

FLUID FLOW BEHAVIOR AND DISTRIBUTION IN PERFORATED TUBES

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ABSTRACT

Perforated tubes play a vital role in nuclear reactors. The flow coming out of the perforation has special significance with the process involved in the system. As example, perforated sparger tubes are used for filling and circulating moderator in the calandria of earlier generation PHWRs in India. Perforated tubes are used for profile matching with the heat generation pattern in the moderator. In the poison injection system and in the primary shut down system, perforated tubes are used with perforations made to match certain design requirements. Perforated tubes have numerous engineering applications. Present paper is about the mathematical approach to predict the flow pattern from perforated tubes.

INTRODUCTION

The design of perforated tube for achieving desired flow distribution, involves arriving at the size of the holes and its spacing along the length and circumference. In case of spargers introduced in Indian PHWRs, the design is validated by rigorous experimentation. For sparger tubes, the size and location of holes were arrived based on series of experiments in a full-scale test facility. The size and location of holes were arrived based on series of mockup trial in a full-scale test facility, aimed to carry out study of flow pattern and hydraulic resistances to optimize the flow pattern from the sparger tube [1], [2]. The emergency core cooling injection in the new generation reactor under design (Advanced Heavy Water Reactor AHWR) is through perforated tubes [3], [4], [5].

In view of large-scale use of perforated tube as in-core components in the reactors, it becomes important to study outflow pattern through perforated tubes. Though solving 3-D Navier Stokes equations by computational methods, out-flow pattern can be predicted for given perforated tube. But, if some flow pattern is needed and perforated tube is to be designed to meet the requirement, computational fluid dynamics (CFD) method cannot be directly used. CFD methods can predict flow when geometry is known, but cannot easily configure the geometry for a given flow.

So it becomes important to develop simplified theories to study out-flow pattern and predict perforations (hole size and pitch variations with length) needed for the desired flow pattern. A theoretical model is developed based on physics of flow behavior through perforated tubes. Analytical method discussed in this paper is capable of arriving at the design of perforated tubes that can achieve the end objective.

The paper is about the mathematical approach to predict the flow pattern from perforated tubes. The study is divided in two parts. In first part steady state flow profile is considered in which inlet flow velocity into the perforated tube is not varying with time. A simplified model is made by conservation of mass and momentum of fluid and resulting non linear differential equation is solved analytically. In mass balance equation fluid is treated as incompressible fluid. In momentum balance equation, assumption is that flow in pipe is approximated as one dimensional flow (means total momentum over cross-section area is balanced) as L/D ratio is high. Loss coefficient is taken to model pressure losses in perforated holes. After some rearrangements and substitutions, a second order nonlinear differential equation is obtained in velocity as a dependent variable. General solution of this differential equation is obtained. After putting the appropriate boundary conditions, one arrives at flow pattern. Some non-dimensional parameters are identified from governing equation, which play important role in understanding of flow pattern behavior. Effect of variation of these non-dimensional parameters on flow pattern is also discussed.

In the second part, perforated tube design for some desired flow pattern is derived, which is very useful for practical applications. In this regard presented theory has upper hand compare to CFD methods. CFD methods can predict flow when geometry is known, but cannot easily configure the geometry for a given flow.

Theoretical model presented can be used for estimating the flow profile for existing tubes. The paper also presents discussion on effects of various geometrical parameters, on flow pattern.

STEADY STATE FLOW PROFILE

For the steady state flow in a pipe, main assumptions of formulation are: Input velocity in the tube is constant with time and fluid is incompressible. Another assumption is that in momentum equation, flow in pipe is approximated as one dimension flow (means total momentum over cross-section area is balanced) as L/D ratio is high.

