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A 5-30 kg/s Orifice Plate Cooling Water Flow Meter Design

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***Abstract*— The flow measurement is a very important task specifically in industry sector. This is because of its widespread use for accounting purposes and because of its applications in manufacturing processes. In the research laboratory, advanced flow measurements provide new insights into a wide range of engineering flow problems in hydrodynamics, combustion, aerodynamics, and performance predictions. The main objective of this work is to generate an awareness and understanding of the range of contemporary flow measurement techniques available with the emphasis on devices and techniques associated with wide applications in the engineering field. The focus is devoted to cheap meters with reasonable accuracy; the differential pressure flow meters are employed to measure the flow rates, according to pressure drops across restrictions in the flow passages. An orifice plate meter is designed to measure the required flow rate to cool a nuclear reactor at a design point of 20 kg/s. Meter operation at off design conditions; 5 and 30 kg/s flow rates with maximum allowable orifice pressure drop of 200 kPa was investigated. An orifice plate meter with a diameter ratio of 0.7 is designed to satisfy the constraints over the desired operating range.**

***Keywords*— Behavior of differential pressure flow meters, Design of Flow meters, Flow measurement, orifice plate meters**

NOMENCLATURE

Symbols	Description
ρ	Fluid density, kg/m^3
p	Local Static Pressure, Pa
V	Average flow velocity, m/s
Z	Local elevation, m
g	Gravitational acceleration, 9.81 m/s^2
A	Cross-sectional area, m^2
$\dot{m}$	Mass flow rate, kg/s
D_t	Orifice plate diameter, m
D_1	Pipe diameter, m
D_2	Vena contracta diameter, m
β	Orifice plate beta ratio (D_t/ D_1)
ΔP	Static Pressure difference, Pa
C_d	Orifice discharge coefficient
Re	Flow Reynolds number
	Indices;
	1 Upstream inlet
	2 Vena contracta section
	t Orifice openning section

I. Introduction

Flow measurement can be defined as the process of determination of the quantity of the fluid running through the passage, either as a rate or as an integrated value. There are several types of flow measurement; each one has to have specific considerations, including accuracy constraints, cost implications, and using flow characteristics in order to obtain the desired end results [1,5,6,7,8]. Normally, flow meters used to measure flow indirectly by measuring related common dimensions; differential pressure across the flow restriction or the flow velocity in the desired passage where fundamental physical principles should be used in the analysis of the flow through measurement devices.

Differential pressure flow meters deduce the flow rate from measurements of pressure drops across restrictions in pipes and ducts for many years. They represent the reliable method available. They have a wide popular usage despite the development of higher performance modern devices, mostly on account of exceptionally well researched and documented standards.

These devices consist of a primary element that restricts the flowing stream resulting in a pressure difference (pressure drop) across the element. The related secondary devices consist of a differential pressure measuring unit with connecting piping and other measuring units required to define the flowing variables of the fluid, such as pressure, temperature, and composition. The pressure and differential-pressure transducer are often combined into a single unit, as shown in Figure 1, [8,9,10].

II. Types Of Flow Meters

A flow meter is then a device that meters movement of fluids in a conduit or an open channel. Fluids could be water, chemicals, air, gas, steam or solids. There are various kinds of the flow meters available in the market and classified into mechanical and non-mechanical types. Non-mechanical types are also known as pressure difference flow meter and include; Orifice plate, Venturi tube, Pitot tube, Nozzle and variable area (Rotameter) types.

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Mechanical type flow meters include; Positive displacement; Velocity and mass flow meters. The Positive displacement types are; Reciprocating piston; Oval gear; Nutating disk and Rotary vane types. While the velocity types are, Turbine, Vortex shedding, Swirl; Electromagnetic; Ultrasonic Doppler And Ultrasonic Transit-time. The mass flow meters types are; Coriolis and Thermal. Other meter types include the optical type meters. These meters are made of several basic technologies and each type has a niche and can generally be used for many applications [5,7,9,10,11].

