Effect of Reynolds number and Boundary Layer Thickness on the Performance of V-cone Flowmeter using CFD

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Abstract

The effect of Reynolds number and boundary layer thickness on the performance of V-cone flowmeter has been evaluated using computational fluid dynamics (CFD). The shear stress transport k-ω (SST k-ω) turbulence model has been adopted for closure. The performance of two V-cone flowmeters with different beta ratios (β) viz., 0.6 and 0.7 for a fixed vertex angle (φ) of 60° has been analysed as a function of Reynolds number (Re). The results show that the coefficient of discharge (C_d) increases with Reynolds number in the laminar and transition flow regimes whereas it is nearly constant in turbulent flow regime. From the results, it can be concluded that C_d is independent of Re for values equal to 4000 and beyond. Further, it is also seen that the performance of the V-cone flowmeter is not affected by the upstream boundary layer thickness if the velocity profiles having different boundary layer thickness are extracted from an axial distance of 10D and more are fed at 5D upstream of the meter. However, the meter is sensitive to the extracted velocity profile from an axial distance of 5D and uniform velocity profile being fed at 5D upstream. The value of C_d may be sensitive as a result of the pressure variation due to the obstruction.

1. Introduction

Flow measurement plays an important role in our day to day life as well as in many industries. There are large numbers of flow measuring instruments commercially available for different applications. From an engineering application, flow measuring instruments are selected on the basis of space available for installation, fluid being handled and the level of accuracy required. For industries involved in commercial activity, accuracy is of prime importance as it is one of the determinants of profit or loss in flow handling business. In other industries, flow rate measuring instruments are used for accurate monitoring and flow control of a process or operation of a device or machine. Conventional obstruction flow metering devices such as orifice meter, venturi meter and nozzle meter are used extensively in various fields due to their simplicity in design and low maintenance. In industries, the use of these flowmeters is restricted due to the space constraints for installation and accuracy in measurement for wide ranges of flow conditions. The concept of V-cone flowmeter was introduced in late 1980s [1] to overcome these drawbacks of conventional obstruction flowmeters. Today it is extensively being used in place of conventional flowmeters where there are space constraints and the accuracy required for flow measurement is high. The performance of the V-cone flowmeter has been studied by many researchers ever since it was introduced commercially by McCrometer [2]. Ifft et al. [3] carried out experiments using equivalent diameter ratios (β) of 0.5 and 0.75 and concluded that requirement of upstream and downstream lengths of the pipe for the V-cone flowmeter are 0 to 3D and 3 to 5D respectively whereas the conventional flowmeter requires any length above 16D depending on the upstream flow conditions. They also reported that the presence of the cone directs the high velocity fluid from the core towards the pipe wall where low velocity exists forcing flow uniformity. This phenomenon causes flattened velocity profiles just upstream of the cone element. Prabhu et al. [4] conducted experiments on cone meter and orifice meter with β-value of 0.75 in the Reynolds number range of $3x10^4$ to $5x10^4$ using water as the working fluid. They measured the pressure distribution downstream of the orifice meter and cone flowmeter in order to estimate and compare the permanent pressure loss. They also investigated the effect of inlet swirl and observed that V-cone flowmeter is less sensitive to swirl flow and the overall pressure loss for cone flowmeter is 50% less than that of the orifice meter. Erdal and Anderson [5] using CFD evaluated the performance of V-cone flowmeter and showed that the predictions using standard k-ε turbulence model have significant deviation from experimental results. Joshi [6] carried out extensive studies on V-cone flowmeter over a wide range of Reynolds number and concluded that performance of V-cone flowmeter is better under all conditions than any other obstruction type flow measuring device. Singh et al. [7] conducted an experimental study for β-values of 0.64 and 0.77 to establish the effect of Reynolds number and skewed velocity profile on the coefficient of discharge (C_d). They established that C_d was independent of inlet Reynolds number and increases with increase in skewness of the inlet velocity at 5D upstream of the cone. Weiguang Liu et al. [8] carried out a study on a dual support structure cone (DSSC) considering the safety of the cone element. They concluded that V-cone flowmeter with DSSC possess better repeatability and safety. Within the range of β-value between 0.45 and 0.65, they optimized the location of the rear support as 0.8D downstream of the cone. They further observed that if the low-pressure tapping point is placed at 0.05D downstream of the cone, linearity of the C_d with respect to the Reynolds number increases. Singh et al. [9] also used CFD to establish the effect of swirl on the performance of V-cone flowmeter. Based on the validation studies they have shown that the RNG k-ε turbulence model provides a much better flow prediction and the deviation between experimental and predicted results was less than 4%.

