Experimental Investigation of the Permeability and Inertial Effect on Fluid Flow through Homogeneous Porous Media

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ABSTRACT: *The value of the permeability in fluid flow through porous media is important for process investigation. In low Reynolds number, the classic Darcy's law is suitable for simulation of fluid flow. In this paper, an experimental study for evaluation of preformed fiber permeability has been done. Also, the deviations from the classical Darcy law by experimental and numerical simulation of the Navier-Stokes equations has been studied, and the coefficient of inertial term evaluated. The fluid flow in a geometry which is similar to the experimental system has been modeled as the Stokes flow on multi particles. Kozeny-Carmen relation for characteristic diameter of particles has been used as the characteristic dimension in numerical analysis. Numerical solution has been done based on the boundary elements method and the results are used for the K calculations. With experimental investigations for the fluid flows with higher Reynold's number, the coefficients for Forchheimer term could be obtained.*

KEY WORDS: *Porous media, Permeability, E-glass fiber, Darcy's law, Fluid flow.*

INTRODUCTION

Investigation of single-phase fluid flow in porous media is to characterize the system in terms of Darcy's law [1], which assumes that a global index, the permeability K, relates the average fluid velocity u through the process with the pressure drop, Δp, measured across the system,

$$U = \frac{-K}{\mu} \nabla p \tag{1}$$

Darcy's law is an empirical law, which states that the flow rate in a porous media is proportional to the pressure gradient in the medium.

The constant of proportionality is called the permeability and the magnitude is a function of the pure structure, which contents the porosity or fiber volume content.

The validity and applicability of Darcy's law have been questioned by many authors. *Jackson et al.* [2] identified differences in the measured permeability brought about by changes in injection pressure.

Gauvin et al. [3] suggested that the flow rate, pressure and the nature of the fluid are among the factors that could strongly influence the permeability measurements. *Parseval et al.* [4] and *Steenkamer et al*. [5] found different permeability values depending on the infiltrating fluid.

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1021-9986/08/2/33 6/$/2.60

If the fluid velocity is high enough that Darcy's law is not valid, then one has to add some correction terms to the basic Darcy's law in order to take into account the effect of the deviations. *Forchheimer* suggested a second order term for velocity in order to show the deviation from the Darcy's law [6].

Vafai and *Tien* [7], analyzed the effects of a solid boundary and the inertial forces on flow in porous media. In this paper, a numerical and experimental investigation was presented in order to estimate the K value and the coefficient of inertia term. Also, the effect of inertia term on the flow front position was studied

Shahnazari et al. [8,9] with the use of numerical solution the Stoke's fluid passing the bed of spheres have estimated the system permeability based on the Darcy's law. In addition to the numerical solution for the Stoke's fluid around the spherical grains and the result comparison with the Darcy's law of fluid simulation output, they presented the relation between the permeability (K) and bed parameters (specific diameter and porousity).

The mass flow rate, fluid velocity and also the pressure loss measurements could give the possibility of fiber permeability estimation with the use of numerical methods explained later. The average porosity has been calculated based on the direct and adaptive methods with the use of saturated and advancing front flow procedures.

For this purpose the mould which contains the fiber with different amounts of constant pressure gradients has been filled. Afterwards that, the model has been solved for constant permeabilities (around the experimental results) regarding the filling time comparison, the fiber permeability amount has been estimated.

EXPERIMENTAL SYSTEM

A rectangular mold for the observation of the fluid passing through the fiber has been chosen. The fluid flow injected into a cavity with the dimension of 2 × 24 ×40 cm.

The experimental system was constructed to be able to control the resin injection rate and injection at constant pressure (Fig. 1). The flow rate was measured by a ultrasonic flow meter (Fluxus 6725).

The resolution of flow meter is 0.025 cm/s. The top plate of mold was made of Plexiglas to ensure the uniform velocity during the injection. A E-glass fiber with two different porosities was chosen as the porous media data (Fig. 2).

