frac{\upsilon^2 \rho}{2} + \rho gh + p = cons\tan t \quad \text{-------------2.3}$$

Where P = static pressure
ρ = density
h= height of the tube
v = fluid velocity
g = acceleration due to gravity

3.2 Rig Design

Design can be taken to mean all the processes of conception, invention, visualisation, calculation, refinement and specification of detail which determine the form of a product [15]. Therefore, design is a decision making process, which entails the creation of alternative proposals to fulfil a need. This involves the translation of the optimum solution into a working drawing as shown in Figure 3.2, and instructions to both the manufacturer and the assembly team of the test cell to produce that which is reliable, safe and well proportioned. The rig design incorporates a laminar flow element, a butterfly valve, control valves, Rotameter, orifice plates, Venturi, compressors, refrigerator dryer, an upstream development length of 14 equivalent diameter pipe length, 2-inch pipe dimensions and other accessories. Accurate installation of the equipment is essential to a successful flow measurement and control; as such, adequate precaution should be taken for a good assembly, which in turn enhance better performance of the system.

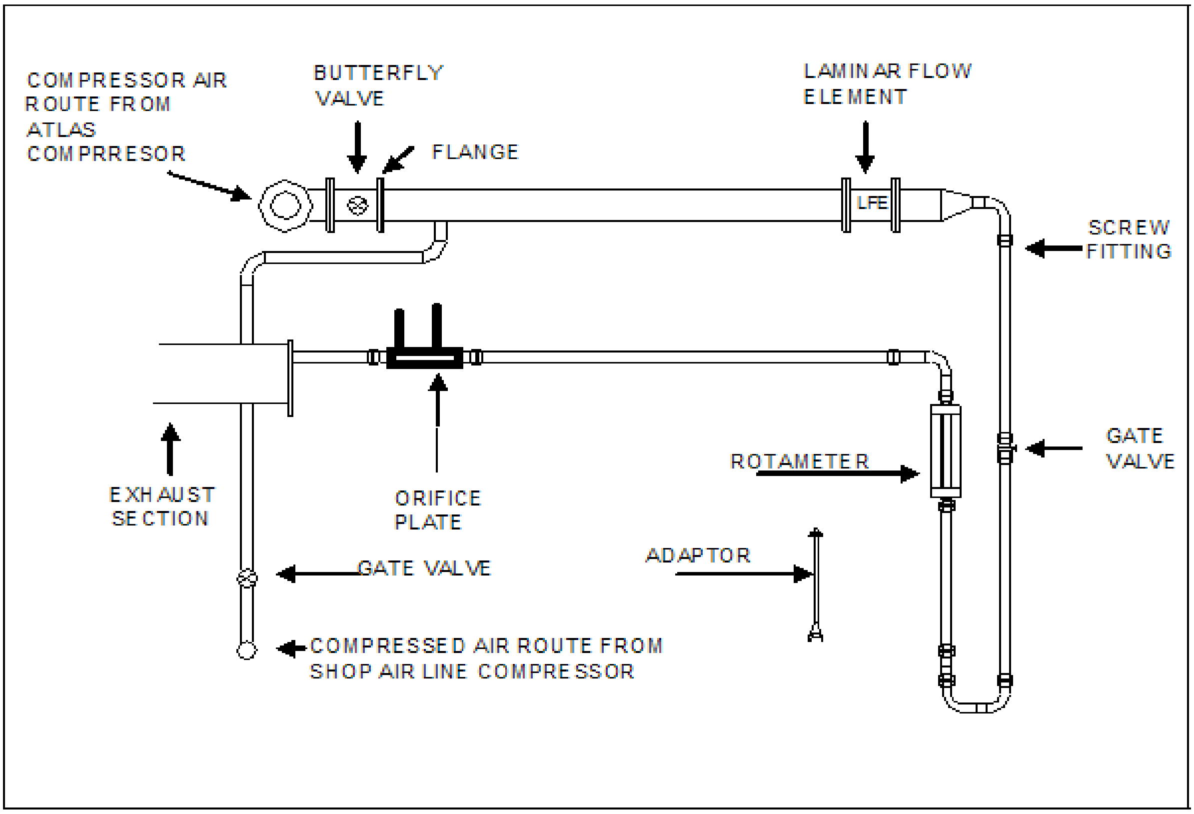


Figure 3.2: Orifice Plate Flow Rig Assembly Drawing

3.3 Mass flow rate analysis using orifice plate

When a fluid passes through an orifice constriction, it will experience a pressure drop across the orifice. This change in pressure is called differential pressure and used to measure the flow rate of the fluid. Analysis involving orifice plates requires accurate measurement of this pressure difference which is made possible by the measurement of fluid properties which includes upstream and downstream pressures, upstream temperature and other parameters like the pipe diameter, orifice diameter, and computing parameters such as beta ratio, orifice area, density, Reynolds number, absolute viscosity, discharge coefficient, pressure ratio, flow velocity and mass flow rate.