Ying et al.[10] carried out numerical experiments for the performance evaluation of the V-cone flowmeter using turbulence model *RNG k-ε* in the Reynolds number range of $8\text{x}10^4$ to $1.2\text{x}10^7$. They have chosen three geometrical parameters for the study. These are i) β-values (0.50, 0.65 and 0.85), ii) fore-vertex angles (40°, 45° and 50°) and iii) aft-vertex angles (120°, 130° and 140°). They have reported that the variation of C_d is an inverse function of β-values. Further they have observed that for a fixed value of 'β', the aft-vertex angle has an impact on the linearity of the coefficient of discharge up to certain extent. They have also observed that the coefficient of discharge tends to become independent of Reynolds number with increase in fore-vertex angle.

Nasiruddin et al. [11] has carried out numerical experiments to establish the effect of vertex angle and vertex tip radius on the performance of the V-cone flowmeter. They have chosen a fixed beta value (β) of 0.6 and studied different vertex angles (φ) for three modes of cone arrangement namely without support, front and rear support. The evaluation was done on the basis of coefficient of discharge (C_d) and the extent of uncertainty (U_{Cd}) present in predictions within the range of Reynolds number ($1\text{x}10^3 \leq$ Re $\leq 1\text{x}10^6$) studied. They have reported that the cone element with vertex angle of 75° gives nearly constant discharge coefficient for Re ≥ 1000 with minimum uncertainty and it is true for all the three modes of the cone arrangement. They further claimed that vertex tip radius has no effect on the performance of the V-cone flowmeter.

Nasiruddin et al.[12] have introduced a curved surface at the base of the cone to establish its effect. The study was conducted for a fixed β-value of 0.6 and three fore-vertex angles (φ) namely 60°, 75° and 90° in the Reynolds number range of $1\text{x}10^3$ to $1\text{x}10^6$ using CFD. They replaced the aft-cone with curved surface for four non-dimensionalized radii of curvature (R/d) namely 0.5 (hemispherical), 0.55, 0.625 and 0.6905. In addition, a semi-elliptical based cone with 20 mm semi-major axis and10 mm semi-minor axis has also been studied. In all the cases, the chord length is kept constant and arc length is varied gradually. The radii of the curvature were chosen so as to locate the centre of the spheres and ellipse on the axis either in the frustum or cylindrical part of the cone. They have shown that the introduction of curved surface at the cone base improves the performance of the V-cone flowmeter. Further, they have concluded that the V-cone flowmeter with curved base of R/d = 0.55 has higher C_d value and smaller standard deviation compared to a device with an aft vertex cone. Their close scrutiny also reveals that for the hemispherical and semi-elliptical based V-cone flowmeter, the coefficient of discharge is dependent on Reynolds number.

The V-cone flowmeter is a novice device among the differential pressure flowmeters and very recently it has been included in ISO-5167-5:2016 [13]. The recommendations given in ISO-5167-5:2016 for the geometrical parameters fore, aft-vertex angles and range of β-values are 52°±10°, 135°±5° and $0.45 \leq \beta \leq 0.75$ respectively for the range of flow conditions of $8\text{x}10^4 \leq Re \leq 1.2\text{x}10^7$. However, ISO-5167-5:2016 suggests calibrating all the V-cone flowmeters for their accuracy.

The literature shows that there are many flow parameters whose effect on the performance of the flowmeter has not been investigated and one of the parameters is the inlet velocity profile with varying boundary layer thickness. Secondly, the effect of Reynolds number in the lower range is also not well documented. The present study is aimed to analyse the effect of Reynolds number in the lower range and the inlet boundary layer thickness on the performance of V-cone flowmeter using CFD after establishing the most appropriate turbulence model.

2. Working Principle

The working principle of V-Cone flowmeter is similar to other types of differential pressure flowmeters. The composite cone element is placed co-axially in the pipe as shown in the figure 1. The annulus space between the cone and the pipe restricts the fluid flow and the flow separates downstream of the cone. This causes a differential pressure between the pressure tap locations upstream and downstream of the cone.