GOVERNING EQUATIONS

Darcy Law

In this study the fluid was assumed to be Newtonian and incompressible. For laminar and inertia-free the governing equations under these assumptions are given as follows:

$$\frac{\partial u}{\partial x} = 0 \tag{2}$$

$$u = \frac{-K}{\mu}\frac{\partial P}{\partial x} \tag{3}$$

$$u = \frac{dx}{dt}\varepsilon \tag{4}$$

Where u is the Darcy velocity, x is the local coordinate, K is the perform permeability also known as the flow conductance, μ is the resin viscosity, P is the pressure, dx/dt is the flow front velocity, and ε is the porosity of the preform.

By discretized with a first order finite difference approximation of the above equations, the direct method for estimation of $\overline{K}$ was obtained:

$$x_k - x_{k-1} = \frac{\Delta t_k}{\varepsilon_k A} Q_k \tag{5}$$

$$x_k - x_{k-1} = \frac{\overline{K}_k \Delta t_k (P_i - P_a)_k}{\mu \varepsilon_k} \tag{6}$$

Where Q is the flow rate ($= \varepsilon \frac{dx}{dt} A$), A is the cross-sectional area, P_i is the inlet pressure, P_a is the ambient pressure and $\overline{K}_k$ is a spatially averaged permeability of interval.

Also, by rearranging these equations as follows, the adaptive estimation algorithm for $\overline{K}$ was obtained

$$Q_k = a_k (x_k - x_{k-1}) \frac{A}{\Delta t_k} \tag{7}$$

$$x_k = \overline{K}_k (P_i - P_a) \frac{A}{\mu Q_k} \tag{8}$$

$$\mu(x_k - x_{k-1}) Q_k . Q_{k-1} = K_k . A[Q_{k-1}(P_i - P_a)_k - Q_k (P_i - P_a)_{k-1})] \tag{9}$$

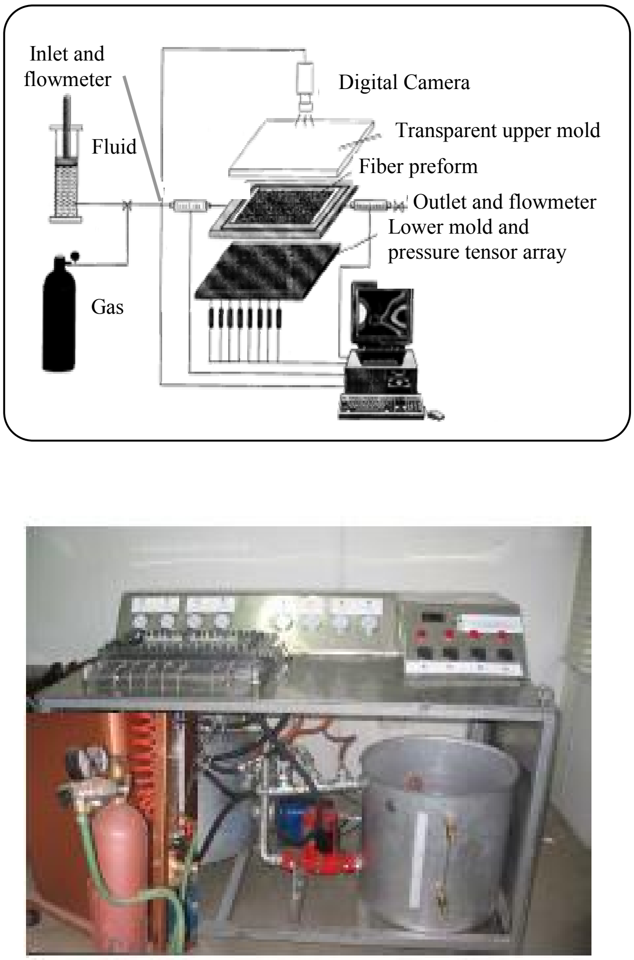
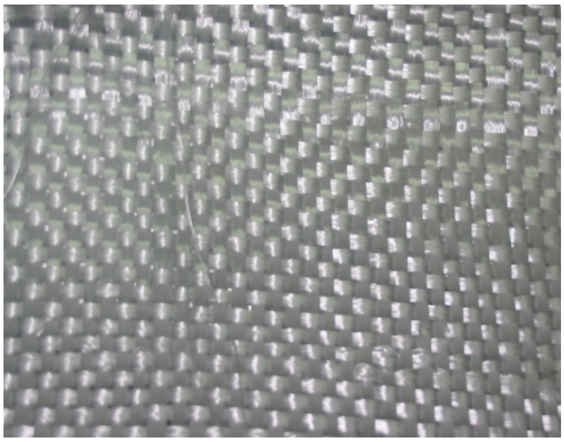
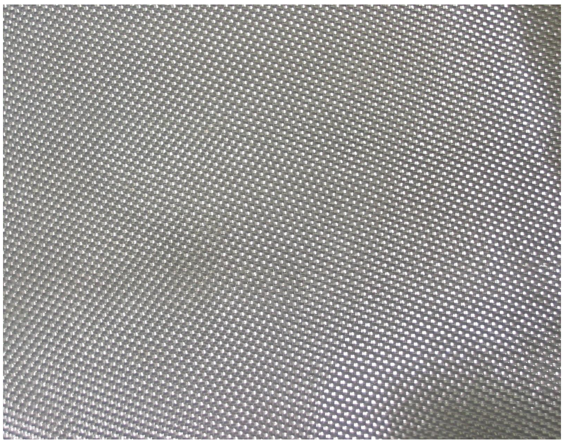