The following principle and equations such as the Reynolds number, Sutherland's law, Bernoulli's principle, continuity equation, discharge coefficient and mass flow rate equation are employed for effective analysis involving orifice plate thereby successfully measuring the mass flow rate of the fluid.

IV. RESULTS AND DISCUSSION

The mass flow analysis is presented to illustrate computations of mass flow in an orifice plate installation to ISO 5167 standards. This procedure uses an Excel spreadsheet program to provide an automated analysis and enable alternative geometric configurations to be evaluated.

4.1 Computation Analysis

To determine the mass flow rate in an orifice calibration rig, having an orifice plate with D and D/2 tappings, installed in a pipe of 50 mm nominal diameter as shown in Figure 3.2. The orifice plate dimension is 25 mm. If the pressure difference indicated is 4000 Pa. The fluid is air at 120^0C and the upstream absolute pressure indicated is 2 bars.

$$\therefore \beta = \frac{d}{D} = \frac{25}{50} = 0.5$$

From $\rho_1 = \dfrac{P_1}{RT_1}$

$T_1 = 120 + 273.15 = 393.15$ K

R = 287 J/kgK

P_1 = 2 bar = 2 x10^5 N/m^2

$$\therefore\ \rho_1 = \frac{2x10^5}{287x393.15} = 1.77 \text{ kg/m}^3$$

Let q_m= 0.01 kg/s be the first guess,

The orifice area is given by A= $\frac{\pi d^2}{4} = \frac{3.142x0.025^2}{4}$ = 4.91 x 10^{-4} m^2

From u= $\frac{q_m}{\rho_1 A}$,

$$\therefore\ u = \frac{0.01}{1.77x4.91x10^{-4}} = 11.5 \text{ m/s}$$

To calculate μ = viscosity for air at 393.15 k, reading values from Thermodynamic and Transport Properties of Fluids 5th Edition by G.F.C. Rogers and T.R. Mayhew [16].
At T = 375 K, μ = 2.181 x10^{-5} kg/m s, at T = 400 K, μ = 2.286 x10^{-5} kg/m s and at T = 25 K, μ = 0.105 x10^{-5} kg/m s.

But Δ (393.15 – 375) = 18.15 K

At Δ 18.15 K, we have that $\frac{0.105x10^{-5}x18.15}{25} = 7.623x10^{-7}$ kg/m s

∴ μ at 393.15k, = 7.623 x 10^{-7} + 2.181 x 10^{-5} = 2.2572 x 10^{-5} kg/m s

The Reynolds number, $Re_D = \frac{\rho_1 uD}{\mu}$

$$= \frac{1.77x11.5x0.05}{2.2572x10^{-5}} = 45089$$

Then coefficient of discharge C_d for β = 0.50 at Re_D = 45089 by interpolation is given as,
At β = 0.50, for 3 x 10^4 = 0.6012
and for 5 x 10^4 = 0.6079
∴ Δ 2 x10^4= (0.6079 – 0.6012) = 0.0067
But Δ (5 x10^4 – 4.5089 x10^4) = 4911