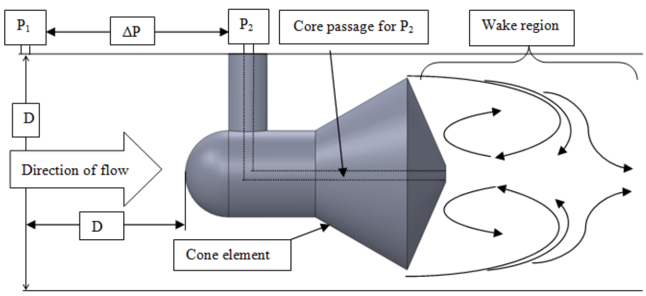

Figure 1: Schematic diagram of V-Cone flowmeter

The upstream pressure (P_1) is measured from a pressure tap fixed at 1D upstream of the cone on the pipe wall and P_2 is the pressure in the wake of the cone on the pipe axis. The calculated differential pressure (ΔP) is invoked in equation (1) to evaluate the theoretical flow rate and the actual flow rate fed at inlet allows evaluation of the value of C_d.

$$Q_{th} = \frac{1}{\sqrt{1-\beta^4}} \frac{\pi}{4}\left(D^2 - d^2\right)\sqrt{2\rho\Delta P}\ \ kg/s \ldots\ldots\ldots\ldots(1)$$

Where, β is the equivalent diameter ratio and is given by

$$\beta = \sqrt{1 - \frac{d^2}{D^2}}$$

3. Equations and mathematics

CFD has provided a platform by replacing the time consuming and cumbersome experiments for understanding any physical phenomena provided well documented data sets are available to establish the authenticity of CFD for that physical phenomena. This section describes the mathematical formulation in brief for the sake of completeness.

3.1 Governing equations

The conservation forms of mass continuity and momentum equations for steady state incompressible flow are:

$$\frac{\partial}{\partial x_i}\left(\rho \bar{u}_i\right) = S_m \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$\frac{\partial}{\partial x_j}\left(\rho \bar{u}_i \bar{u}_j\right) = -\frac{\partial P_i}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) .(3)$$

Where S_m is the source term, P_i is the static pressure, ρg_i is the body force per unit volume due to gravity and F_i is the external body force. The term τ_{ij} represents the stress tensor. The Reynolds stress terms $\left(-\rho\overline{u_i' u_j'}\right)$ need to be modelled to have closed form solution. Boussinesq hypothesis relates the Reynolds stresses to the mean velocity gradient using proportionality constant $\frac{\mu_t}{\rho}$.

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\left(\rho k + \mu_t \frac{\partial \bar{u}_i}{\partial x_i}\right) \ldots\ldots(4)$$

In the equation (4), k is the turbulent kinetic energy and μ_t is the turbulent viscosity. Various two equation turbulence models have been proposed by researchers to get the closure solution. None of the turbulence model is universally applicable to all type of flows. As the flow across the V-cone is highly turbulent and separated, different two equation turbulence models have been tried for closure solution and it was found that SST k-ω turbulence model predicts the performance reasonably well.

3.2 Turbulence model

The two equation SST k-ω turbulence model has been adopted for the closure solution based on the recommendation of [11, 12]. Mentor [14] developed this model with effective and accurate blending of the k-ω model for near wall region and k-ε model in the free stream zone. Thus, the flow statistics at near wall as well as in the far field are captured effectively. The kinetic energy and specific dissipation equations of SST k-ω turbulence model are:

$$\frac{\partial}{\partial x_i}\left(\rho k \bar{u}_i\right) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + \tilde{G}_k - Y_k + S_k \ldots\ldots\ldots\ldots(5)$$

$$\frac{\partial}{\partial x_j}\left(\rho \omega \bar{u}_j\right) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + S_\omega + D_\omega \ldots..(6)$$

$\tilde{G}_k$ represents generation of turbulent kinetic energy (k) due to mean velocity gradient, G_ω represents the generation of vorticity/specific dissipation (ω). Γ_k and Γ_ω represent effective diffusivity of k and ω respectively. Y_k , Y_ω are the dissipation of k and ω due to turbulence. S_k , S_ω are user defined source terms. D_ω is cross-diffusion term. The details of these terms are given in Fluent Manual [15].

