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Experimental Investigation on Non-Linear Flow in Porous Media Through Converging Boundaries

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***Abstract*: Water movement through the soil layers iscomplex in nature. But its contribution to the well-being of the human kind as a whole is significant. The subject of seepage flow is one, which appears initially simple, after in depth and detailed study, however, the character of flow of a fluid particle through the tortuous passages of a granular medium assumes an almost incomprehensible complicacy. Most of the practical cases, in addition to size, shape, and angularity of the porous media, convergence of the flow may be expected to playan important role in influencing the flow behavior. The present work envisages carrying out analysis of the data systematically based on the drag on the individual particle, regime wise. In order to meet the objectives of the present investigation, aradial flow permeameters with different angles are fabricated and crushed rock and marbles are used as porous media. Water and diesel are used as the fluid media to develop curves relating friction factor and Reynolds number for different radial flow lines with different ratios of radii of the test section of the permeameter. Analysis is carried out in two phases. In the first phase 'volume diameter' is used as characteristic length to compute coefficient of resistance and Reynolds number as defined by Kovacs. In the second phase of analysis 'Hydraulic radius' is used as characteristic length while defining coefficient of resistance and Reynolds number.**

***Index Terms:* Permeameter, Reynold's number, radial flow,porous media, volume diameter, hydraulic radius, characteristic length,**

I. INTRODUCTION

The process of flow through permeable media is of interest to various fields of engineers, scientists and economists who identify the importance of groundwater flows and in the field of oil retrieval processes. The one- dimensional empirical equation suggested by Darcy in 1856 is the starting point for number of practical applications and as a constant challenge for researchers. The original conditions studied by Darcy can be found in many practical cases, it is the extensions to more general cases that are in need of theoretical analysis where experiments are difficult to perform. The first such situation is the fully three- dimensional flows which applicable for groundwater flows and oil recovery methods. While this form of Darcy's law is applied frequently, it appears to be no experimental validation obvious tonsorial depiction of Darcy's philosophy.

A porous media is stated as a solid body containing void spaces, distributed more or less frequently all over the medium in either regular pattern or at random. In porous media pores may be interconnected or indiscriminate, but at least a part of the pore system must be interconnected to make the fluid pass through the medium. This interconnected pore space is called "effective pore space of the medium". Pores may vary in shape, size and magnitude therefore it provides curvilinear paths for the fluid to flow. A matter exists in either the solid state or the fluid state. The fluid state is further divided into liquid and gaseous states. Theoretically fluid is as a substance, capable of flowing. It has no definite shape of its own but conforms to the shape of the containing vessel. The fluids are classified into ideal and real fluids. Fluids having no viscosity and surface tension are called Ideal fluids and are incompressible. Real or Practical fluids are those which are available in nature. Real fluids having the properties such as viscosity, surface tension and compressibility.

II. LITERATURE REVIEW

From the pioneering experiments of Darcy on flow of water through filter beds, a significant amount of theoretical and experimental investigations taken place on seepage flow Hubbert, M.K [4]. A survey of past work indicates that the aim of all the researchers had to connect flow resistance to its behavior in terms of quantifiable properties of the fluid and the medium. Forchheimer conducted experiments on a sandbox model and suggested a quadratic equation. Irmay.S. [5]. But this equation does not take care of transitional regime. While a number of authors Ahmed and Sunada [1] and Anadakrishnan and Varadarajulu [2] have used Darcy's equation to analyse their experimental data. Rose [10] and Rizk [11] conducted dimensional analysis and present a quadratic equation by correlating coefficient of resistance and Reynolds number. But when the data of Dudgeon [3], Niranjan [8] and Pradip Kumar [9] are plotted using the equation suggested by Rose and Rizk, it is found that Reynolds no. attains a low value as 9. Wright [12] and Kovacs [6] have done considerable work on the conditions of limits. Wright [12] published the results of research on a vertical converging permeameter. Moccorquodale [7] analysed the effect of convergence in a horizontal permeameter by applying finite element method.

III. EXPERIMENTAL SETUP

Figure 1 depicts the details of the converging flow permeameter used in the present study. The set-up consists of a vertical converging section of 1000 mm height and width varying from 750mm at top to 150mm at bottom. The angle of convergence is 50^0 to 70^0. The radii of convergence

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at the top and bottom piezometers are 111cm and 26cm respectively. A row of piezometric holes were drilled along the centre line of the permeameter. The piezometric Tapping points are provided at 50mm centre to centre spacing along the centre line of the front face of the permeameter. The short copper tubes attached to these holes are connected to a manometer board by tubes. The piezometric heads are measured to an accuracy of ±0.5 mm. At the bottom of the permeameter, 3.5 mm thick perforated aluminum screen, with more than 85% of the area perforated, was kept retaining the material. A similar screen was kept at the top also, to ensure uniform flow throughout the cross section of the permeameter and to help in producing radial flow entry into the test sample.