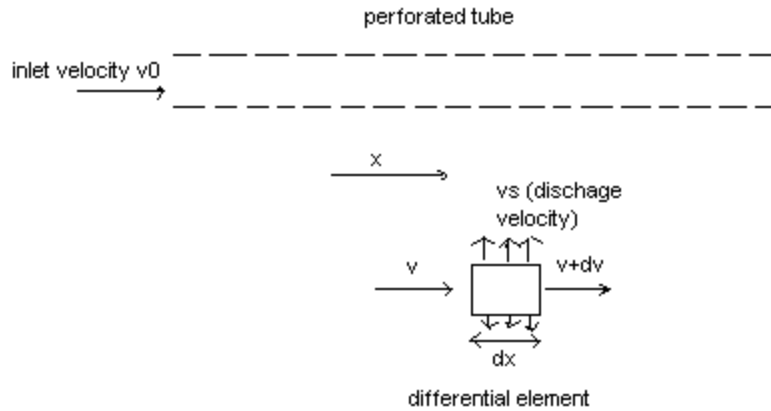


Fig. 1 Simplified illustration of a perforated tube

The detailed steps to arrive at specific equations are presented below.

Mass balance equation:

Let water flow rate from periphery of perforated tube be $v_s \times Pdx$ from small element of the pipe dx
 Continuity equation can be written as

$$v_s Pdx = - \frac{d}{dx} (Av) dx \quad \dots(1)$$

$$v_s = - \left(\frac{A}{P} \right) \frac{dv}{dx} \quad \dots(2)$$

Where, v_s = velocity of fluid coming out along the periphery, P = perimeter of tube, A = cross section area of tube, v = velocity inside the tube.

Momentum Balance Equation

Let frictional pressure loss in pipe within elemental length dx be

$$dp = \frac{1}{2} f \left(\frac{dx}{D} \right) \rho v^2 \quad \dots(3)$$

Then, momentum balance equation is given by

$$\frac{d}{dx} (\rho v^2) dx + \frac{dp}{dx} dx + \frac{1}{2} f \left(\frac{dx}{D} \right) \rho v^2 = 0 \quad \dots(4)$$

Where, D = diameter, p = pitch, f = friction factor, ρ = density of fluid

It is assumed that in steady state flow, the velocity from surface area of tube will not be continuous and the water issues from the holes.

Let total area of holes be $A_h dx$ & velocity be v_h in elemental length dx . Volume flow rate of the fluid is given by $v_h A_h dx$.

Taking $v_s = \frac{v_h A_h}{P}$ (5) (here Pdx is surface area of tube in length dx and so v_s will be average velocity over length dx. v_s can be dealt as continuous variable)

Let p_{out} be pressure outside the tube. Then pressure loss across holes is given by

$$p - p_{out} = \frac{1}{2} k_1 \rho v_h^2 = \frac{1}{2} k_1 \rho \left(\frac{P}{A_h}\right)^2 v_s^2 \quad \dots(6)$$

Here k_1 is loss coefficient. The above equation is written as

$$\frac{dp}{dx} = \frac{d}{dx} \left(\frac{1}{2} k_1 \rho \left(\frac{P}{A_h}\right)^2 v_s^2\right) \quad \dots(7)$$

As $v_s P dx$ is the volume of fluid coming out from small element dx, the continuity equation will be

$$v_s P dx = - \frac{d}{dx} (Av) dx \quad \dots(8)$$

$$v_s = - \left(\frac{A}{P}\right) \frac{dv}{dx} \quad \dots(9)$$

For momentum balance, frictional pressure loss in pipe by equation (3)

Then, momentum balance equation is given by

$$\frac{d}{dx} (\rho v^2) dx + \frac{dp}{dx} dx + \frac{1}{2} f \left(\frac{dx}{D}\right) \rho v^2 = 0 \quad \dots(10)$$

$$\text{Let } \frac{f}{2D} = k_2 \quad \dots(11) \text{ and } \frac{1}{2} k_1 \left(\frac{A}{A_h}\right)^2 = a_2^2 \quad \dots(12)$$

It can be seen that ‘ a_2 ’ is function of x and a_2 will be constant only when A_h is constant, meaning that the tube has uniform holes. In some cases k_2 can be function of v also.