4. Validation

Numerically obtained results are acceptable if these have been validated against experimental results for similar geometries. Validation against experimental results also helps in evaluating the most appropriate turbulence model for closure solution as there is no universal turbulence model to predict all types of flow. The author has carried out the validation study [16] after reproducing the experimental set up and flow conditions of [7] considering all two equation turbulence models. He has found that the simulation results using SST k-ω turbulence model matched well with the experimental findings of Singh et al. [7] with a deviation in mean value of C_d being 3.1% only. However, the variation in mean value of coefficient of discharge obtained from RNG and Realizable k-ε turbulence model was lower than SST k-ω turbulence model for the range of flow conditions adopted in the experiments. To examine this further, the flow conditions were simulated extending it up to laminar and transition flow regime. The result revealed an interesting observation that the performance of both RNG and Realizable k-ε turbulence model was poor at lower Reynolds number (Re ≤ 4000) and the coefficient of discharge became dependent on Reynolds number. Whereas, SST k-ω turbulence model showed consistency in the result over the entire ranges of flow conditions (from laminar to turbulence). Thus, SST k-ω turbulence model was chosen as the appropriate turbulence model for simulating the present work.

5. Details of geometrical parameters studied

Flow predictions are carried out to study the effect of boundary layer thickness on the performance of V-cone flowmeter for two β-values namely 0.6 and 0.7 with fixed vertex angle of 60° in the Reynolds number range of 500 to 500000. The V-cone is mounted coaxially in a circular pipe of diameter 50 mm. The maximum cone diameters for the two values of β are 40 mm and 37.5 mm respectively. No supporting struts were simulated as the pressure tap holder is strong enough to hold the cone element [9]. The computational domain is chosen as 5D and 30D long in the upstream and downstream regions of the V-cone respectively. In order to nullify the constraining effects of outlet boundary condition on cone element, the downstream length is kept reasonably long. The 3D cone element has been modelled using SolidWorks-2014 [17] software and imported in Ansys 15.0 DesignModeler [15] where the rest of the geometry was modelled. The cone element and related parameters are shown in figure 2. After the modelling, the mesh generation for the computational flow domain is carried out. Grid generation is the most important part of simulation work as it determines the level of accuracy in the results. Fine grids are required in the flow domain where high velocity gradients exist and reasonably coarse grids can be applied to the regions with smooth flow condition. On the pipe and cone wall boundaries inflation layers were generated in order to produce fine meshes for capturing the steep velocity gradient. Grid refinement leads to better accuracy but it also increases the cost of simulation in terms of CPU hours. However, a reasonable grid resolution is required for the flow simulation to achieve the acceptable accuracy level in results.

Grid independence checks were carried out in order to reach to a state after which the results do not change significantly with further refinement of the grids. To study grid independence, nine different sizes of mesh elements were chosen. The value of C_d at Reynolds numbers of $2.18x10^5$ has been calculated for each mesh size. The optimum number of mesh elements for rough pipe was determined as$13.31x10^5$ because further refinement of the grid resulted in insignificant changes in C_d value. Grids consist of mixed tetrahedron and hexahedron elements which were converted into polyhedral cells in Fluent [15]. This conversion into polyhedral mesh reduces the cell counts to one-third and the solutions get converged within 5000 iterations. The same sizes grids are used for the present study. The boundary conditions are velocity-inlet, pressure outlet as zero-gauge pressure and pipe and cone surfaces as wall with roughness height of 0.5 mm and roughness constant of 0.5. Turbulent intensity and hydraulic diameter are calculated from the relations $I=0.16 \text{ x } (Re)^{-0.125}$ and H=4A/P where A is cross-sectional area of the pipe and P is wetted perimeter. A total of 160 converged runs are conducted.

