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CONVERGENT ANGLE EFFECT ON NON-UNIFORM FLOW THROUGH POROUS MEDIA

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ABSTRACT : *An experimental investigation on the effect of convergent angle on the non-uniform flow through porous media was studied in a converging permeameter. The scope of the present paper is to study the relationship between friction factor (F_K) and Reynolds number (R_K) for flow in porous media with converging boundaries, using intrinisic permeability (K) as characteristic length and also studied the variation of friction factor (F_K) and Reynolds number (R_K) with linear parameter, **a**, and non-linear parameter, **b**, for different convergent angles and for different rate of flows. Using friction factor (F_K) and Reynolds number (R_K) relationship, theoretical curves, which are similar to Moody diagram used for pipe flow are developed and verified with the help of existing experimental data. From the set of theoretical curves so obtained, the Reynolds number (R_K) at which the friction factor (F_K) and Reynolds number (R_K) relationship deviates from Darcy's law and the Reynolds number (R_K) at which turbulent flow is fully established are identified. In the present case, McCorquodale data of size 1.66 cm was used as media, to develop curves relating friction factor (F_K) and Reynolds number (R_K) for different ratios of radii of the test section of permeameter.*

Key Words: Converging Permeameter; Friction Factor; Reynolds Number; Porous Media; Intrinisic Permeability; Linear And Non-Linear Parameters.

1. INTRODUCTION

The practical importance of non uniform flow lies in the fact that the majority of the field situations are convergent or divergent. The study of the flow of fluids through porous media is important in flow through rock fill dam and banks, flow in the area adjacent to a pumping well, flow through filters and flow through fissured rocks in Civil Engineering, geology, petroleum and other related fields. Investigation in porous media between parallel boundaries has been carried out extensively in the last five decades. In the case of parallel flow, for a given rate of flow through a known size of the medium, the gradient of head loss i.e., hydraulic gradient is constant. But in the case of non-uniform flow, such as radial flow, the gradient of head loss i.e., hydraulic gradient is not constant for a given rate of flow through a known size of the medium.

McCorquodale (1970) and Nasser (1970) conducted experiments on converging permeameter and assumed that convergence of streamlines mainly affects only non-Darcy component of Forchheimer equation and assumes that Darcy parameter is same for both parallel and converging flow. Bhanu Prakasham Reddy and Rama Mohan Rao (2004) studied the effect of convergence on Darcy and non-Darcy parameter for different radial flow lines with different ratios of radii and also studied the variation of friction factor (f_K) and Reynolds number (R_K) using intrinsic permeability as characteristic length for different radial flow lines with different ratios of radii. Bhanu Prakasham Reddy and Rao (2006) studied the effect of convergence on linear and non-linear parameter for different radial flow lines with different ratios of radii and showed that both **a** and **b** are varied along the radial direction of flow with different ratio of radii. Bhanu Prakasham Reddy (2006) investigated the influence of convergent factors on the resistance law relating friction factor (f_k) and Reynolds number (R_k) using intrinsic permeability as characteristic length was examined. Reddy and Reddy (2007) developed curves relating friction factor (F_k) and Reynolds number (R_k) with efficiency (η) for different rate of flows of the test section of permeameter. Reddy and Reddy (2010) developed curves relating friction factor (F_k) and Reynolds number (R_k) with Power (P) for different rate of flows of the test section of permeameter and also studied the variation of Darcy Parameter, **a** and Non-darcy Parameter, **b** with Power (P).

Darcy (1856) related velocity of flow and hydraulic gradient by conducting experiments and arrived at an equation given by

$$V = KI \qquad (1)$$

where V = macroscopic velocity or seepage velocity; I = hydraulic gradient, and K is the coefficient of permeability which depends upon the particle size and shape, and other factors like void ratio, structure of the soil mass, fluid properties etc.

Forchheimer (Scheidegger 1963) conducted experiments on a sand-box model and proposed an equation in a quadratic form as,

$$I = aV + bV^2 \qquad (2)$$

for the non-linear regime of flow, in which **a** and **b** are the coefficients determined by the properties of the fluid and porous media, and are known as linear and non-linear parameters.