At Δ 4911, $\frac{0.0067x4911}{2x10^4} = 0.001645185$

∴ At Re_D= 45089,C_d = 0.001645185 + 0.6012 = 0.602845

$$\therefore C_d = 0.6028$$

Expansibility factor ε, at k = 1.4 for air is determine by calculating the pressure ratio.
From P_1= 2bar = 2 x 10^5 N/m^2
ΔP = 4000 N/m^2
But ΔP = P_1- P_2
∴ P_2 = 2 x 10^5 – 4000 = 1.96 x 10^5 N/m^2

$$\therefore\ \frac{P_2}{P_1} = \frac{1.96x10^5}{2x10^5} = 0.98$$

∴ At β = 0.50 and $\frac{P_2}{P_1} = 0.98,$

∴ ε_1= 0.994 from Expansibility (expansion) factor table for Orifice plates based on ISO 5167 and BS 1042 standards.
Substituting all the values in the mass flow rate formulae,

$$q_m = C_d \varepsilon_1 \frac{\pi d^2}{4} \frac{\sqrt{2\Delta P \rho_1}}{\sqrt{1-\beta^4}}$$

$$q_m = 0.6028x0.994x\frac{3.142}{4}x0.025^2 x\frac{\sqrt{2x4000x1.77}}{\sqrt{1-0.5^4}}$$

$$q_m = 3.615x10^{-2} \text{ kg/s}$$

Let continue the calculation by iterating the mass flow rate until it converged to 4 S.F.

Substituting $q_m = 3.615x10^{-2}$ kg/sin u= $\frac{q_m}{\rho_1 \mathrm{A}}$,

$$u = \frac{3.615x10^{-2}}{1.77x4.91x10^{-4}} = 41.60 \text{ m/s}$$

$$\therefore \mathrm{Re_D} = \frac{\rho_1 u D}{\mu} = \frac{1.77x41.60x0.05}{2.2572x10^{-5}} = 163105$$

$\therefore$ For C_d, at Re_D= 163105 and β = 0.50 by interpolation,
C_d = 0.6072,

$$\therefore q_m = 0.6072x0.994x\frac{3.142}{4}x0.025^2 x\frac{\sqrt{2x4000x1.77}}{\sqrt{1-0.50^4}}$$

$$q_m = 3.642x10^{-2} \text{ kg/s}$$

Again substituting $q_m = 3.642x10^{-2}$ kg/s in u= $\frac{q_m}{\rho_1 \mathrm{A}}$,

$$u = \frac{3.642x10^{-2}}{1.77x4.91x10^{-4}} = 41.91 \text{ m/s}$$

$$\therefore \mathrm{Re_D} = \frac{\rho_1 u D}{\mu} = \frac{1.77x41.91x0.05}{2.2572x10^{-5}} = 164320$$

And for C_d, at Re_D= 164320, and β = 0.50, by interpolation,
C_d = 0.6049,

$$q_m = 0.6049x0.994x\frac{3.142}{4}x0.025^2 x\frac{\sqrt{2x4000x1.77}}{\sqrt{1-0.5^4}}$$

$$\therefore q_m = 3.628x10^{-2} \text{ kg/s}$$

Substituting $q_m = 3.628x10^{-2}$ kg/s in u= $\frac{q_m}{\rho_1 \mathrm{A}}$,

$$u = \frac{3.628x10^{2}}{1.77x491x10^{-4}} = 41.75 \text{ kg/s}$$

$$\therefore \mathrm{Re_D} = \frac{\rho_1 u D}{\mu} = \frac{1.77x41.75x0.05}{2.2572x10^{-5}} = 163693$$

And for C_d, at Re_D =163693 and β = 0.50, by interpolation
C_d = 0.6048,

$$q_m = 0.6048x0.994x\frac{3.142}{4}x0.025^2 x\frac{\sqrt{2x4000x1.77}}{\sqrt{1-0.5^4}}$$

$$\therefore q_m = 3.627x10^{-2} \text{ kg/s}$$

Substituting $q_m = 3.627x10^{-2}$ kg/s in u= $\frac{q_m}{\rho_1 A}$,

$$u = \frac{3.627x10^{-2}}{1.77x4.91x10^{-4}} = 41.73 \text{ m/s}$$

$$\therefore \mathrm{Re}_D = \frac{\rho_1 u D}{\mu} = \frac{1.77x41.73x0.05}{2.2572x10^{-5}} = 163614$$

And for C_d, at $Re_D =$ 163614 and β = 0.50, by interpolation,
C_d = 0.6048

$$q_m = 0.6048x0.994x\frac{3.142}{4}x0.025^2 x\frac{\sqrt{2x4000x1.77}}{\sqrt{1-0.5^4}}$$

$$\therefore q_m = 3.627x10^{-2} \text{ kg/s}$$

The mass flow rate converged at 3.627 x 10^{-2}kg/s to 4 significant figures.