Putting $\frac{dp}{dx}$ of equation (7) and v_s of equation (9) in equation (10), we get

$$2v \frac{dv}{dx} + 2a_2 \frac{da_2}{dx} \left(\frac{dv}{dx}\right)^2 + 2a_2^2 \frac{dv}{dx} \frac{d^2v}{dx^2} + k_2 v^2 = 0 \quad \dots(13)$$

By non-dimensionalising ‘x’ with total length L and v with initial velocity v_0 equation (13) becomes

$$2v \frac{dv}{dx} + 2a \frac{da}{dx} \left(\frac{dv}{dx}\right)^2 + 2a^2 \frac{dv}{dx} \frac{d^2v}{dx^2} + kv^2 = 0 \quad \dots(14)$$

$$k = k_2 L \quad \dots(15), \quad a = a_2 / L \quad \dots(16)$$

Using this equation, the pitch and size of hole along the length of tube for the desired fluid discharge profile can be calculated.

Firstly, the velocity profile for equal diameter holes and uniform pitch is found and then the effect of variable parameters like ‘a’ and ‘k’ on velocity profile is estimated. The result of above estimation is compared with experimental result and the required number of holes, hole diameter and pitch is found out for the desired fluid discharge profile.

VELOCITY PROFILE IN TUBES WITH UNIFORM HOLE WITH EQUAL PITCH

In equation (13), parameter a_2 is taken constant as pitch and hole size is uniform.

So equation (13) can be written as

$$2v \frac{dv}{dx} + 2a_2^2 \frac{dv}{dx} \frac{d^2v}{dx^2} + k_2 v^2 = 0 \quad \dots(17)$$

This is a non-linear differential equation needed to be solved.

Let inlet velocity be v_0 and length of perforated tube be L.

The boundary conditions are

$$\text{At } x=0; v=v_0 \quad \dots(18)$$

$$\text{At } x=L; v=0, \dots(19)$$

Let $L = 0.225\text{m}$, $v_0 = 1\text{m/s}$, $a = 1516$ and $k = 4.5$

Substituting $dv/dx = p$ and $v/p = \mu$ for solving the differential equation. Solution becomes

$$v = .913(\mu^2)^{.52}(\mu + .487)^{-.075}(\mu^2 - .042\mu + .02)^{-.486} e^{-.114 \tan^{-1} \frac{(\mu - .021)}{.14}} \dots(20)$$

$$x = 0.2 + .018 \ln \frac{(\mu + .487)^2}{\mu^2 - .042\mu + .02} + 0.133 \tan^{-1} \frac{(\mu - .021)}{.14} \dots(21)$$

This gives parametric relation between v and x and v_s can be calculated by

$$v_s = -\left(\frac{A}{P}\right) \frac{dv/d\mu}{dx/d\mu} \dots(22)$$

The plots of v and v_s versus x is as shown in figure (2a) and figure (2b)

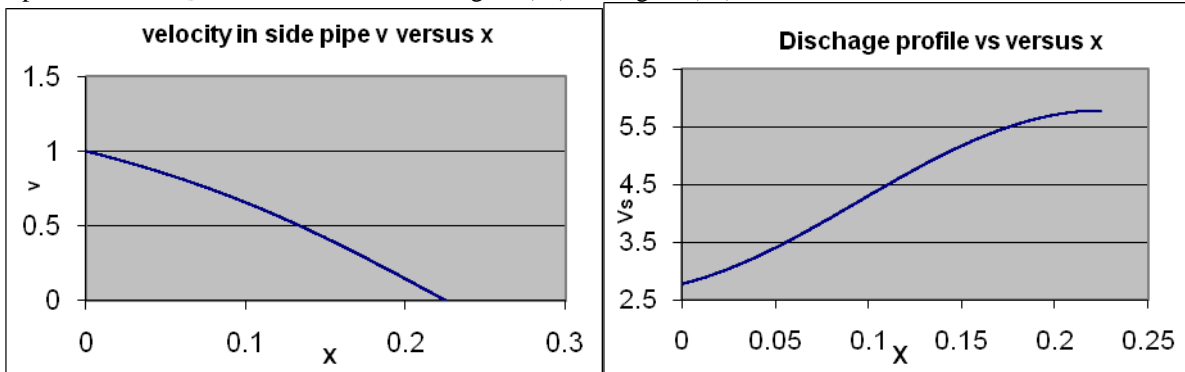


Fig. 2a: Velocity inside pipe v versus x

Fig. 2b: Discharge profile V_s versus x

It can be seen from figure (2a) that more water flows out from the holes at the closed end and little water flows out from holes at the entry the tube. However, this is not general profile. The change in the profile can be evaluated from the dimensionless equation (14). There are two parameters a and k which influence the discharge profile greatly.