Ward (1964) obtained the relationship between the friction factor (f_K) and Reynolds number (R_K) by defining a friction factor f_K as $\frac{Ig\sqrt{K}}{V^2}$ and Reynolds number R_K as $\frac{V\sqrt{K}}{\nu}$

$$f_K = \frac{1}{R_K} + C_W \qquad (3)$$

2. EXPERIMENTAL PROCEDURE

Experiments on convergent flow through porous media were conducted in the 122 cm long test section of the 30.5 cm wide by 122 cm high flume shown in **Fig.1**.This flume had a 180 cm long plexiglass window for viewing the flow in the media. Piezometric tapping points along the bottom of the permeameter, connected to a manometer board facilitated measurement of piezometric heads. Water was supplied to the flume by a centrifugal pump, which could be operated to discharge directly through a constant head tank. A stem valve in the inflow pipe regulated the discharge in to the flume and also a venturi meter was located in the inflow pipe to measure the discharges. Experiments were conducted at different heads and the rate of flow through the media and the head loss in the permeameter were measured for different convergent angles.

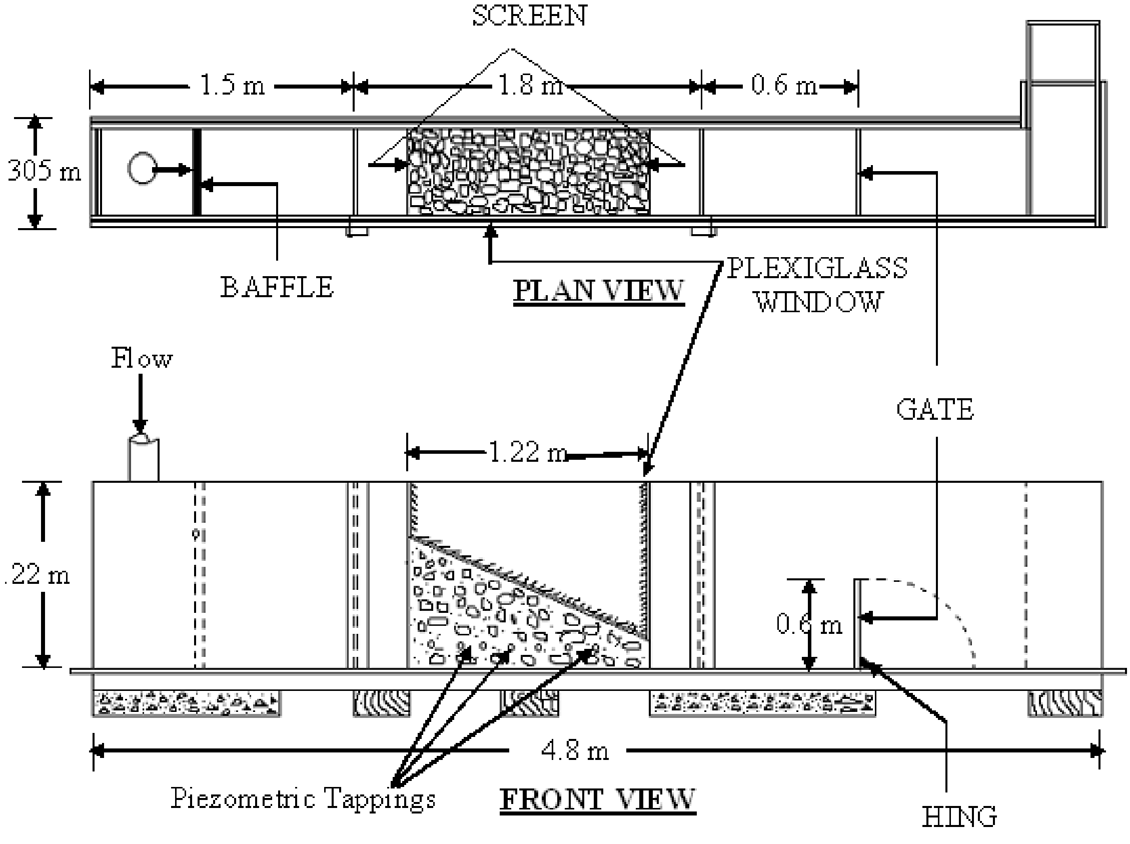

Fig.1. EXPERIMENTAL SET UP

3. RESULTS AND DISCUSSIONS

3.1. Determination of linear parameter, a and non-linear parameter, b

The values of a and b are computed based on the flow rate and the piezometric heads at the approach section at a radius R_1 and an exit section at a radius R_2 the entrance velocity V, and the hydraulic gradient I are computed. For different flow rates for the same medium, the corresponding entrance velocity and hydraulic gradient are obtained. For this ratio of R_1/R_2, the values of a and b are then obtained from a plot of I/V versus V, which is a straight line, where V is seepage velocity at section at R_1 equal to flow rate Q/flow area A_1 at approach section.