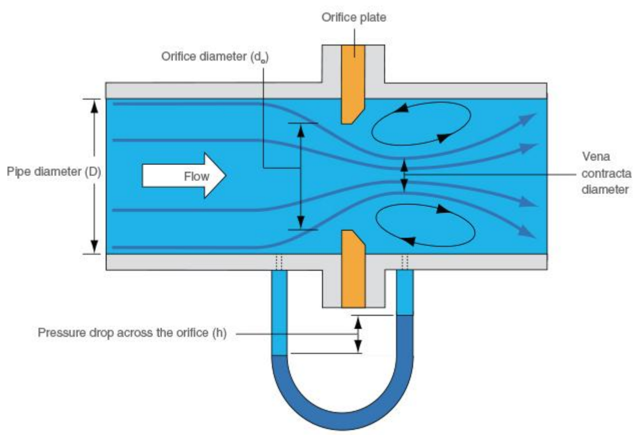

Figure 1 An orifice plate flow meter with vena contracta.

III. Selection Criteria

It needs a lot of effort to select a suitable flow meter for a particular application. There are a wide variety of flow meters in the market. It requires a considerable evaluation of many factors. These include the total cost, fluid state, flow conditions, fluid properties, range ability, mechanical installation constraints and accuracy requirements. The chief engineer should determine exactly the design operating conditions. Pressure and temperature of the fluid flow should be provided to help in the selection process. A specific gravity or density analyzer could be required to account for variability in stream composition. Referring to the economic analysis, one should be aware of the equipment cost, installation cost, maintained cost, and operating cost. These must be carefully evaluated in terms of meter size and operating pressure [7,8,9]. For example, small sized Venturi meters could be of comparable cost to an averaging Pitot tubes. However, as the size increases the cost of the Venturi rapidly exceeds that of the averaging Pitot tubes for a given pipe size.

Similarly, as the design pressure increases the cost has to go up with the same effect.

Accuracy is a common term used in flow meters for flow measurements. Accuracy term is perhaps misunderstood. It is considered to be a sales tool widely used in the commercial world by suppliers and users of flow meters. The supplier wins the bid according to the accuracy best number. While, users sometimes require accuracies beyond the capabilities of any flow meter available. In previous decades, accuracy was the term most commonly employed to describe the ability of flow meters to measure flow. This was defined as the ratio of an indicated measurement to actual measurement. The term of uncertainty is an expression for the maximum possible limit of error at a defined confidence target. Accuracy remains, then very important for flow meters because it is related to money. For example, referring to a flow meter unit for measuring products of $2 million per day, with measuring inaccuracy of ± 0.2%, could lead to lose $4,000 per day, which equals to $1,460,000 per year. This amount is high enough to justify making considerable investment in order to improve the accuracy of flow measurements. The same inaccuracy could happen in a station measuring products of a value of $1,000 per day. This leads to lose only $2 per day. Here, where the judgment is necessary, low benefits lead to move with limited investment in order to improve measurement accuracy.

Differential type flow meters are cheap to install and manufacture being the orifice type meters typically the less expensive with reasonable accuracy. In addition, with the exception of the orifice meter, almost all flow meters require a fluid flow calibration at flow and temperature conditions closely approximating service operation in order to establish accuracy [8,9,11,12]. Thus, without requiring direct fluid flow calibration and have no moving parts, orifice meters remains simple, rugged, widely accepted, reliable and relatively inexpensive.

IV. Orifice Plate Meters

The orifice plate meters are very simple devices that installed in a straight run of pipes and ducts. The orifice plates are thin plates manufactured with openings usually in the middle of the plates. The going flow experiences an increase in the flow velocity which leads to practice a static pressure drop. Here, the differential pressure could be related to the flow rate. As the flow approaches the orifice plate opening, the flow is to be forced to converge in order to go through the small opening.