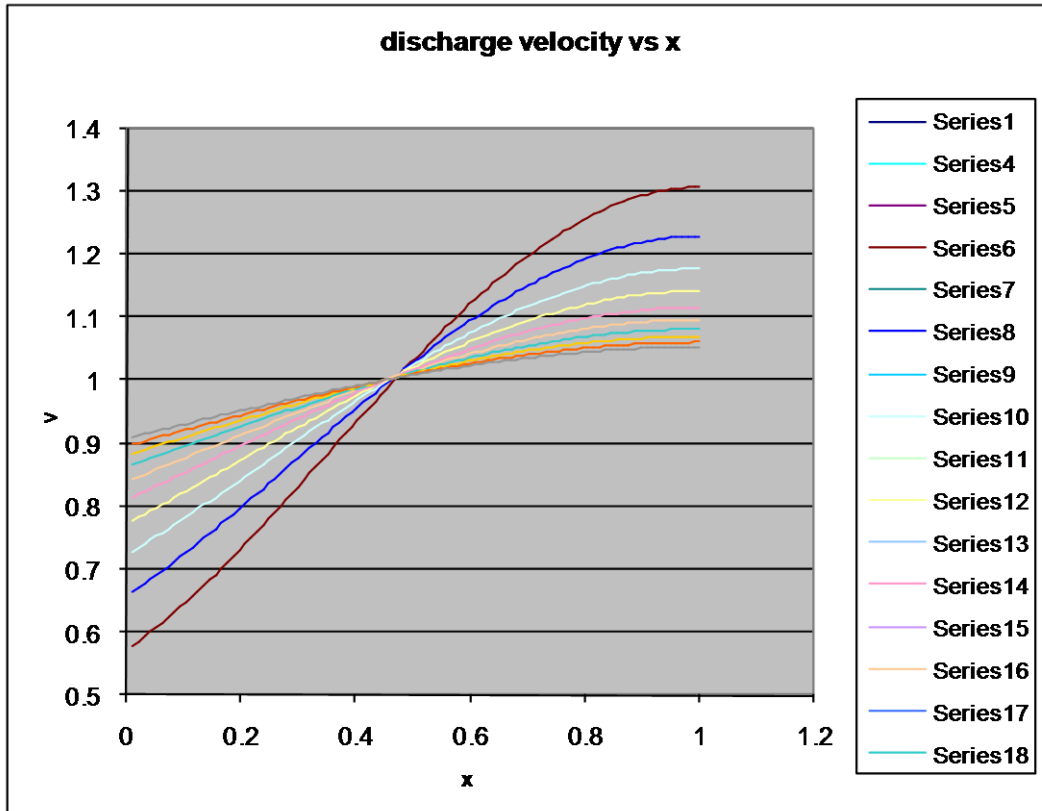


Fig. 3: discharge velocity versus x

It is important to see that when length of pipe increases **a** decrease and **k** increases and when diameter of tube increases, **k** does not change while **a** increases. Figure (3) shows variation of non-dimensionalised discharge velocity when **k** is held constant and **a** is varied in equation (14). It can be seen that when **a** increases discharge at the end of the tube decreases. In the above figure, $k = 0.787$ and **a** is varied from 0.6 (series 6) to 1.6 (series 24). In between, **a** increases uniformly. At series *j* value of **a** is $0.6 + 0.055(j-6)$.