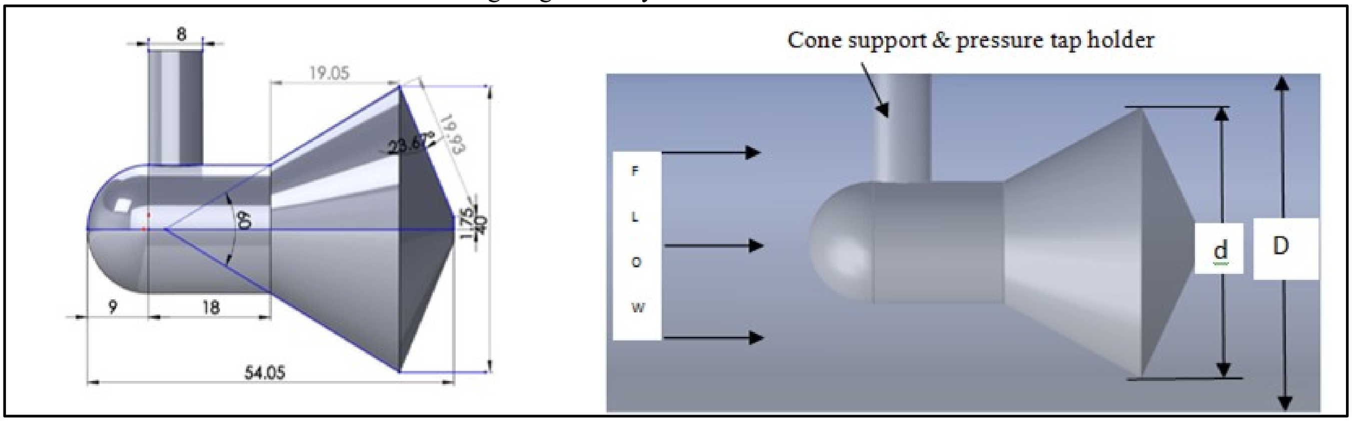

Figure 2: Geometrical details of one of the V-cone flowmeters with beta ratio 0.6 and vertex angle 60° used for present study (All dimensions are in 'mm').

6. Results and discussions

The present numerical study reports the effect of Reynolds number and boundary layer thickness on the performance of front supported V-cone flowmeter. Prior to carrying out simulations for the cone flowmeter with different velocity profiles being fed at 5D upstream of the cone, it was essential to generate the different velocity profiles.

6.1 Inlet velocity profiles

Two flow simulations were done in pipe separately, one in a straight pipe of length 60D and another in 83D long pipe with a V-cone coaxially placed at an axial distance of 60D from inlet. For both the cases, a uniform velocity profile of same magnitude was fed at the inlet to establish if there was any effect of obstruction on the velocity profiles in the pipe. Fig. 3 gives the comparison of velocity profiles at 50D axial distance from inlet for the two cases. From the figure it is seen that the presence of V-cone has a tendency to flatten the velocity just before the cone. This implies that any

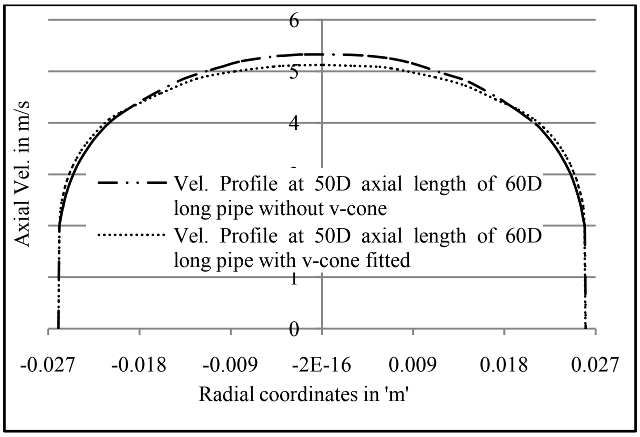

Figure 3: Comparision of velocity profiles for pipe flow simulation with and without V-cone fitted.

velocity profile fed at any distance from the cone will have a tendency to flatten the velocity profile before the cone. After establishing this effect, in the present study, two pipe simulations were carried out for the range of Reynolds number considered. One was straight pipe from where the velocity profiles at different axial distances namely 05D, 10D, 20D, 30D, 40D, 50D and 60D were extracted. The another pipe fitted with V-cone was simulated after feeding these extracted velocity profiles at the inlet (5D upstream of the cone). In addition, simulations are also done for uniform flow. Feeding different velocity profiles helps to establish the effect of the boundary layer thickness on the value of C_d without increasing the actual domain length.

6.2 Results with β=0.6

The effect of boundary layer thickness on the performance of the V-cone flowmeter has been investigated by feeding the extracted velocity profiles at 5D upstream of the cone. Fig.4a gives the variation of coefficient of discharge as a function of Reynolds number. The study reveals that the value of C_d is nearly constant if uniform velocity is fed at 5D upstream of the V-cone for Reynolds number greater than 1000 with deviation of ± 0.32% from the mean value (C_d= 0.7839). Fig 4a also gives the variation of C_d for different extracted velocity profiles. For 5D extracted velocity profile the C_d value increases linearly upto Reynolds number of 4000 and beyond 4000 the values of C_d are nearly constant and has an average value of 0.7161 with ±0.76 % deviation. For 10D extracted profile the variation of C_d is oscillatory upto Re value of 2500 and C_d becomes weak function of Re in the range of 2500 to 20,000 and then it is nearly constant. Treating the value of C_d as constant beyond Re=4000, the average value of C_d is 0.6912 with ±0.85% deviation. The value of C_d's for other extracted velocities being fed at 5D also follow the similar trend beyond Re=4000. The average values of C_d 's are given in Table 1 along with deviations. The mean values of C_d reduces continuously upto 20D extracted velocity beyond which it increases back and is nearly constant for extracted velocity of 30D and beyond. Further, if the Reynolds number is greater than 4000 we can conclude that C_d is independent of Re and is not affected by the boundary layer thickness upstream of the cone (for the velocity profile 10D and beyond). The value of C_d is sensitive to the uniform velocity and 5D extracted velocity due to the pressure variation as a result of the obstruction.