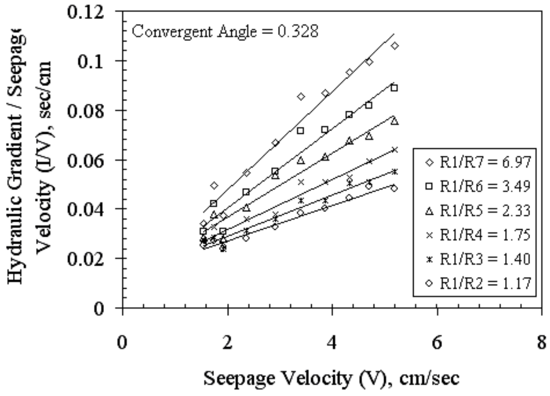

Fig.2.a.Variation of I/V with V for 1.66 cm Crushed rock

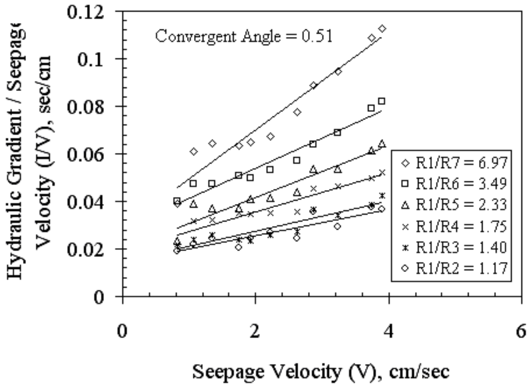

Fig.2.b.Variation of I/V with V for 1.66 cm Crushed rock

Figs. 2(a-b) depicts variation of I/V with V for different R_1/R_2 ratios and for different convergent angles for the media of size 1.66 cm crushed rock with water as fluid flows through the media. Linear equations fitted to these line by the method of least square yields the values of a and b. It is observed that I/V increases as the seepage velocity (V) increased and also I/V increases with increase of R_1/R_2 ratios. The variation of I/V with V for different converging angles for the same R_1/R_2 ratio is depicted in **Fig.3.** It is noticed that the variation of I/V with V is increased with increase of convergent angle for the same R_1/R_2 ratio. The values of **a** and **b** are depicted in **Table.1**. for both convergent angles for different ratio of radii.