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The maximum convergence section of the peak uniform velocity actually occurs in a section shortly downstream of the position of the orifice. This section with a minimum cross-sectional area is called “vena contracta”, as shown in Figures 1 and 4. As it does so, the velocity and the pressure changes. Beyond the vena contracta, the fluid expands and the velocity and pressure change once again. By measuring the difference in fluid pressure between the upstream normal pipe section and at the vena contracta, the theoretical volumetric and mass flow rates can be obtained directly from Bernoulli's equation [1,8,13,14]. There are three tap arrangements; corner taps, flange taps, and D & D/2 taps, as indicated in Figure 2.

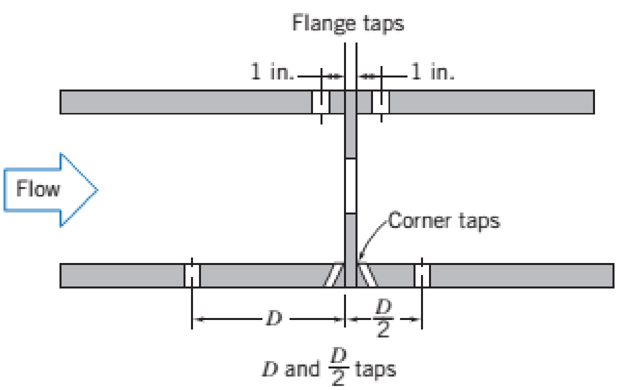

Figure 2 An orifice geometry and pressure tap locations [7,8,13].

V. Meter Working Principle

As the flow approaches the orifice plate, the flow cross-sectional area converges gradually where the flow velocity increases and the flow static pressure decreases according to mainly Bernoulli Equation. The pressure continues to decrease all the way upstream of the vena contracta. Downstream of the vena contracta the pressure gradually increases along the flow passage to approximately 5 to 8 diameters to reach a peak static pressure point. This peak value is lower than the entrance pressure value upstream of the orifice. This is due to the mild resistance of the flow meter. In other words, as the flow leaves the section of the vena contrcta, the static pressure increases and tends to return to its original value. The pressure drop is not recovered completely due to friction and turbulence losses in the flow stream. It is well known that the measured differential pressure drop is proportional to the square of the velocity.

Hence, if all other factors remain constant, then the differential pressure should be proportional to the square of the flow rate [4,6,7].

VI. Meter Applications

Orifice plates are usually installed in flow pipes. They are employed mostly for continuous measurement of fluid flow. Also, they are used to measure flow rates in small river systems at locations where the river passes through a culvert or drain. There are a limited number of rivers that are appropriate for the use of orifice meters, since the meter should be remain completely immersed. That requires full approach pipe and rivers should be substantially free of debris. These orifice meters are devices cover a very wide applications including dirty fluid flows in large pipe and duct diameters sizes. Generally, the orifice plate has three different geometries, concentric, eccentric and segmental as shown in Figure 3, [2,3,7,8,13].

VII. Mathematical Model

A considered number of the non-mechanical flow meters used for internal flow measurements are based on accelerating the flow stream through an opening as shown in Figure 4. There would be a flow separation at the sharp edges of the opening throat, causing a recirculation zone that leads to form a flow wake as shown by dashed line downstream from the opening. As indicated above, the main flow stream continues to accelerate from the throat to the vena contracta section. The flow then decelerates again to fill out the duct. At the vena contracta the flow area is a minimum, where the flow stream lines are essentially straight and parallel. This leads to have a uniform pressure across the channel, as shown in Figure 4.

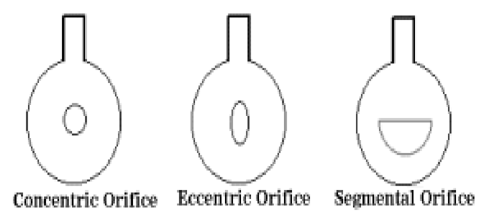

Figure 3 Geometries of the orifice plate.

