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Impacts of Short Tube Orifice Flow and Geometrical Parameters on Flow Discharge Coefficient Characteristics

M. Metwally

Lecturer, Ph.D., MTC, Cairo, Egypt

Abstract

Modern offset printing machine, paper folding machines and printing application machines require high dynamic performance actuators to achieve the printing job. The electro-operated pneumatic directional control valve that used in synchronization of feeding paper drums in the offset printing machines are carefully design.

Most of these control valves contain short tube orifices. Their discharge flow coefficient is a sensitive design parameter. In this paper, the discharge flow coefficient of short tube orifice has been investigated numerically. Different short tube orifice geometrical parameters and different flow conditions have been studied to determine their influence on the discharge coefficient.

The studied Reynolds number rage is of 500 to 2000 and the orifice diameter to pipe diameter is of range from 0.6 to 0.9 and the short tube orifice length is from 0.25 to 1. The numerical simulation has been carried out using a commercial CFD package, namely Fluent, for the studied conditions.

The numerical results of the discharge coefficient have been correlated with to the operating flow and geometrical conditions. It has been shown that the discharge flow coefficients were depending on Reynolds's number and the short tube orifice geometrical parameters ratios.

Keywords

CFD, short tube orifice, discharge flow coefficient

1. Introduction

Modern offset printing machine, paper folding machines and printing application machines require high dynamic performance actuators to achieve the printing job. Consequently, it is important to have linear, fast accurate response, as well as, low friction and mechanical impedance actuators. Traditional geared electrical motors cannot provide these characteristics. Direct drive actuators is not appropriate for the activation time synchronization. Yet, applications such as feeding paper mechanism require a special timing map combined with static high force output to hold the paper with the required force for the appreciated time.

Pneumatic actuators can offer a superior alternative to electrical and hydraulic ones for this type of application due to clean, safe and easier to work with. However, position and timing control of these actuators in applications that require high precision is often difficult. This is mainly due to air compressibility and high nonlinearity in the flows through pneumatic system components. The valve selection to a specific application is not only depend on the valve function ports, method of operation and control but also on the internal construction of the valve which has a great effect on the valve dynamic response.

The air mass flow rate in the pneumatic valve air system is affected and controlled by the valve loss which could be considered as a short tube orifice between moving and fixed components. Consequently, the short tube orifice has to be metered to enhance the valve performance and the actuator life. A typical pneumatic control valve is shown in Fig.1. A discharge flow coefficient of the short tube orifices has been studied as one of the main sources to control the air flow in the pneumatic valves.

On the other hand, for economy reasons, short tube orifices are widely used, especially as fixed restrictors in the flow passages. The fluid flow through a short tube orifice is subjected to the friction losses as well as the minor losses at inlet and outlet. Therefore, these orifices are viscosity- dependent. The discharge coefficient of a short tube orifice depends on the Reynolds number and the orifice geometry. The following expressions are widely used to calculate the discharge coefficient for the turbulent and laminar for incompressible fluid [4].

The air mass flow rate through thick plate orifices with different approaching profiles as perpendicular or inclined flow relative to the orifice axis has been experimentally investigated in [1]. Analytical predictions and experimental studies were made of the coolant flow and pressure distributions in a transpiration-cooled vane [2]. The effect of manifold cross-flow on the discharge coefficient and cavitation characteristics of sharp-edged orifices over a wide range of flow-rates, back-pressures and cross-flow velocities was studied [3].