4.2: Excel (spread sheet) program

This provides an automated analysis and enables alternative geometric configurations to be evaluated. Table 4.1 shows the excel program result of variation of orifice diameter and the corresponding increase in the diameter ratio, area, and hence the corresponding increase in the mass flow rate of the fluid. The excel program flow rate result of orifice diameter 25 mm with the diameter ratio of 0.5 is in good agreement with the computed analysis in section 4.1.

Table 4.1: The excel program result of variation of orifice diameter with other parameters

SN	Orifice diameter (mm)	Diameter ratio	Area (m^2)	Mass flow rate (kg/s)
1	5	0.1	19.64	0.035147
2	10	0.2	78.55	0.035173
3	15	0.3	176.75	0.035288
4	20	0.4	314.20	0.035604
5	25	0.5	490.94	0.036298
6	30	0.6	706.95	0.037671
7	35	0.7	962.28	0.040317
8	40	0.8	1256.80	0.045739

The result indicates that an increase in the orifice diameter will increase the diameter ratio, the orifice area, hence, an increased in the mass flow rate. These results are shown graphically as Figure 4.1, Figure 4.2 and Figure 4.3 respectively.

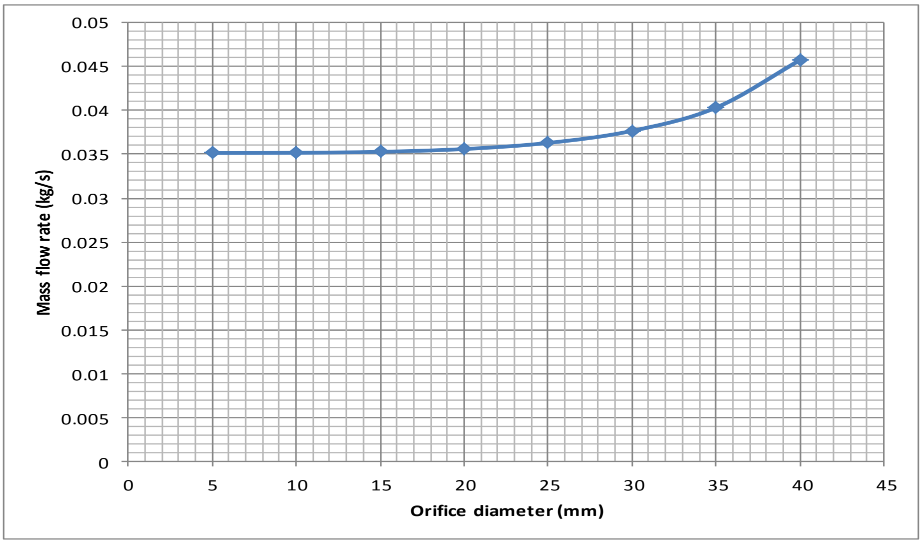


Figure 4.1: The variation of mass flow rate with the increased in orifice diameter