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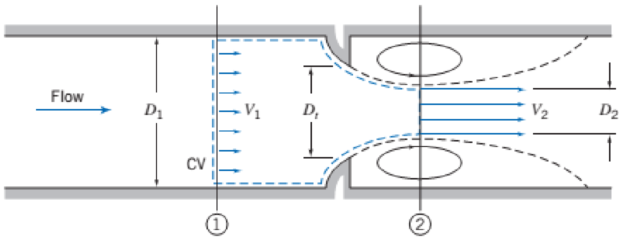

Figure 4 The selected control volume for the flow analysis in the flow meter [7.8.10].

The theoretical flow rate may be related to the pressure drop by applying the continuity and Bernoulli equations. The empirical correction factors may be applied to obtain the actual flow rate. The basic integral equations according to the selected control volume can be represented as follows [1,3,7,8,10];

$$0=\int_{c.v.}\frac{\partial}{\partial t}(\rho)d\forall+\int_{c.s.}\rho\hat{n}.\vec{V}dA \tag{1}$$

$$\frac{p_1}{\rho}+\frac{V_1^2}{2}+gz_1=\frac{p_2}{\rho}+\frac{V_2^2}{2}+gz_2=\text{const} \tag{2}$$

Where p is the static pressure, V is the average flow velocity, z is the local centerline elevation, ρ is the fluid density, A is the cross sectional area, and g is the gravitational acceleration. The considered assumptions may include the following;

Steady flow
Incompressible flow
Flow along stream lines
Frictionless flow
Uniform velocity at sections 1 and 2
No streamline curvature at sections 1 or 2, hence, the pressure is uniform across each section.
Horizontal pipe installation, i.e. $z_1=z_2$

From Bernoulli equation we may have;

$$p_1-p_2=\frac{\rho}{2}(V_2^2-V_1^2)=\frac{\rho V_2^2}{2}\left[1-\left(\frac{V_1}{V_2}\right)^2\right] \tag{3}$$

Applying continuity equation, the static pressure drop becomes;

$$p_1-p_2=\frac{\rho V_2^2}{2}\left[1-\left(\frac{A_2}{A_1}\right)^2\right] \tag{4}$$

Solving for the theoretical velocity V_2, we obtain;

$$V_2=\sqrt{\frac{2(p_1-p_2)}{\rho\left[1-\left(\frac{A_2}{A_1}\right)^2\right]}} \tag{5}$$

Hence, the theoretical mass flow rate is given by;

$$\dot{m}_{theoretical}=A_2\sqrt{\frac{2\rho(p_1-p_2)}{1-(A_2/A_1)^2}} \tag{6}$$

As well known, the flow rate is to be directly proportional to the square root of the pressure drop across the meter taps, which is the basic idea of such devices. As indicated above, the calculation of the actual mass flow rate through the meter depends on several factors. Usually, the actual vena contracta flow area, A_2, is unknown. The upstream velocity profiles are uniform only at high turbulent flow Reynolds numbers. Frictional effects could be considered especially downstream region from the meter when the meter contours are abrupt. In addition, the location of static pressure taps influences the differential static pressure readings.

Here, The theoretical equation is adjusted, for the above points including the effect of Reynolds number and diameter ratio Dt/D1, by defining an empirical discharge coefficient C_d such that, replacing (Eqn. 6), we have;

$$\dot{m}_{actual}=\frac{C_d A_t\sqrt{2\rho(p_1-p_2)}}{\sqrt{1-\left(\frac{A_t}{A_1}\right)^2}}=\frac{C_d A_t\sqrt{2\rho(p_1-p_2)}}{\sqrt{1-\beta^4}} \tag{7}$$

Here, $1/\sqrt{1-\beta^4}$ is defined as the approach factor for the velocity. The combination of the discharge coefficient and velocity of approach factor is frequently represented by a single flow coefficient;

$$K\equiv\frac{C_d}{[1-(\beta)^4]} \tag{8}$$

Where, $\beta=D_t/D_1$. Hence, in terms of this flow coefficient, the actual mass flow rate can be expressed as;

$$\dot{m}_{actual}=KA_t\sqrt{2\rho(p_1-p_2)} \tag{9}$$

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And the volumetric flow rate can be then determined by the following expression;