6.3 Results with β=0.7

The effects of boundary layer thickness on discharge coefficient for V-cone configuration with beta value of 0.7 is shown in Fig. 5a. The variation in C_d is seen to be nearly same as β=0.6. The average value of C_d beyond 4000 for different extracted velocity profiles along with deviations are also given in Table 1. Feeding uniform velocity at 5D upstream of the V-cone results show linear variation in C_d with Reynolds number upto 4000 thereafter the value of C_d is nearly constant (C_d=0.7906) with ± 0.44% deviation from mean value. For all extracted velocity profiles fed (at inlet i.e. 5D upstream of the cone), the value of C_d increases linearly upto Reynolds number 2500 and this linear increase shows a strong dependence on Reynolds number in the laminar range. The linear increase in C_d beyond Reynolds number 2500 and upto 20000 shows weak dependence on Reynolds number. Neglecting this weak dependency for 5D extracted profile fed at the inlet, one can treat the value of C_d is nearly constant for Re=4000 and beyond with an average value of 0.725 and ±0.67 % deviation. For other extracted velocity profiles the trend looks to be similar to the cone cofiguration of β=0.6.

Close scrutiny of the results given in Table 1, show that for extracted velocity profiles from 10D onwards and fed at 5D upstream of the cone, the mean value of discharge coefficient is nearly same for all allextracted velocity profiles. Hence a mean value for extacted velocity profiles can be taken. This value for β=0.6 is 0.6904 whereas it is 0.6959 for β=0.7. The respective adjusted standard deviations are ±0.0040 and ± 0.0039. The deviations of the mean C_d value for each extracted velocity profile from the mean C_d value taking all the extracted velocity profiles are plotted in figure 4b (for β=0.6) and 5b (for β=0.7) with 2% error bar. From the analysis it can be concluded that the effect of boundary layer thickness on discharge coeficient is neglgible except for uniform velocity profile and extracted 5D velocity profile. Further, the C_d values for both the β-ratios of 0.6 (0.7839) and 0.7 (0.7906) for uniform velocity fed at 5D upstream of the cone lie within ±5% of the C_d value (0.82) given in ISO-5167-5:2016.

Table 1: Values of Mean C_d for Re ≥4000 and its % deviation for β=0.6&0.7

Velocity Profile Extracted from the pipe flow without V-cone fitted	Velocity Profile fed at 5D upstream of the V-cone	Mean C_d and % deviation for β=0.6		Mean C_d and % deviation for β=0.7	
		Mean C_d	% Deviation	Mean C_d	% Deviation
NIL	Uniform Velocity	0.7839	0.32	0.7906	0.44
05D	Extracted Velocity Profiles	0.7161	0.76	0.7217	0.67
10D		0.6912	0.85	0.6964	0.76
20D		0.6825	0.66	0.6882	0.55
30D		0.6907	0.98	0.6964	0.86
40D		0.6932	1.06	0.6986	0.94
50D		0.6925	1.07	0.6980	0.95
60D		0.6925	1.04	0.6977	0.92