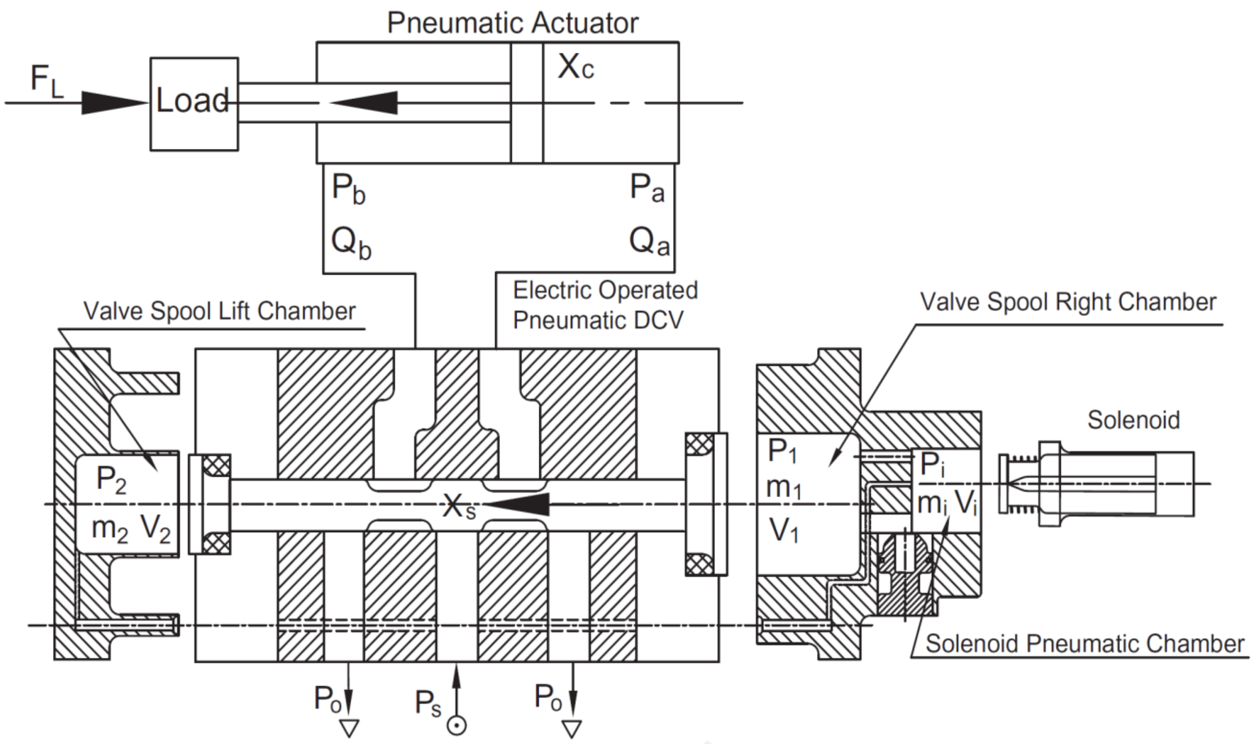

Fig.1. Schematic drawing of the studied pneumatic system.

$$C_d = \left[1.5 + 13.74\left(\frac{L}{Re\ d}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}} \quad \text{for } \frac{Re\ d}{L} > 50$$
$$C_d = \left[2.28 + \frac{64\ L}{Re\ d}\right]^{\frac{1}{2}} \quad \text{for } \frac{Re\ d}{L} < 50 \qquad (1)$$

Calculation process for incompressible static orifice flow is summarized from different sources. Two pressure correction algorithms are compared with measurements and an algorithm based on is subsequently applied. The impact of boundary layer pumping for a rotating disk and cross-flow on rounded inlet orifices is correlated [6]. The understanding of discharge coefficient performance at very small Reynolds numbers has been performed in this area for the Venturi, standard orifice plate, V-cone, and wedge flow meters using (CFD) FLUENT program [7].

A method to determine the flow rate characteristic parameters was directly obtained by using an integral algorithm. The pneumatic components flow rate was characterized by pressure response and flow rate at isothermal process [8].

Different factors of uncertainty that affecting flow rate measurements are discussed with precautionary measures [9].

In this paper; the discharge flow coefficient through short tube orifice with approaching profile parallel to the orifice axis has been conducted numerically. Different flow and geometrical parameters have been investigated through 3-D models to show the effect of flow and geometrical parameters. These parameters include the effect of Reynolds' number, orifice diameter, orifice length, pipe diameter and back-pressures. Effects of the short tube inlet shape (sharp or rounded edge) are considered in these models. A commercial CFD package, FLUENT, has been used to model flow discharge coefficient of the short tube orifice at different flow and geometrical parameters as shown in Fig 2.

2. Modeling of Short Tube Orifice

The production costs of sharp edged orifices with a ratio of L/d are lower than those of well rounded nozzles, the approach to model flow reduction caused by contraction and losses can be combined to model this kind of restriction. A mass flow passing through a sharp tube orifice concentric to the flow direction can be calculated theoretically based on a derived gas dynamic equation, the local total and static flow conditions, as well as some gas properties as used in Eq.(1):