$$Q_{actual} = KA_t\sqrt{\frac{2(p_1 - p_2)}{\rho}} \qquad (10)$$

The flow discharge coefficient found in the literature have been determined for fully developed turbulent velocity distribution at the upstream section of the meter entrance (section 1). Various relations for the coefficient are available under certain conditions. Here, the discharge coefficient, C_d, can be calculated by employing the following selected empirical equation (ISO);

$$C_d = 0.5959 + 0.0312\beta^{2.1} - 0.1840\beta^8 + 0.0029\beta^{2.5}\left(\frac{10^6}{Re}\right)^{0.75} + 0.0900(L_1/D)[(\beta^4/(1-\beta^4))] - 0.0337(L_2/D)\beta^3 \qquad (11)$$

Where; β is the ratio of the diameters; D_t/D_1, Re is the Reynolds number, and the constants L_1=0.4333 and L_2=0.47 for the considered D and D/2 taps type. The discharge coefficient, C_d, varies considerably with changes in the area ratio and Reynolds number. The discharge coefficient C_d is around the value of 0.60. This value may be taken as standard value, however, the coefficient varies noticeably at low Reynolds numbers and high diameter ratio, as shown in Table 1.

Table 1
Discharge coefficient as function of Reynolds number and diameter ratio [1,3,10]

Discharge coefficient, C_d				
Diameter ratio β= D_t/D_1	Reynolds number (Re)			
	10^4	10^5	10^6	10^7
0.2	0.6	0.595	0.594	0.594
0.4	0.61	0.603	0.598	0.598
0.5	0.62	0.608	0.603	0.603
0.6	0.63	0.61	0.608	0.608
0.7	0.64	0.617	0.609	0.609

The pressure recovery is limited for the orifice plates and the permanent pressure loss depends primarily on the area ratio, refer to Figure 5. For an area ratio of 0.5, the head loss is about 70 - 75% of the orifice differential head.

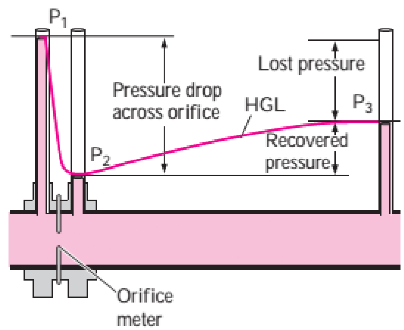

Figure 5 Associated pressure drop and pressure loss in the flow meter.

There are general bench marks for the orifice meter; The meter is recommended for both clean and non-clear liquids and for some slurry services, the flow rates that can be measured accurately have approximately a 4:1 range, the pressure loss across the meter is considered to be pronounced, typical accuracy is within 2 to 4% of full reading scale, the viscosity effect is relatively high represented by the flow Reynolds number, and the meter relatively has low cost.

VIII. METER DESIGN CONSTRAINTS

The orifice beta ratio (β) should lie in the range of 0.2-0.8 [1,3,7,8,10]. However, it is advised to remain below the value of 0.7 and above 0.2, as this affect strongly the percentage of uncertainty of the discharge coefficient .

1. The orifice plate is a thin plate with circular concentric hole and with sharp edges.
2. The eccentricity of the orifice bore diameter D_t to the upstream pipe bore D_1 can result in an error in the discharge coefficient. The following equation can be used to maintain the maximum permissible eccentricity;

$$e_x < \frac{0.0025D}{0.1 + 2.3\beta^4} \qquad (12)$$

While in line sizes of nominal 75 mm or less, the eccentricity should be no greater than 0.8 mm.

3. The minimum edge thickness of the orifice e of the orifice shall be equal or greater than 0.1 D_t but not less than 0.125mm. The maximum shall be equal to or less than $0.02D_1$ or equal to or less than $0.125D_t$ whichever is smaller, but not greater than e (the plate thickness), as shown in Figure 6.