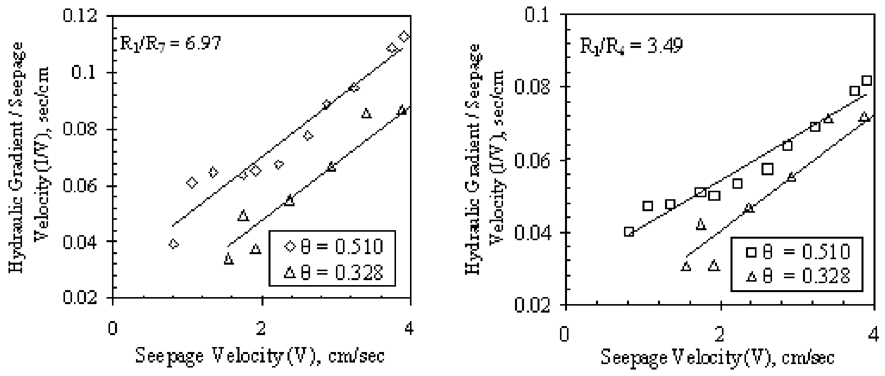

Fig.3.a. I/V vs V for $R_1/R_7 = 6.97$ Fig.3.b. I/V vs V for $R_1/R_6 = 3.49$

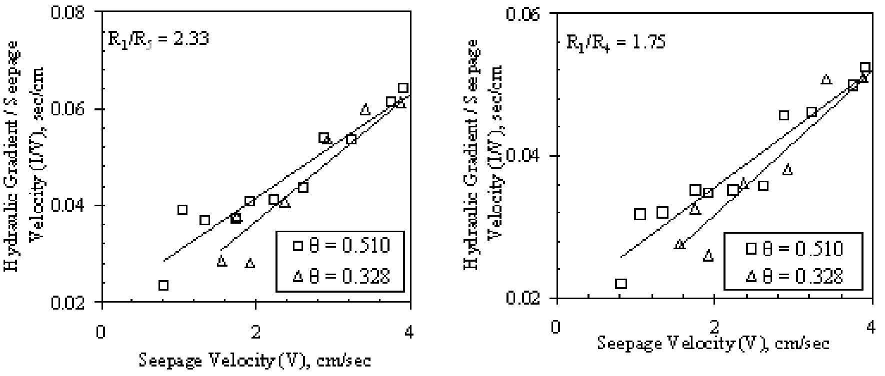

Fig.3.c. I/V vs V for $R_1/R_5 = 2.33$ Fig.3.d. I/V vs V for $R_1/R_4 = 1.75$

Fig.3. Variation of I/V with V for Different Converging Angles for 1.66 cm Cr.Rock

3.2. Effect of convergence on the linear parameter, a and non-linear parameter, b

The linear parameter, **a** and non- linear parameter, **b** are not constant along the length of travel when flow takes place through porous media with converging boundaries. **Fig. 4(a)** depicts the variation of **a** for converging flow, with R_1/R_2 ratios for different converging angles and also shown the variation of media constant (C_W) with intrinisic permeability (K) for the same size of the media was investigated. It may be seen that, for a given size, the value of **a** decreases linearly with decrease of R_1/R_2 ratios. Thus, from **Fig. 4(a)**, for convergent angle (θ) is equal to 0.51, the value of **a** decreases linearly from about 0.0295 to about 0.0073 when R_1/R_2 decreases from 6.97 to 1.17 and it is shown with dotted lines. In the same way, it is observed from **Fig. 4(a)**, for convergent angle (θ) is equal to 0.328, the value of **a** decreases linearly from about 0.0212 to about 0.0072 when R_1/R_2 decreases from 6.97 to 1.17 and these values are small when compared to the convergent angle (θ) is equal to 0.51 for the crushed rock of size 1.66 cm. It is noted from the **Fig. 4(a)** that the value of **a** increases as the convergent angle (θ) is increased, being greater for large convergent angle (θ) than for smaller convergent angle (θ) for the same media.

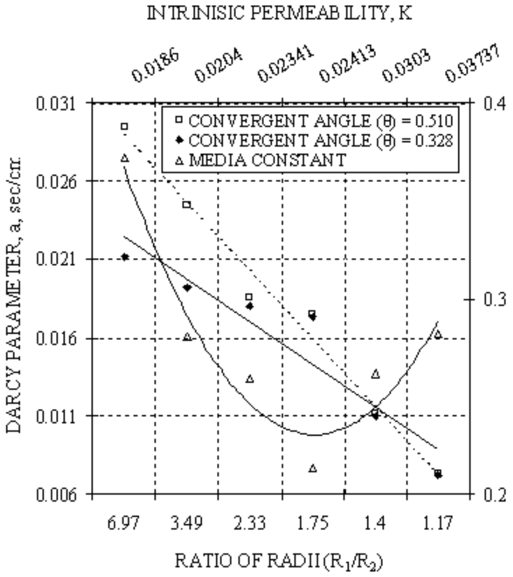

Fig.4.a.Variation of a with R_1/R_2 and C_W with K for Different Convergent Angles

Similarly, from **Fig. 4(b)**, for convergent angle (θ) is equal to 0.51, the value of **b** decreases linearly from about 0.0204 to about 0.0077 when R_1/R_2 decreases from 6.97 to 1.17 and it is shown with dotted lines. In the same way, for convergent angle (θ) is equal to 0.328, the value of **b** decreases linearly from about 0.0168 to about 0.0076 when R_1/R_2 decreases from 6.97 to 1.17. From the foregoing analysis, it may be concluded that as the convergent angle (θ) is increased, both linear parameter, **a** and non-linear parameter, **b** increases and also **a** and **b** increases with increase of R_1/R_2 ratios due to the effect of convergent angle on the behaviour of flow through the porous media. The relationship between media constant (C_W) and intrinisic permeability (K) in the **Fig.4.(a)** and **Fig.4.(b)** are useful to predict linear parameter, **a** and non-linear parameter, **b** for a particular intrinisic permeability (K).