In the present study a closed circuit system of supply of fluid was adopted. Fluid collecting tank is pumped to the header tank which is discharged to the collecting tank with the help of a connecting pipe. A perforated horizontal pipe fixed at the end of the delivery pipe dampened turbulence. Further, this arrangement does not allow the fluid to fall in the form of a thick jet at one point near the inlet of the fluid in the tank during each run.

Figure1. 50° Convergent Permeameter

Figure 2. Marble

Figure 3. Gravel

IV. METHODOLOGY

A converging permeameter is designed and experimented to accomplish the objective of the study. Series of experiments were conducted on porous medium in converging flow permeameter for all regimes of flow. Flow discharge, velocity and hydraulic gradient are calculatedfrom the test data of converging boundary set up.

Test material is filled up to the top of the experimental set up and the porosity of the medium is calculated. Fluid (Water/Diesel) is pumped from bottom tank to inlet of the permeameter and it is allowed to flow through test material. At the starting of test, flow is passed about 1 to 2 hours to get steady state of flow. The liquid is collected in the measuring tank. From the discharge, velocities are calculated at every pressure taping section of the setup. Simultaneously, pressure heads are measured in the manometer board. The area of the flow was calculated by multiplying the observed pressure head with width of the permeameter at that section. Flow velocities are also calculated at every piezometric taping. Temperatures are measured at the outlet of the setup, for calculation of kinematic viscosity. Tests are repeated for different discharges to cover all states of flow. From the test observations, hydraulic gradient, bulk velocity, radius of piezometric location, width of instrument at that piezometric section, bottom level, cross section area, kinematic viscosity, porosity, void ratio, seepage velocity, volume diameter, discharge is estimated.

A. Experimental Step:

i. The test setup is filled with the solid medium, under gravity, to get even packing.

ii. The flow is allowed through the permeameter such that a constant head is maintained in the header tank.

iii. A time log of about 15 to 30 minutes is allowed before the readings of piezometric heads are noted, to ensure that no further reorientation of the particles occurs.

iv. Once the flow is stabilized and air bubbles are removed, the time taken for collecting 10 cm depth of fluid in the measuring tank is noted for discharge measurement.

v. Fluid level readings in piezometers are noted. It is used todetermine the head loss through the medium.

vi. The above procedure is repeated for several discharges, for a prescribed size of medium. During every run temperature of outflow is noted.

vii. The test material is removed and the permeameter is filled with another size of test material.

The above steps are repeated for all sizes of the solid media.The observations are tabulated.

V. RESULTS OF THE EXPERIMENT

This section presents the test results in a radial flow setup covering laminar, non-linear laminar, turbulent, transitional regimes of flow through both crushed rock and glass spheres. The analysis is carried out in two stages. While in the first stage volume diameter is used as characteristic length to explain resistance coefficient and Reynolds number, in second stage hydraulic radius is used as characteristic length to explain these two parameters. The following paragraphs enunciate briefly the special features of all the regimes. In laminar regime, viscous forces are very high as compared to inertial fore. The seepage velocity is constant and head loss is proportional to the velocity of flow. Darcy's law is governing equation.

The viscous and inertial force influence the motion in non-linear laminar regime, but due to gradual increase of inertial force, the flow deviates from the linear relationship as suggested by Darcy's law. The seepage velocity is constant, and the state of flow is still laminar phase. Stationary vertices are formed at the top end of the regime. In the turbulent, transitional stage of flow the seepage velocityoscillates with the regular frequency and loss of head dependents more on the velocity square. Inertial actions dominate and vertices are shed at regular intervals from individual particles. Turbulence may begin in phases as the flow velocity is increased. In the fully turbulent phase, the viscous forces practically disappear and only these inertial forces govern the flow. The seepage velocity oscillates haphazardly about an average value. The loss of head may be assumed to vary with the square of the velocity. Since fully developed turbulent flow regime had been extensively investigated the same is excluded from the present investigation.

A. Stage – I experimentation:

In the first stage particle volume diameter is used as the characteristic length.

The values of λ_k and Re_k are computed. No difficulty was faced in obtaining lower values of Reynolds (Re_k) number as diesel was one of the fluids used. Further, small size media of sizes 1.65 cm, 1.162 cm are also used.

It facilitates comparison of fitness and trend of the present work. The variation of coefficient of resistance (λ_k) with Reynolds number (Re_k) is less than 10 is depicted in figure 4 gravel diesel.

The values of Reynolds number (Re_k) thus computed for both diesel and water for all sizes of media are segregated into 3 ranges as (i) Less than 10 (ii) Between 10 and l00 and

(iii) Between 100 and 100. By doing so, two objectives are achieved. It adds to the existing literature on low regime flows where there is no much of the work reported with volume diameter as characteristic length in case of high regime flows.