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4. The orifice edge thickness, e, should be uniform over the plate area.
5. The bevel angle shown in Figure 6 should be approximately 45°.
6. For D and ½ D taps arrangement, the center line of taps shall meet the pipe center line at right angles to it (±2 deg). For nominal pipe size 50 – 75 mm, the maximum diameter of tap holes is 10 mm. While nominal pipe sizes > 100 mm, the maximum diameter of tap holes is 13 mm.

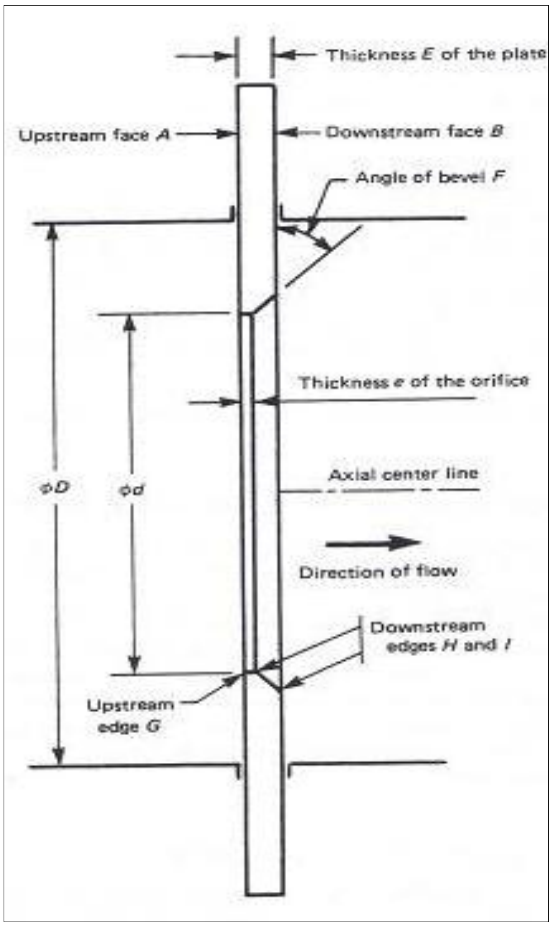

Figure 6 Standard orifice plate [1,3,8]

More detailed expressions and discussions can be found elsewhere; Mustapha S. Mansour, M. Sc. Thesis [16].

IX. Meter Design - Input Data

To be able to design an orifice plate meter, some important input data should be provided such as; the required range of the flow rate to be measured; the pressure drop permissible range; the tap type and accordingly the sensors position; the liquid type and accordingly its density; the installation pipe inside diameter; the liquid kinematic or dynamic viscosity and finally the off design conditions. All required data for the desired design process was summarized as follows [15];

1. The required flow rate to cool a nuclear reactor at the design point is 20 kg/s
2. The off design conditions are such; The maximum and minimum water flow rates required are 30 kg/s and 5 kg/s, respectively. The maximum permissible pressure drop is 200 kPa
3. The water temperature is 20 ^{o}C, thus its density is 1000 kg/m^3, and the kinematic viscosity (υ) is 1.03x10^{-6} m^2/s.
4. The pipe line inside diameter is 76 mm.

The design equations were already detailed above. The sequence and procedure of the design point calculation has to go with iterations, peer in mind the contrains including the limitation of the allawable pressure drop. Once the convergence is reached the orifice size is obtained with the desied flow rate range under different set of conditions. Since, the nature of the design calculation process is iterative, and in order to speed up and facilitate the process all relevant meter, An iteration-based Fortran language subroutine is written taking into account the design constraints. The program flow chart is illustrated in Figure 7.

X. Meter Design Calculations

In order to finalize and confirm the design calculations i.e. to select the proper orifice beta ratio (β) (orifice size) with suitable orifice pressure drop, it is required to check the meter at off design conditions by the following procedure;

1. Since the meter geometry and the off design conditions are set, the calculation procedure is repeated with the design orifice beta ratio (β) (i.e. the obtained meter size) by iterating this time the orifice pressure drop only until the orifice beta ratio (β) (i.e. orifice plate diameter) design point value is obtained.