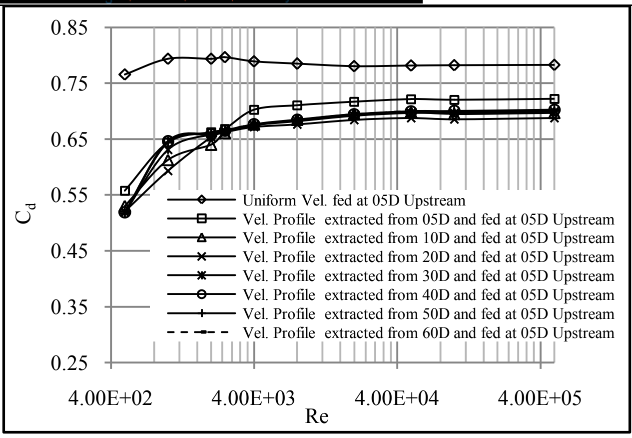

Figure 4a: Variation of C_d with Re for β=0.6 & φ=60°

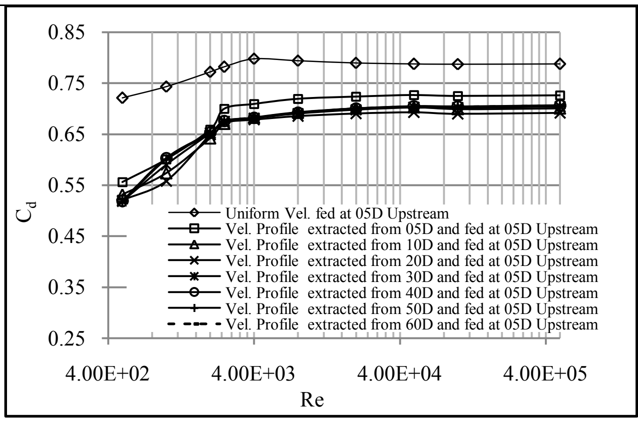

Figure 5a: Variation of C_d with Re for β=0.7 & φ=60°

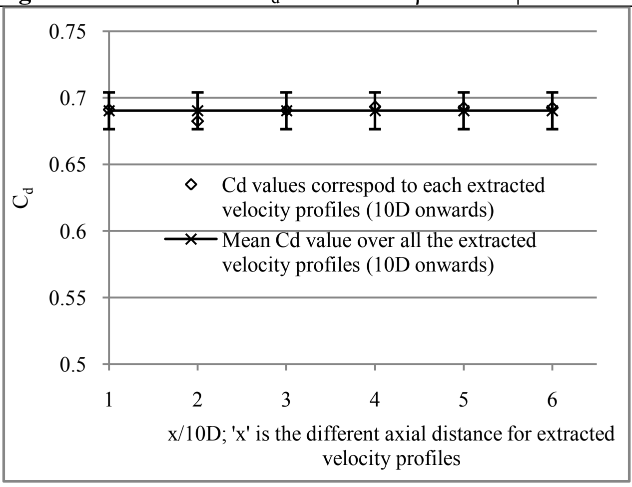

Figure 4b: C_d value for different extracted profiles with ±2% error bar (β=0.6& φ=60°) for Re ≥ 4000

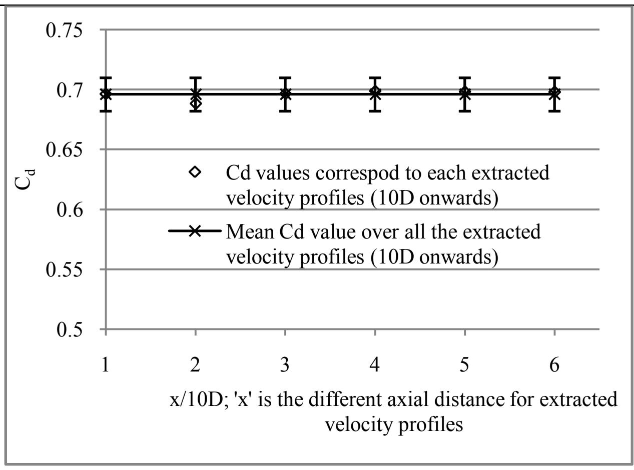

Figure 5b: C_d value for different extracted profiles with ±2% error bar (β=0.7 & φ=60°) for Re ≥ 4000

7. Conclusions

On the basis of the results obtained the following observations are enumerated.

1. For the chosen β-values of 0.6 and 0.7, the coefficient of discharge is linearly dependent on Reynolds number in the laminar and transition regimes. The C_d value is nearly constant for turbulent flow regime beyond Reynolds number of 4000.

2. The performance of the V-cone flowmeter is not affected by the boundary layer thickness except for the uniform flow and 5D extracted velocity profile (negligible boundary layer thickness) which were fed at 5D upstream of the meter. For the uniform flow fed, the deviation is around 14%. Whereas, feeding the boundary layer thickness formed due to 5D extracted profile, at the inlet the deviation is less than 4%. This is true for both the β-values.

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