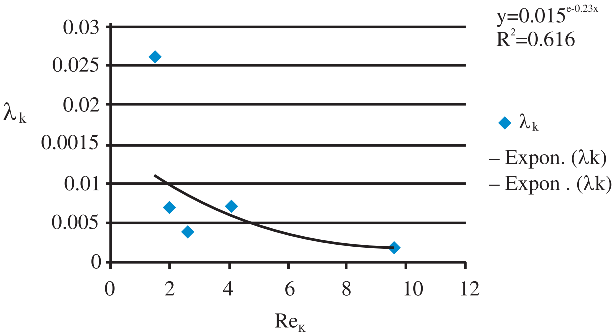

Figure 4. Variation of coefficient of resistance with Reynolds number Re_k less than 10

The data corresponding to present work are seen to lie along a line using method of least squares; an equation is fit to the line which is expressed as

$$\lambda_k = 0.015\ Re^{-.23x} \tag{1}$$

It may be noted that the Reynolds number Re_k in equation is -.23 it indicates that as Reynolds number increases the coefficient of resistance decreases. Theabsolute value of the indexes is 0.015. This infers the coefficient of resistance varies linearly (inversely) with Reynolds number. Comparison of equations shows that in the case of radial laminar flow the numerical constant is 0.015 while in the pipe flow is 64. Therefore, it indicates that the resistance is higher in radial seepage flow comparedto pipe flow, for a given Reynolds number lying in the laminar regime. The tortuous nature of flow channels in a porous medium may be main reason for this observation. The variation of coefficient of resistance with Reynolds number for non-linear regime is shown in figure 4. An equation relating these two parameters is obtained from the method of least squares.

$$\lambda_k = 0.051 Re_k^{-.06x} \tag{2}$$

Equation (2) can however be simplified as

$$\lambda_k = 0.051 Re_k^{-0.6x} \tag{3}$$

Summing up all the above observations, theequations proposed for different regimes are

$$\lambda_k = 0.015 Re_k^{-.23x} \tag{4}$$

$$\lambda_k = 0.05\ Re_k^{-0.6x} \tag{5}$$

Therefore, once the values of Reynolds number for a given discharge through medium of known size, is determined from experimental data, then using the corresponding equation the value of coefficient of resistance (λ_k) can be computed.

TABLE I.
Stage - I (Coefficient Of Resistance And Reynolds Number Are Computed Using "Volume Diameter” As Characteristic Length)
Fluid: Water

Material	**Parameter**	**Average values for different permeameter angle**			**For parallel flow**
		70°	**60°**	**50°**	
Marble	Re_r	0.0658	0.106	0.134	64
	Λ_r	0.0006	0.00034	0.000222	64
Crushed rock	Re_r	0.116	0.1	0.11	64
	Λ_r	0.0003	0.00055	0.00025	64

TABLE II.
Stage - II (Coefficient Of Resistance And Reynolds Number Are Computed Using "Hydraulic Radius” As Characteristic Length)
Fluid: Diesel

Material	**Parameter**	**Average values for different permeameter angles**			**For parallel flow**
		70°	**60°**	**50°**	
Marble	Re_k	10.204	16.888	21.069	64
	λ_k	0.0335	0.00781	0.00595	64
Crushedrock	Re_k	15.66	19.999	23.5	64
	λ_k	0.0809	0.03453	0.02685	64

TABLE III.
Comparison of Re_K and Λ_K Values Between Water and Diesel
(Stage–**I**)

Material	Parameter	Avg. value for different permeameter angles		Avg. value for different permeameter angles		Observed % of variation	
		70^0	60^0	70^0	60^0	70^0	60^0
Marble	Rek	10.2	16.89	2.25	3.75	78	77.81
	λk	0.036	0.008	0.021	0.012	37.91	35.98
Crushed Rock	Rek	15.66	20.0	4.78	4.28	69.46	78.6
	λk	0.081	0.035	0.014	0.022	82.58	37.45

TABLE IV.
Comparison of Re_K and Λ_K Values Between Water and Diesel
(Stage–**II**)

Material	Parameter	Avg. value for different permeameter angles		Avg. value for different permeameter angles		Observed % of variation	
		70^0	60^0	70^0	60^0	70^0	60^0
Marble	Rek	0.23	0.495	0.066	0.106	77.9	78.56
	λk	0.001	0.0002	0.001	0.0003	32.14	33.43
Crushed Rock	Rek	0.378	0.483	0.116	0.1	69.39	79.3
	λk	0.002	0.001	0.0003	0.001	83.83	33.97

VI. CONCLUSIONS

A. *Stage I (Marble):*

- Observed percentage variation of Re_k with 70^0 converging permeameter is 78.
- Percentage variation of 77.81 has been observed in Re_k value with 60^0 converging permeameter.

B. *Stage I (Crushed Rock):*

- Percentage variation of 69.46 has been observed in Re_k value with 70^0 converging permeameter.
- Observed percentage variation of Re_k with 60^0 converging permeameter is 78.6.

C. *Stage II (Marble):*

- Observed percentage variation of Re_r with 70^0 converging permeameter is 77.9.
- Percentage variation of 78.56 has been observed in Re_r value with 60^0 converging permeameter.

D. *Stage II (Crushed Rock):*

- Percentage variation of 69.39 has been observed in Re_r value with 70^0 converging permeameter.
- Observed percentage variation of Re_r with 60^0 converging permeameter is 79.3.

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