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2. On the meantime, the converged orifice pressure drop should be ≤ the maximum off design allowable value. When this requirement is fulfilled (i.e. design point orifice beta ratio (β) (i.e. size) with its corresponding orifice pressure drop, the design calculations are valid and accordingly, the design drawings of the meter can be prepared for production purposes.

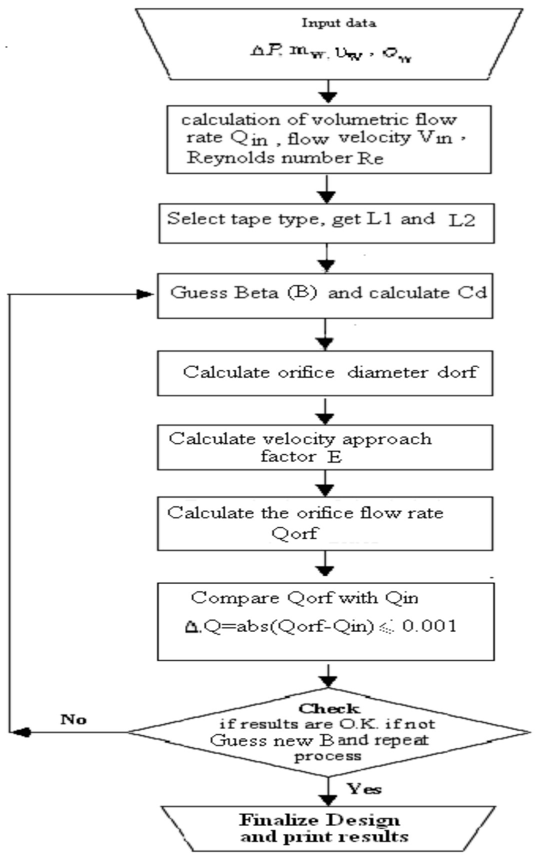

Figure 7 The Orifice plate meter design iteration process chart.

XI. Results And Discussions

The calculations for the design point mass flow rate of 20 kg/s were carried out with different values of orifice pressure drop of 50, 75 and 100 kPa. Here For an orifice pressure drop of 50 kPa, the solution converged with an orifice beta ratio (β) of 0.76. This is exceeding the advisable maximum recommended value of 0.7 and thus excluded from the design compromization.

However, the solution converges for an orifice beta ratio (β) of 0.7 with a given orifice pressure drop of 75 kPa. This orifice beta ratio (β) consides exactly with the advisable maximum recommended value of 0.7, which is the optimum recommended maximum value found in literature that does not affect the pressure drop coefficient.

For a given orifice pressure drop of 100 kPa, the solution converges with an orifice beta ratio (β) of 0.66. However, this is lower than the advisable maximum recommended value of 0.7.

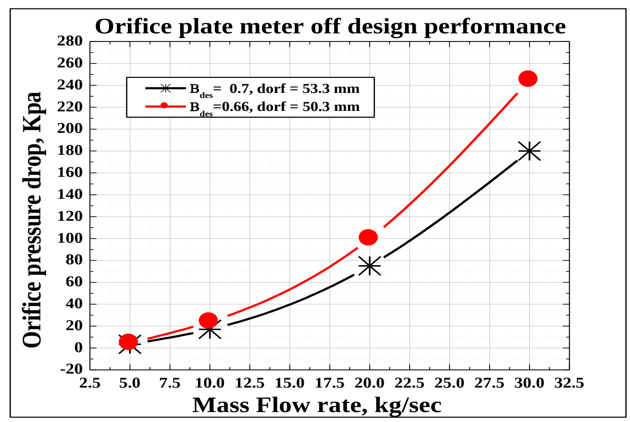

Figure 8 Orifice plate meter off design performance.

In order to finalize the design process, the meter off design conditions are investigated at both extremes; minimum and maximum off design mass flow rates of 5 and 30 kg/s, respectively.