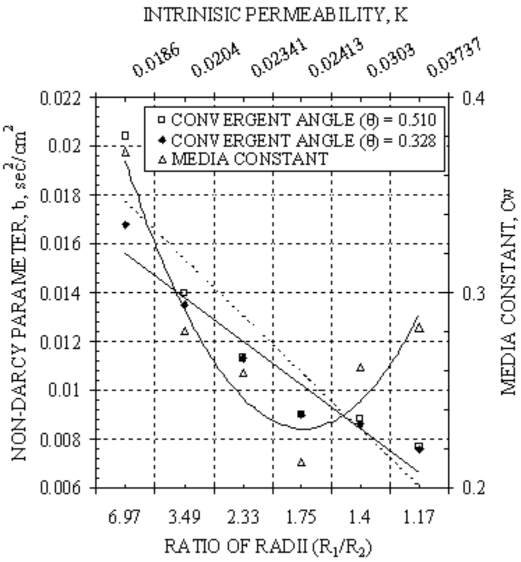

Fig.4.b.Variation of b with R_1/R_2 and C_W with K for Different Convergent Angles

3.3.Relation between friction factor (F_K) and Reynolds number (R_K)

The values of friction factor (F_K) and Reynolds number (R_K) are computed for a given seepage velocity using the values of **a** and **b**. These computed F_K and R_K values are plotted for different ratios of radii for different convergent angles (θ) are shown in **Figs. 5(a-b)**. It is seen from **Figs. 5(a-b)** that for any convergent angle (θ), the Reynolds number (R_K) increases, as the friction factor (F_K) decreases for any ratio of radii and friction factor (F_K) decreases as the ratio of radii decreases for the crushed rock of size 1.66 cm. **Figs. 6(a-b)** shows the variation of Friction factor (F_K) with non-linear parameter, **b** and variation of Reynolds number (R_K) with linear parameter, **a** for different convergent angles and for different rate of flows. In order to distinguish the same the R_K vs **a** curves are shown by dotted lines and F_K vs **b** curves are shown by firm line. It is observed that the

Reynolds number (R_K) increases with decrease of **a** and also Reynolds number (R_K) increases with increase of Rate of Flow for any particular value of **a**. In the same way, it is noted that the Friction factor (F_K) increases with increase of **b** and also Friction factor (F_K) decreases with increase of Rate of Flow for any particular value of **b**.

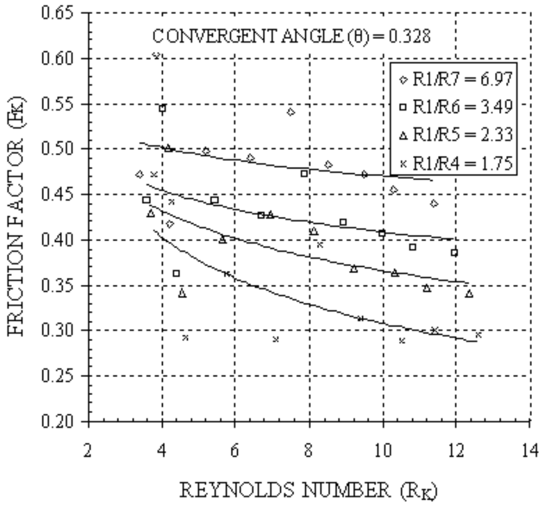

Fig.5.a. Variation of F_K with R_K for Different Ratio of Radii (R_1/R_2)

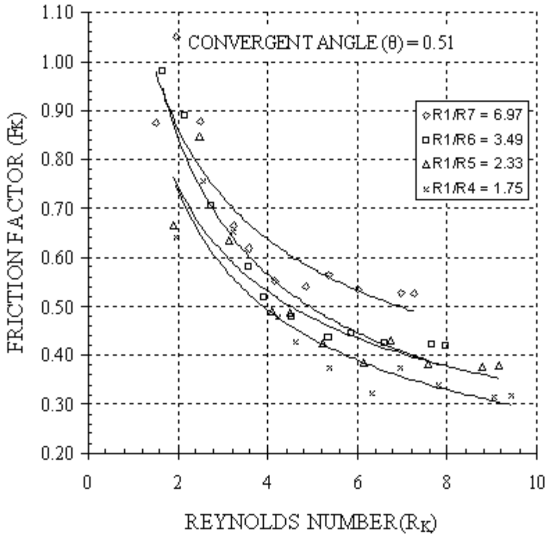

Fig.5.b. Variation of F_K with R_K for Different Ratio of Radii (R_1/R_2)

The variation of Friction factor (F_K) with Reynolds number (R_K) for different converging angles for the same R_1/R_2 ratio is depicted in **Fig.7(a-b)**. It is inferred that the variation of Friction factor (F_K) with Reynolds number (R_K) increases with increase of convergent angle for the same R_1/R_2 ratio.