Fig. 1: The experimental Apparatus.



a) E-glass uni. fiber I.



b) E-glass uni. fiber II.

Fig. 2: The used preform fiber in experiments.

An output signal vector y_k, a parameter vector θ_k, and an input matrix W_k was defined as follows:

$$y_k = \{Q_k, x_k, \mu(x_k - x_{k-1}), Q_k \cdot Q_{k-1}\} \quad (10)$$

$$\theta_k = [\varepsilon_k, \overline{K}_k, \overline{K}_k] \quad (11)$$

$$W_k = \begin{bmatrix} (x_k - x_{k-1}) A/\Delta t_k & 0 & 0 \\ 0 & (P_i - P_a) A/\mu Q_k & 0 \\ 0 & 0 & A[Q_{k-1}(P_i - P_a)_k - Q_k (P_i - P_a)_{k-1}] \end{bmatrix}$$

$$y_k = \theta_k W_k \quad (12)$$

Forchheimer-Darcy Law

For higher velocity Darcy's law is not valid, the Forchheimer-Darcy equation is suitable for modeling the fluid flow as follows [10]:

$$\frac{\Delta P}{L} = \frac{-\mu}{K} u + \frac{\rho_f F}{\sqrt{K}} u^2 \quad (13)$$

By applying this equation with evaluated K from previous section, for higher pressure gradient, F can been obtained.

EXPERIMENTS AND CALCULATIONS

For the fiber permeability (K) estimation, several experiments have been done. First the fiber average porosity was obtained by the saturation test for the static and dynamic conditions and the average amounts of ε presented as the average volumetric porosity (table 1).

Table 1: Porosity evaluation for E-glass fiber.

		Characteristics		
		Density (kg/m^3)	Porosity Amount (%)	Relative Error Percentage
Fiber Type	Glass Fiber Type I	2550	69	±0.09 %
	Glass Fiber Type II	1700	51	±0.1 %

Table 2: Permeability value of E-glass fiber.