For the design point beta ratio (β) of 0.7, the calculation procedure is conducted with minimum and maximum expected off design flow rates of 5 and 30 kg/s, respectively. The iteration process is based this time on the expected orifice pressure drop only. The corresponding orifice pressure drop to measure a flow of 5 kg/s is 3.4 kPa, while to measure a flow of 30 kg/s, the corresponding orifice pressure drop is 180 kPa, which are below the maximum allowable value. Also it is found that the corresponding orifice pressure drop is 17 kPa for measuring a flow of 10 kg/s.

Referring to the design point beta ratio (β) of 0.66, the corresponding orifice pressure drop to meter 5 kg/s is 4.5 kPa, while to meter 30 kg/s, the corresponding orifice pressure drop is 245 kPa, which exceeds the allowable maximum value of 200 kPa.

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Also to meter 10 kg/s, the corresponding orifice pressure drop is 24 kPa. The variation of the desired mass flow rate with the cooresponding orifice pressure drop is plotted in Figure 9.

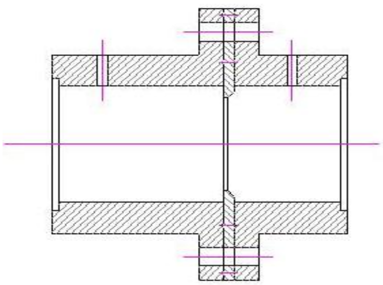

Figure 9 Orifice plate meter assembly.

It is clear that the orifice plate meter with a beta ratio (β) of 0.7 is the most suitable geometry that satisfies all design contraints and covers the documented recommendations. The meter design drawings; the orifice plate meter assembly, left flange, right flange, and orifice plate design, are shown below in Figures 9, 10, 11 and 12, respevtively.

Accuracy and precision of flow meters are the most important metrological parameters in most industries. Hence, before field installation of such meters takes place, calibration test should be conducted in order to adjust the meter readings with the actual flow rates.

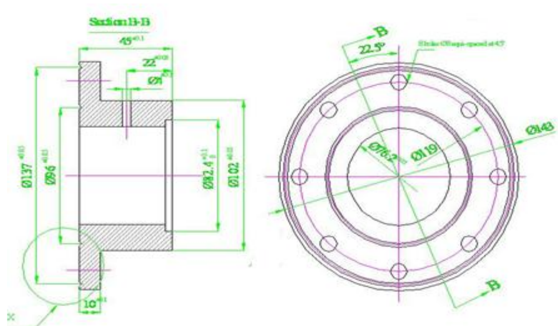

Figure 10 Orifice plate meter left flange design.

When dealing with other liquids than water the density should be replaced in the presented mathematical model. Nozzle and venturi flow meters could be studied similarly for specific tasks; designed, tested, and evaluated. Evaluation of the mathematical model and validation should be made including the flow rate accuracy and sensivity to partial loads.

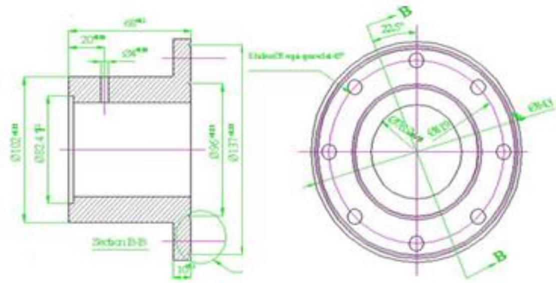

Figure 11 Orifice plate meter right flange design.

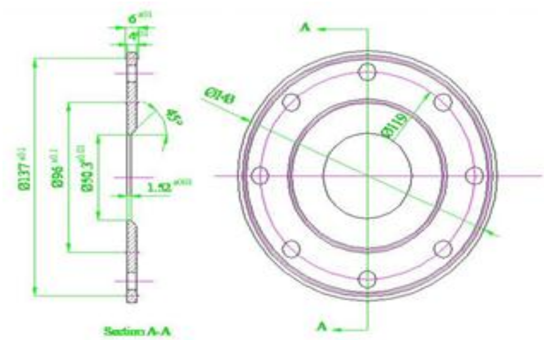

Figure 12 Orifice plate design

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