$$\dot{m} = A\,.\,C_d\,.\,\vartheta\,.\,p_1.\sqrt{\frac{2}{R.T_1}} \qquad (2)$$

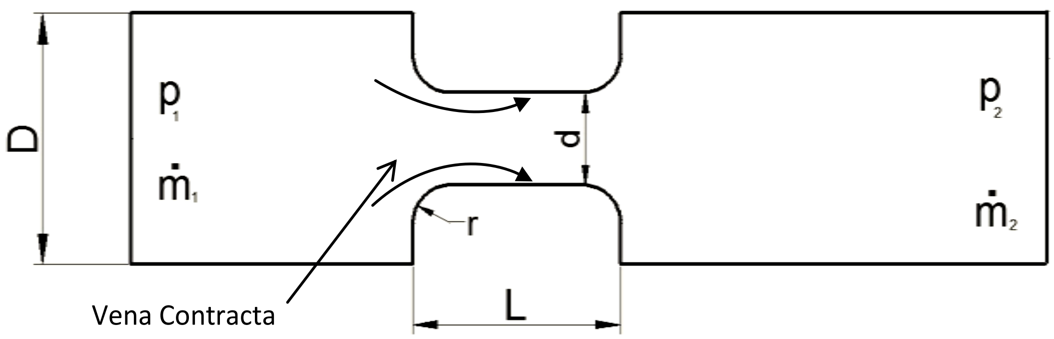

Fig. 2. Short tube orifice geometric and flow parameters

$$\vartheta = \begin{cases} \sqrt{\frac{\gamma}{\gamma-1}\left[\left(\frac{p_2}{p_1}\right)^{2/\gamma} - \left(\frac{p_2}{p_1}\right)^{(\gamma+1)/\gamma}\right]} & \text{for } \frac{p_2}{p_1} > 0.528 \\ \left(\frac{2}{\gamma+1}\right)^{1/\gamma-1}\sqrt{\frac{\gamma}{\gamma+1}} & \text{for } \frac{p_2}{p_1} \leq 0.528 \end{cases} \quad (3)$$

The flow function ϑ = f (p2 , p1) , the maximum of the flow function is (0.484) at critical pressure ratio $^{p_1}/_{p_2} = \left(\frac{\gamma+1}{2}\right)^{(\gamma/_{\gamma-1})}$ where choking occurs.

The flow through a short tube orifice connecting two larger diameter pipes can be represented as the flow through a cross section. Due to the inlet separation from acceleration at the entrance of the orifice, the vena contracta is appeared where the area of the flow is smaller than the orifice geometric area as shown in Fig. 2.

Appearing total conditions in the vena contracta (flow area with parallel flow) are similar to the upstream conditions (p1) and the static pressure is similar to the downstream pressure (p2). Thus the definition of the discharge coefficient is the ratio between the actual and ideal mass flow through the geometrical area:

$$C_d = \frac{\dot{m}}{\dot{m}_i} \quad (4)$$

$$\dot{m}_i = \frac{p_{01}.\ A}{\sqrt{R\ .T_{01}}} \cdot \sqrt{\frac{2.\gamma}{\gamma-1} \cdot \left[\left(\frac{p_2}{p_{01}}\right)^{2/\gamma} - \left(\frac{p_2}{p_{01}}\right)^{(\gamma+1)/\gamma}\right]} \quad (5)$$

At the vena contracta (minimum flow area), the discharge coefficient is calculated based on upstream and downstream conditions as:

$$\dot{m} = f(C_d,\ R_e,\ p_{01}, p_2, T_{01}, A)$$

Discharge coefficient of the short tube orifice is affected by different factors as:

- Re number, that effects on the boundary layer.
- Inlet and outlet shape, that effects on the flow pattern.
- Short tube orifice cross sectional shape (round, rectangular, etc.)
- Orifice length and diameter to pipe diameter ratio, that effect on the flow pattern.
- Pressure ratio, that effects on Ma number (chock flow) and compressibility.
- Flow direction at the inlet and outlet, that effects on the flow pattern.

3. Results and Discussions

The discharge coefficient in this work is presented as a function of flow parameters (Re) at different geometrical parameters (d/D, L/D and r/D). The results are obtained from the theoretical study by modelling the different models with wide variation of geometrical.

A commercial computer package named (Fluent) is use to solve the computational fluid dynamic (CFD) models of short tube orifice at different (Re). Where the models are tested and found that they are number of nodes independent.

Fig. 3 shows the discharge coefficient as a function of short tube orifice length (L/D). The discharge coefficient at (Re=500, 1000) are almost identical at different (L/D) for different (d/D). The discharge coefficients at (Re=1500, 2000) have the same behavior by shift about 5% but this percentage increase by increase of diameter ratio (d/D). Figs 3 show that the discharge coefficient are decrease with increase of (L/D) because the increase of flow resistance. The critical design parameters are at (L/D = 0.5 to 0.6) and (d/D = 0.8) as shown in fig. 3 C.