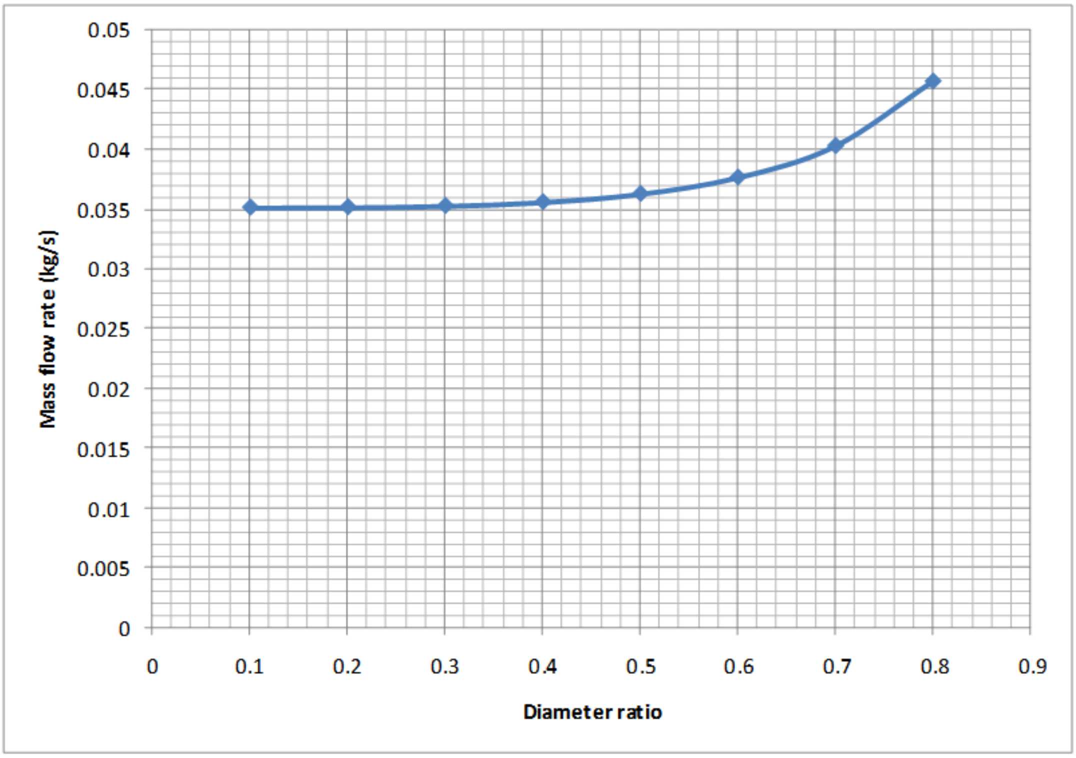


Figure 4.2: The variation of mass flow rate with the increased in diameter ratio

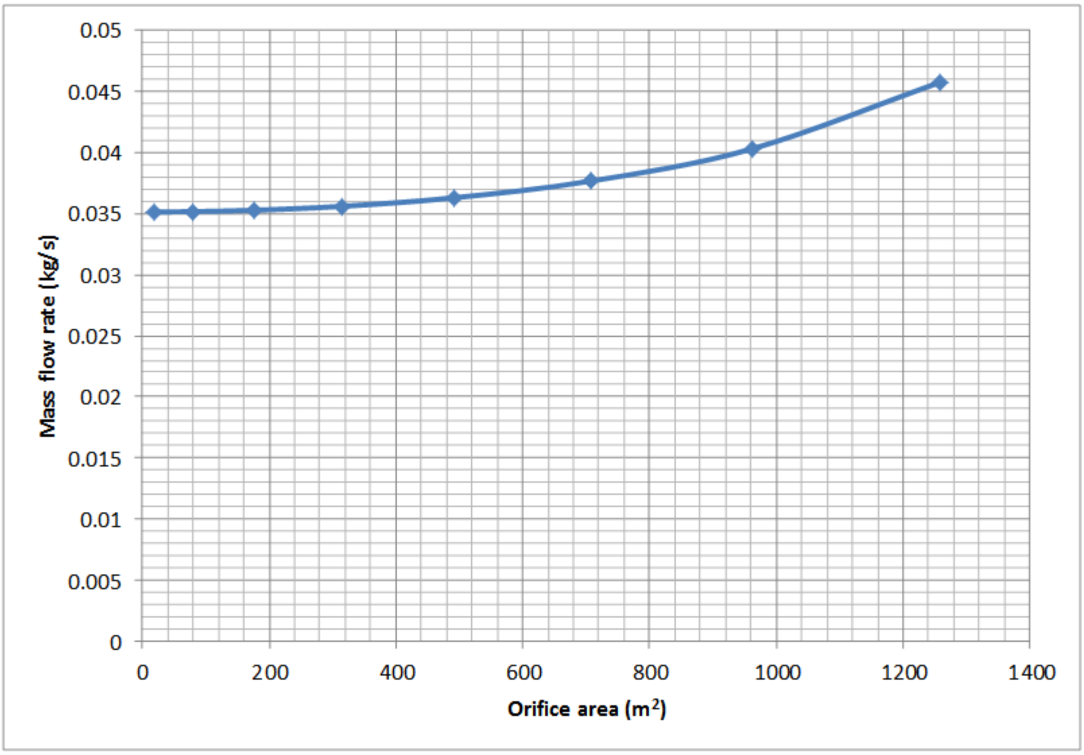


Figure 4.3: The variation of mass flow rate with the increased in orifice area

However, by increasing a flow parameter such as the upstream pressure, brings about an increase in the differential pressure, thereby increasing the mass flow rate which is presented in Figure 4.4.