Eq. (3) is used to draw a set of theoretical curves relating friction factor (F_K) and Reynolds number (R_K) for different values of C_W and is depicted in **Figs. 8(a-b)**. The experimental data of 1.66 cm crushed rock are sorted based on the values of C_W , and are plotted against the corresponding theoretical F_K vs R_K curves. The correlation is seen to be very good with all experimental points falling on the F_K vs R_K curves for the corresponding values of C_W. **Figs. 8(a-b)** shows the variation of friction factor (F_K) with Reynolds number (R_K) for each C_W value, for each convergent angle (θ) and for different R_1/R_2 ratios.

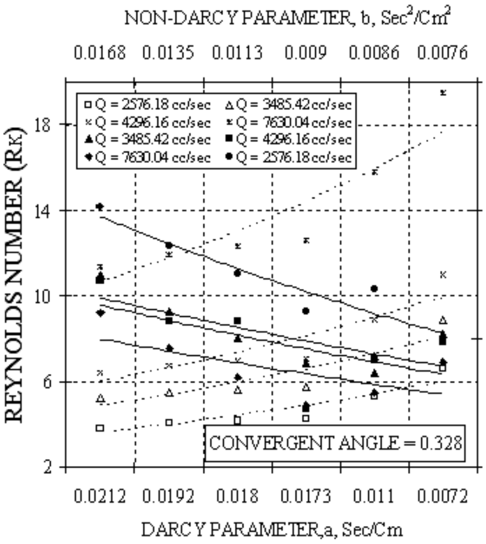

Fig.6.a. Variation of F_K with b and R_K with a

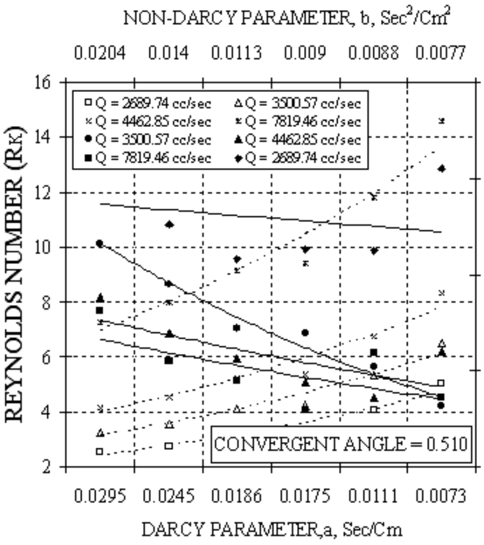

Fig.6.b. Variation of F_K with b and R_K with a

The inclined dashed line in **Figs. 8(a-b)** demarcates, approximated, the R_K at which the flow changes from non-linear transition to wholly turbulent flow.