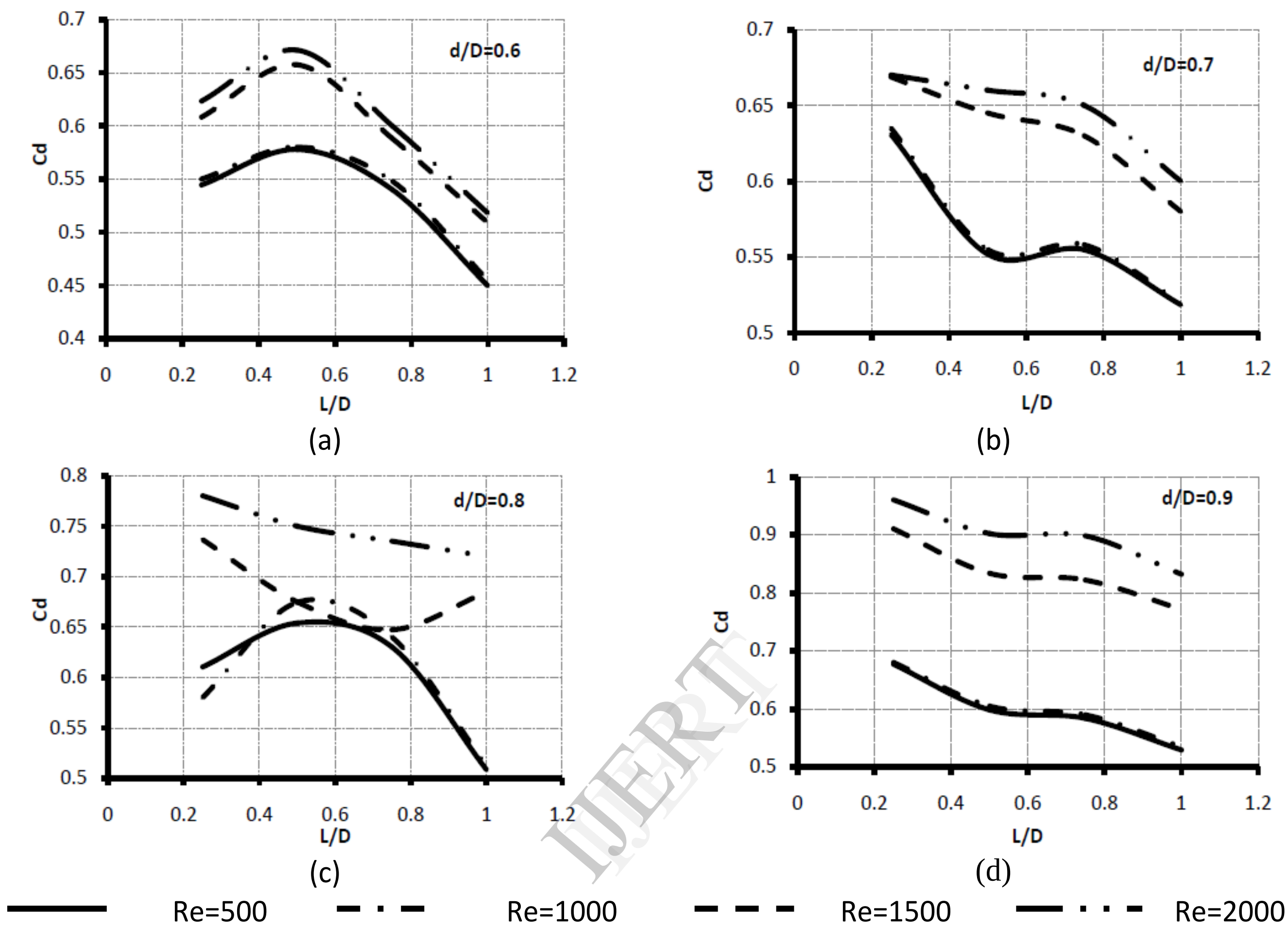

Fig. 3. Discharge flow coefficient for different Reynolds' number, plotting for different (L/D).

Fig. 4 illustrates the discharge coefficient various with the change of diameter ratio (d/D) at different (Re) and (L/D). The discharge coefficient at (Re=1500, 2000) increase with increase of diameter ratio (d/D) at different (L/D). A divergence in discharge coefficients values increase with at diameter ratio (d/D=1) and it seems very close in values at (d/D= 0.6).