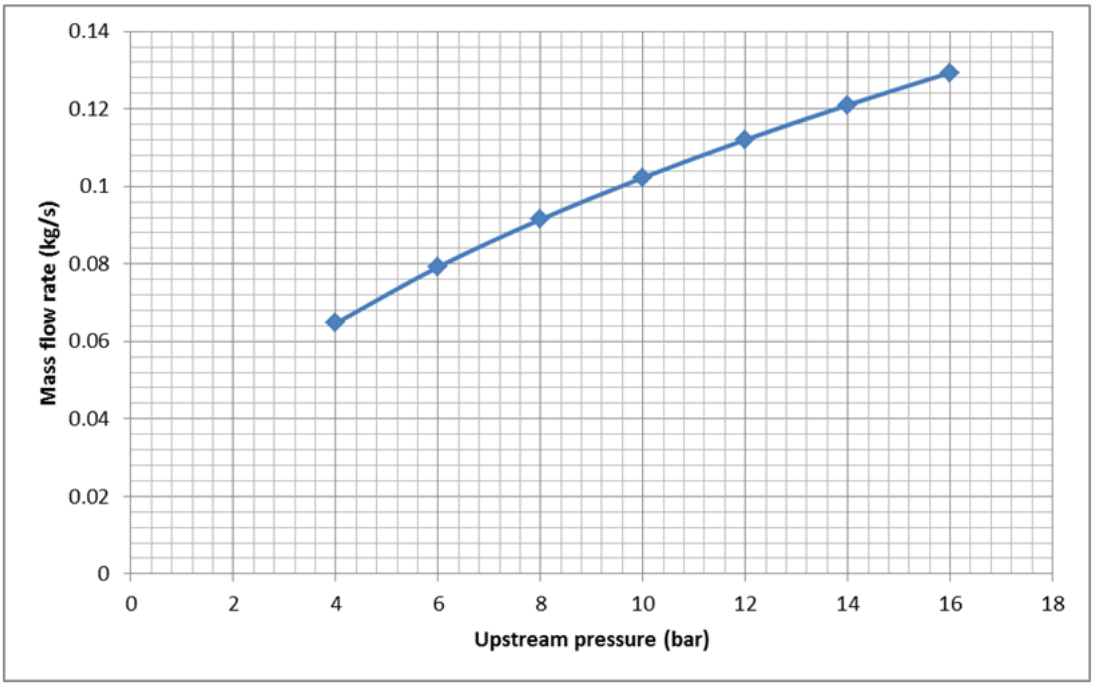


Figure 4.4: The variation of mass flow rate with an increased in upstream pressure

V. CONCLUSION

An orifice plate is thin plate in which a circular aperture has been machined; used to measure the rate of fluid flow. Orifice plates are the most common method of differential flow measurement. Since the mass flow measurement and control is very essential in industrial process because it provides vital information about the flow and may lead to better efficiency of the process, thereby, reducing waste and cost of the operation, it is necessary to calibrate orifice plates with different geometry, hence the need for a test facility for this purpose. It is important to note that an orifice plate produces differential pressures, which depend on both fluid characteristics and the plate's geometry, therefore both orifice plate geometry and fluid properties have a significant effect on mass flow measurement and mass flow control.

This analysis shows the influence of orifice plate geometry and fluid properties on mass flow measurement and mass flow control. The result indicates that an increase in the upstream pressure brings about an increase in the differential pressure, thereby increasing the mass flow rate. Furthermore, an increase in the orifice diameter will increase the orifice area, diameter ratio, hence, an increased in the mass flow rate. In view of the results, the study has successfully analysis the effect of orifice plate geometry and fluid properties of the mass flow measurement and mass flow control. Hence, an orifice plate can be used successfully for mass flow measurement and mass flow control.

This project had enabled selection and confirmation of the pipe network and an instrumentation configuration for a dedicated test rig in the Thermo Fluid Mechanics Research Centre. This rig is used to calibrate flow-measuring devices and enable flow characterisation of orifice plates and other flow limiting devices for use in flow control in gas turbine engine internal flow systems.

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