Fiber type		Permeability evaluated		
		2 layer	5 layer	10 layer
E-glass Uni I	Steady state	1.71±0.04	1.73±0.03	1.75±0.02
	Advanced front flow	1.67±0.04	1.68±0.03	1.69±0.02
E-glass Uni II	Steady state	0.84±0.04	0.87±0.03	0.88±0.02
	Advanced front flow	0.83±0.03	0.85±0.03	0.86±0.02

In advanced front flow method, measurements were made for three pressure differences, 0.1, 0.15 and 0.2 bar, and for different number of fiber layers.

Beside measurements, with fluid observation the flow uniformity has been fixed (Fig. 3).

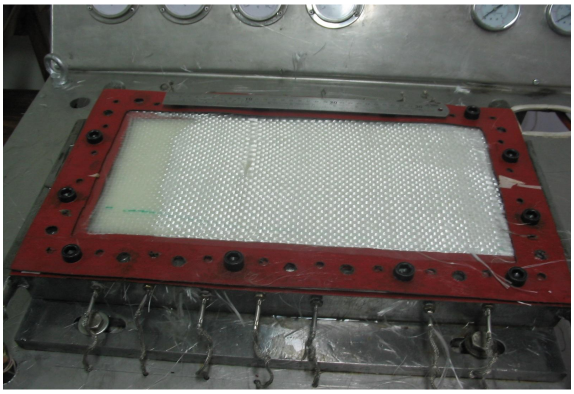


Fig. 3: Experimental uniform flow.

RESULTS AND DISCUSSION

The K value was obtained for two preform fibers by direct and adaptive methods. Reynolds number of fluid was held in low values to ensure validity of Darcy's law of flow.

The average permeability values are presented in table 2. Also, the flow front position for different pressure gradients is shown in Fig. 4.

By experiments with higher pressure gradient, the F values for each perform fiber were estimated. Equation (13) can be rearranged in the form:

$$f = 1/Re + 16 \qquad (14)$$

where $f = \Delta P\sqrt{K} / LF\rho u^2$ and $Re = \rho Fu / \mu\sqrt{K}$, to obtain a friction factor Reynolds number type of correlation which is presumably "universal".

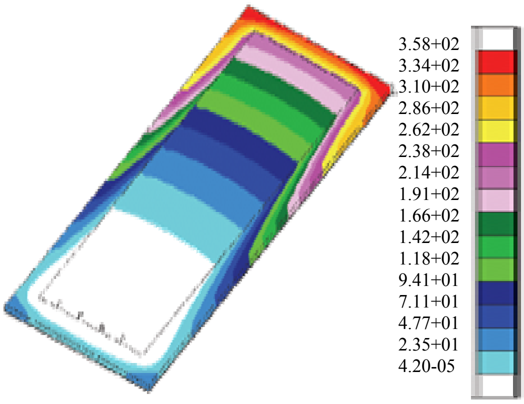
Fig. 5 shows the experimental in terms of the friction factor f and Re for two different values porosity (ε). As to be seen, the point of departure from linear to nonlinear behavior is in the range $10^{-2}<Re<10^{-1}$.

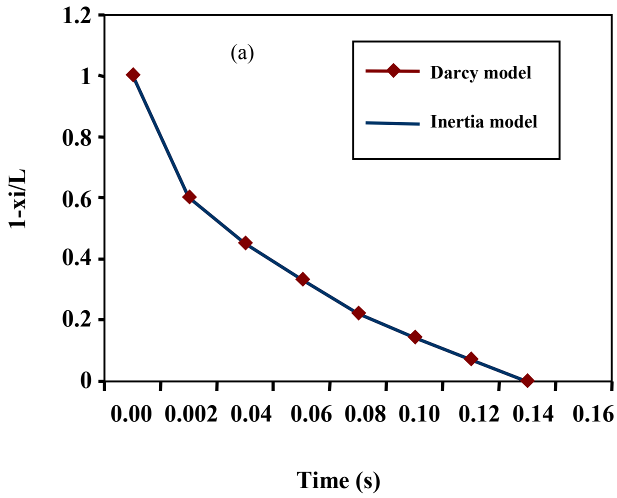
Fig. 6 shows the flow front position for different pressure gradients. Comparing the experimental results with the numerical results for Darcy law shows that, the inertia term for high Reynolds number is important.