Geometrical change effects on the discharge coefficient at different Reynold's number are shown in fig.5. The discharge coefficients have the same behavior at (Re=500, 1000) as shown in figs. 5 (a, b). The contours of discharge coefficient for diameter ratio (d/D=0.6, 0.8) have the behavior with difference about 25% for (Re=500) decrease with increase in (Re=1000) to about 15%.

The difference between the contours of discharge coefficient for diameter ratio (d/D=0.7, 0.9) are changed from 10% to 50% proportionally with Re.

The variation of the (Re) change the flow pattern inside the short tube orifice and pressure inlet/outlet variations which of course effect on the discharge coefficients. The effects of rounded inlet of short tube orifice on the discharge coefficients are shown in fig. 6. The higher value of discharge coefficients are at the sharp ended that for the vortices generated at the sharp edge at the inlet of short tube orifice. The minimum discharge coefficients for different (Re) are at inlet rounded (r/D =0.05) where the minimum vortices created.

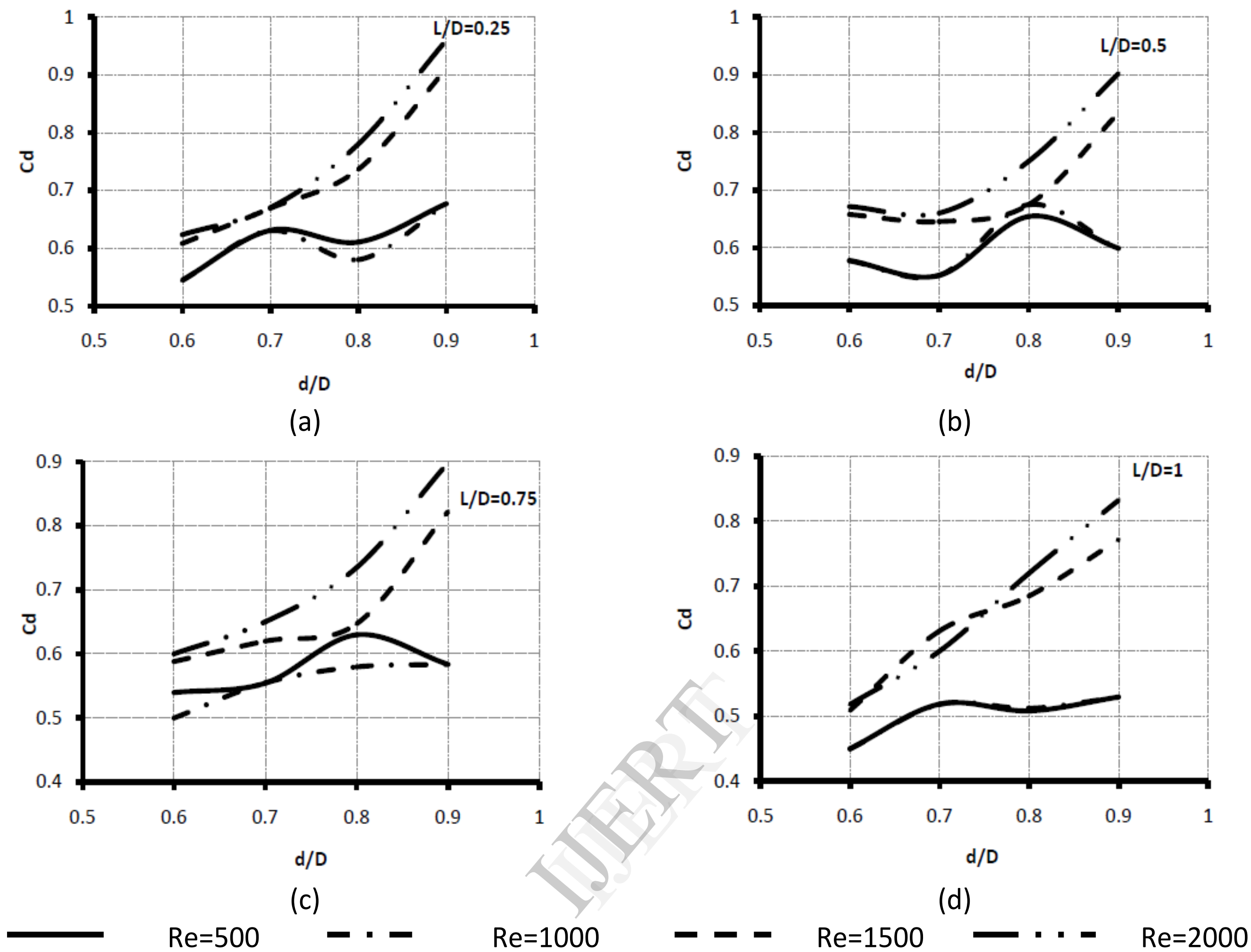

Fig. 4. Discharge flow coefficient for different Reynolds' number, plotting for different (d/D).