Figure 4 shows the trends of discharge profile when **a** is held constant and **k** is varied. It can be seen that as **k** increases, discharge decreases towards the end and increases at the beginning. In short pipes, discharge is more at ends while in very long pipes discharge is more at beginning and less towards the ends.

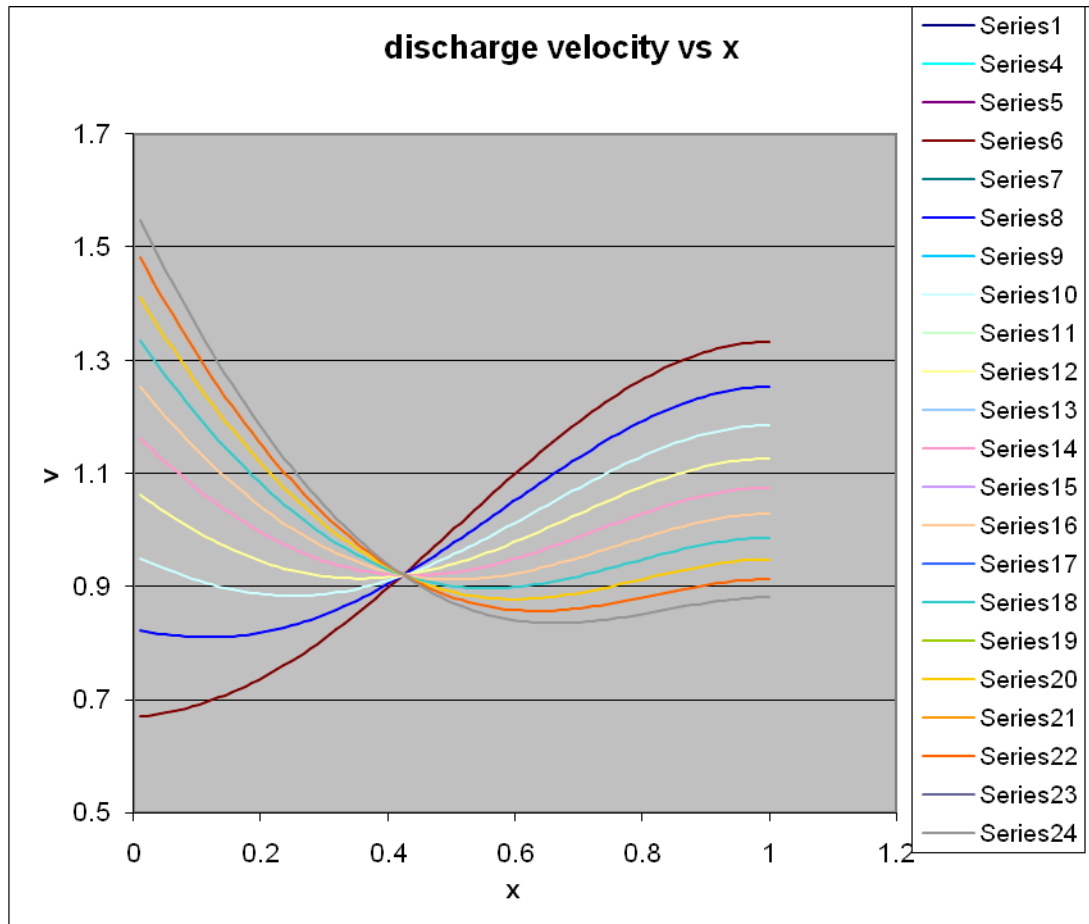


Fig. 4: discharge velocity versus x

In figure 4, a is constant at 0.6 and k varied from 1.28 (series 6) to 5.78 (series 24) and in between k increases uniformly. At series j value of k is $1.28 + 0.25(j-6)$.

CONCLUSION

Perforated tubes are widely used in industries. An attempt has been made to provide an analytical method to model perforated tubes with mass and momentum balance equation. Equations were solved to get flow behavior of perforated tubes. Effect of changing various non-dimensional parameters on flow pattern is also predicted. Theory is extended to design perforated tube for desired flow behavior. The size of the holes, its pitch etc. can be arrived at to get the required flow profile.

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