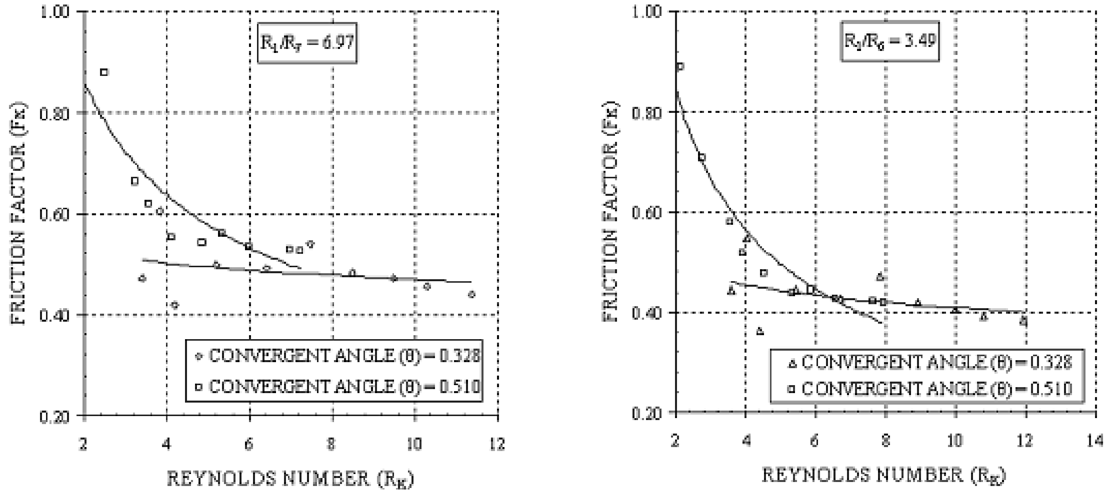

Fig.7.a. Variation of F_K with R_K for $R_1/R_7 = 6.97$ Fig.7.b. Variation of F_K with R_K for $R_1/R_6 = 3.49$

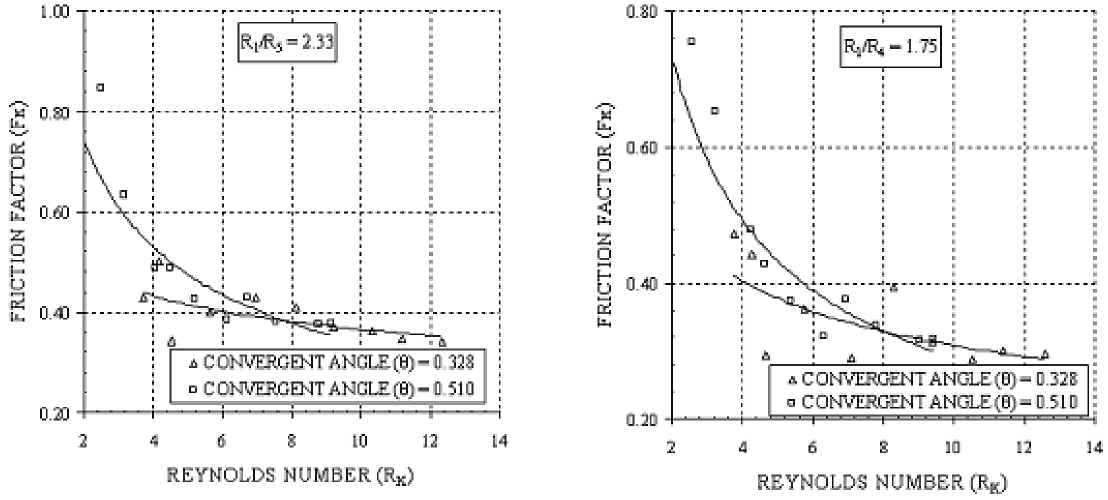

Fig.7.c. Variation of F_K with R_K for $R_1/R_5 = 2.33$ Fig.7.d. Variation of F_K with R_K for $R_1/R_4 = 1.75$

Fig.7. Variation of F_K with R_K for Different Converging Angles for 1.66 cm Cr.Rock

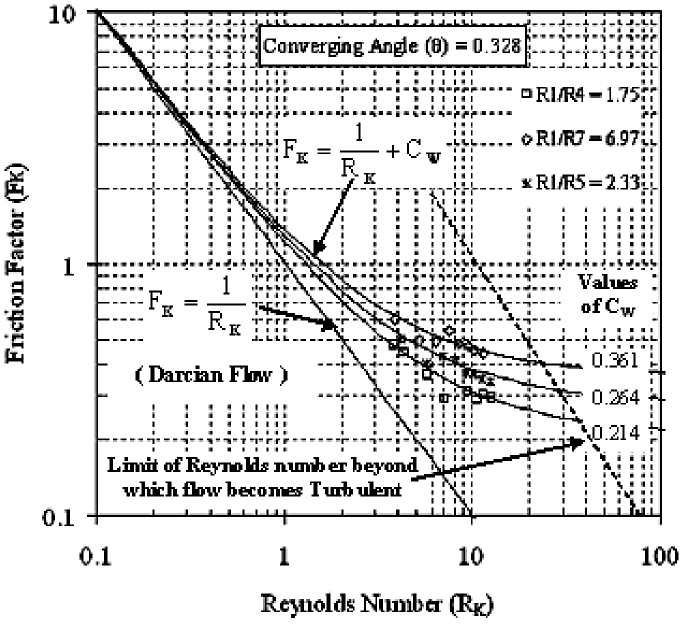

Fig.8.a. Theoretical and Experimental Relationship Between Friction Factor (F_K) and Reynolds Number (R_K) for Convergent Angle (θ) = 0.328