The maximum difference between (Cd) reaches to 50% between (Re=1000 and Re=2000) at (r/D=0.05) where the minimum difference appears at (r/D=0.08) except at (Re=500). This variation can be explained by the change of flow pattern inside the short tube orifice with the change from sharp edge to different fillet radius end of the tube.

The effect of short tube orifice length on the discharge coefficients for rounded inlet orifice at (r/D=0.075) and diameter (d/D=0.6) are shown in fig. 7. The maximum difference between (Cd) reaches to 30% between (Re=500 and Re=2000) at (L/D=0.75) where the minimum difference appears at (L/D=0.25) except at (Re=500).

This variation can be explained, if one considers the relative motion of the vena contracta with the change in (L/D).

The discharge coefficient contours for different diameter ratio and length ratio at different (Re) has plotted in fig. 8. It has shown that the discharge coefficient have the highest values at (d/D=0.8) however the maximum values for all length ration (L/D) are at (Re=2000) and diameter ratio (d/D=0.6). The difference reaches it maximum values about (40%) between the (L/D=0.25 and 1). These variations in values are due to the increase of flow resistance which effects on the discharge coefficient.

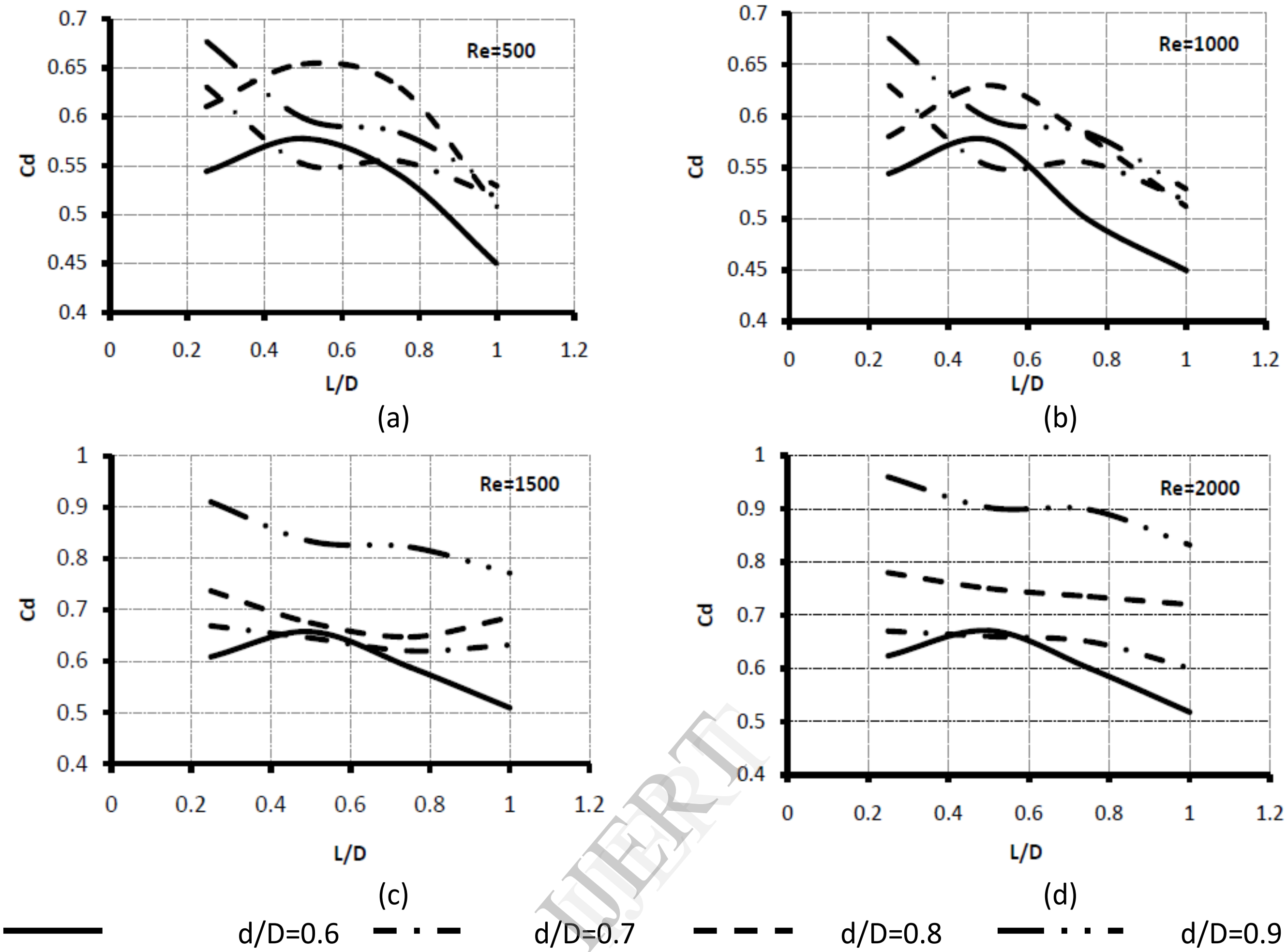

Fig.5. Geometrical change effects on the discharge coefficient at different Re.

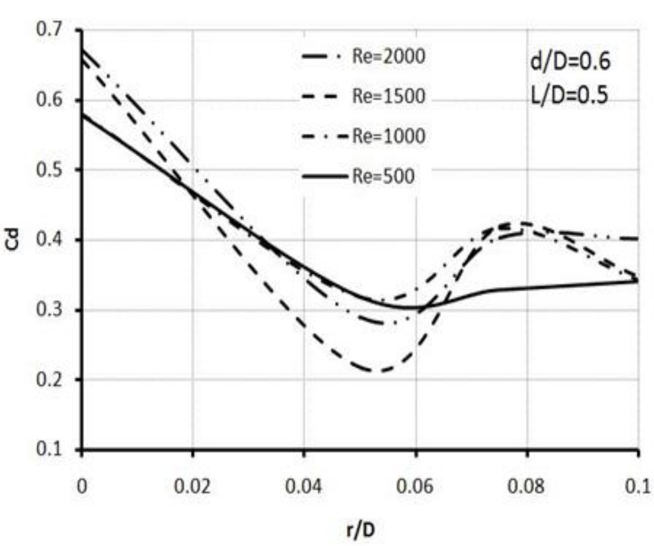

Fig. 6. Effect of inlet radius of short tube orifice on discharge coefficient.

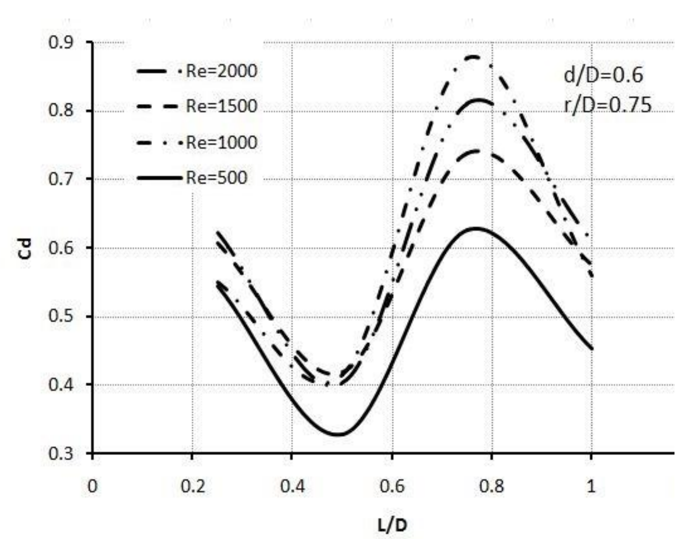

Fig. 7. Effect of short tube orifice length on discharge coefficient for rounded inlet.