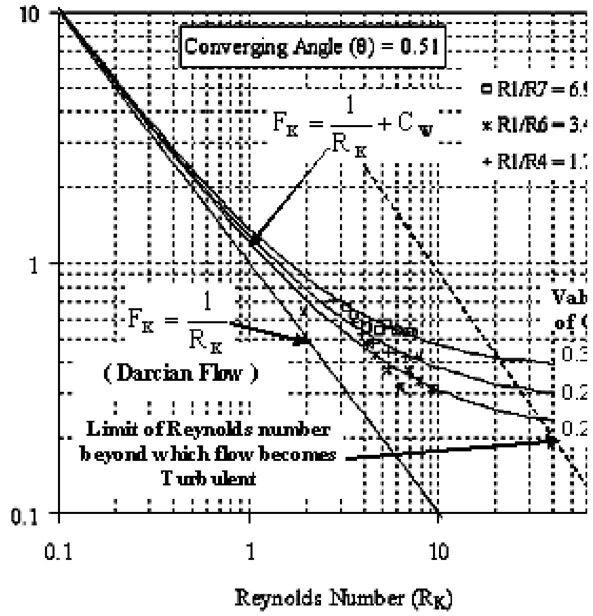

Fig.8.b. Theoretical and Experimental Relationship Between Friction Factor (F_K) and Reynolds Number (R_K) for Convergent Angle (θ) = 0.510

TABLE .1. EXPERIMENTAL RESULTS.

	Convergent Angle = 0.51			Convergent Angle = 0.328		
R_1 / R_2	**a (sec/cm)**	**b (sec^2/cm^2)**	**R^2**	**a (sec/cm)**	**b (sec^2/cm^2)**	**R^2**
R_1/R_7 = 6.97	0.0295	0.0204	0.93	0.0212	0.0168	0.97
R_1/R_6 = 3.49	0.0245	0.0140	0.96	0.0192	0.0135	0.97
R_1/R_5 = 2.33	0.0186	0.0113	0.94	0.0180	0.0113	0.95
R_1/R_4 = 1.75	0.0175	0.0090	0.96	0.0173	0.0090	0.92
R_1/R_3 = 1.40	0.0111	0.0088	0.86	0.0110	0.0086	0.96
R_1/R_2 = 1.17	0.0073	0.0077	0.90	0.0072	0.0076	0.98

4. CONCLUSION

Non - Uniform Flow through porous media with converging boundaries has been analyzed and it is investigated from the experiments that when flow occurs in converging boundaries the values of **a** and **b** vary along the direction of flow and also the values of **a** and **b** increases with increase of convergent angle. The inter relationship between the various parameters of the Forchheimer's equation with intrinisic permeability (K) is presented. It is concluded that the variation of Friction factor (F_K) with Reynolds number (R_K) increases with increase of convergent angle for the same R_1/R_2 ratio.

Resistance equation, relating the friction factor (F_K) and Reynolds number (R_K), using intrinisic permeability (K) as the characteristic length and C_W as a parameter, is plotted on a log-log plot yields a set of curves. The variation of friction factor (F_K) and Reynolds number (R_K) for different C_W values for different convergent angles (θ) and for different ratios of radii are compared with the experimental data and observed lie on the theoretical curve.

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7. NOMENCLATURE

The following symbols are used in this paper:

a = linear parameter or Darcy parameter;
b = non- linear parameter or non-Darcy parameter;
F_K =friction factor using K as the characteristic length;
g = acceleration due to gravity;
I = hydraulic gradient;
K = intrinisic permeability;
Q = rate of flow;
R_1 ,R_2 = radii at approach section and exit section taken arbitrarily;
R_K = Reynolds number using K as the characteristic length;
V = macroscopic velocity or seepage velocity;
θ = angle of convergence in radians;
μ = dynamic viscosity of fluid;
ν = kinematic viscosity of fluid; and
ρ = density of the fluid.