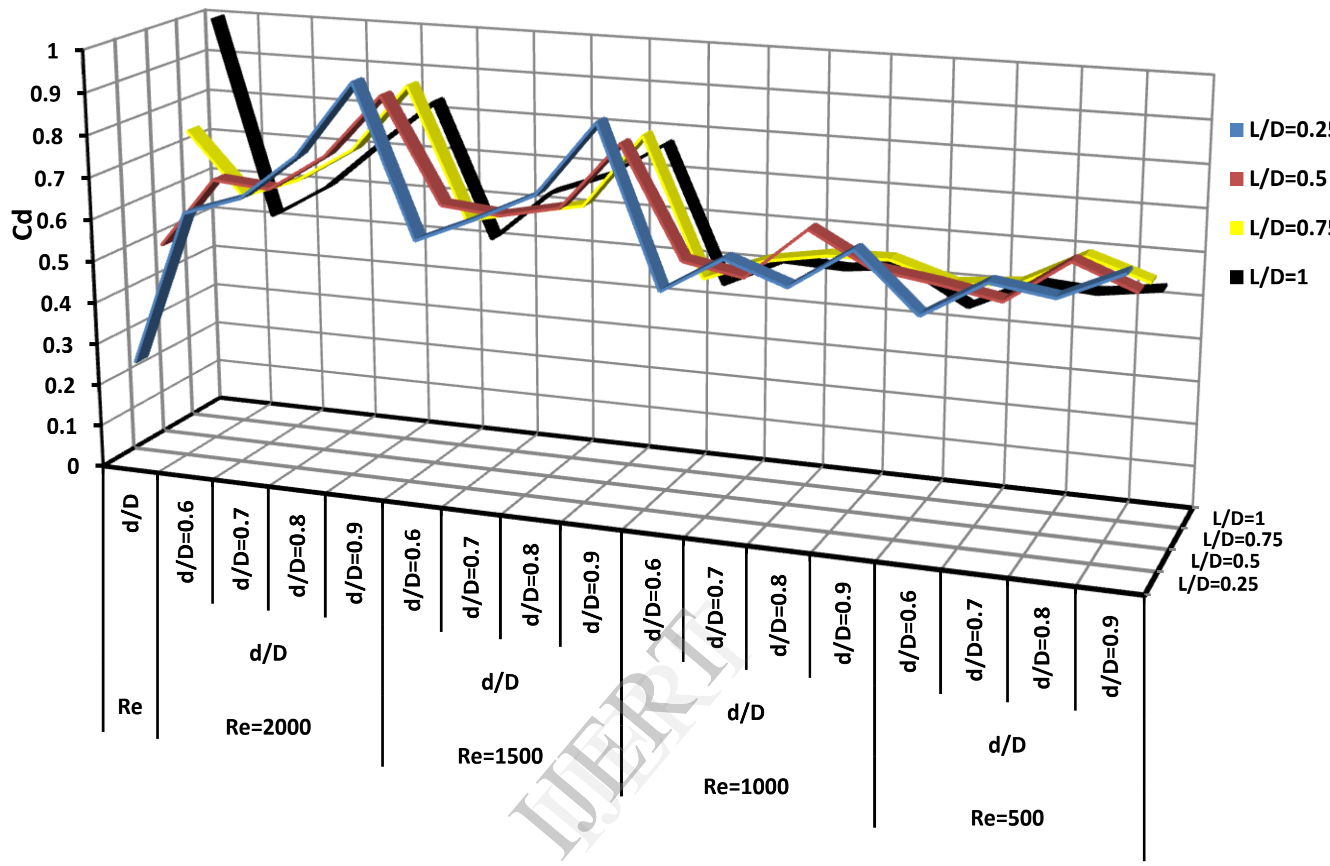

Fig. 8. Discharge coefficient at different geometrical parameters and Reynold's numbers.

4. Summery and Conclusions

The present publication starts with introduction of the theory and definitions of discharge coefficients Cd. Several items, especially geometric parameters, which impact these Cd values, are summarized. These variations were obtained at different Reynolds number. The studied Reynolds number rage is of 500 to 2000 and the orifice diameter to pipe diameter is of range from 0.6 to 0.9 and the short tube orifice length is from 0.25 to 1. The numerical simulation has been carried out using a commercial CFD package, namely Fluent, for the studied conditions.

The models are tested and found that they are number of nodes independent. It has been found that the main factors effects on the discharge coefficient are the geometrical parameters and Re. Some geometrical parameters are a critical design value impacts on the Cd. The effect of rounded end of short tube orifice has a great effect on the discharge coefficient. The vortices generated due to the effect of rounded edge orifice impacts to the great extend on Cd. The flow pattern inside the tube effect to great extend in the discharge coefficient by changing the Re in the mathematical model.

Nomenclature

A = cross-sectional area (m2).
Cd= discharge coefficient
(actual mass flow/ideal mass flow).
d = short tube orifice diameter (m).
D = main pipe diameter (m).
L = length of short tube orifice (m)
$\dot{m}$ = mass flow rate (kg/s).
p = Pressure (Pa)
r = radius at inlet corner (m).
R = specific gas constant (J /kg K).
Re= Reynold's Number.
T = temperature (K).
γ = isentropic exponent.
ϑ = flow function.

Subscript

1 = upstream.
2 = downstream.
i = ideal.
0 = stagnation.
s= supply.

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