CONCLUSIONS

Flow simulations are extremely useful tools to be used desigened to industrial application such as liquid molded composite and resin injection molding. In these applications, permeability is an important factor in flow simulation.

The experimental analysis of the flow measurements was able te estimate K for preform fibers. Also, experimental results indicate that Forchheimer model should be valid for low Re and also for a limited range of hig Reynolds numbers even when inertial nonlinearities can significantly affect the momentum transport at the pore scale.





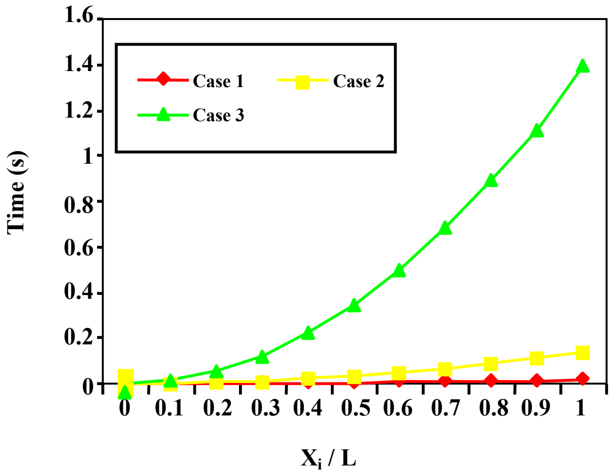
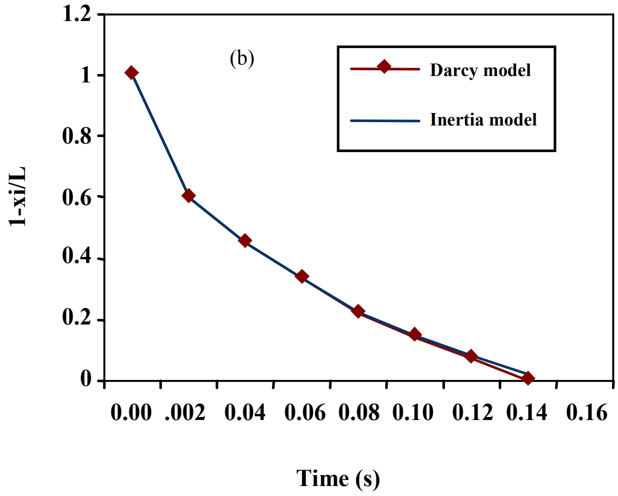
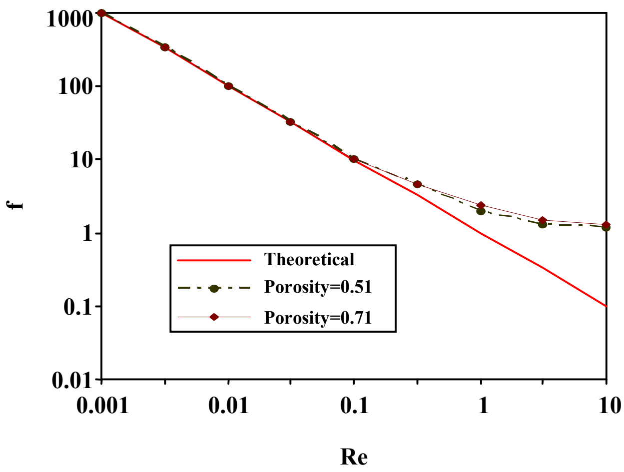


Fig. 4: Free surface position for different gradient pressure. 1: $\Delta P = 5.7\times10^{7}$ Pa. 2: $\Delta P = 5.7\times10^{6}$ Pa. 3: $\Delta P = 5.7\times10^{5}$ Pa.





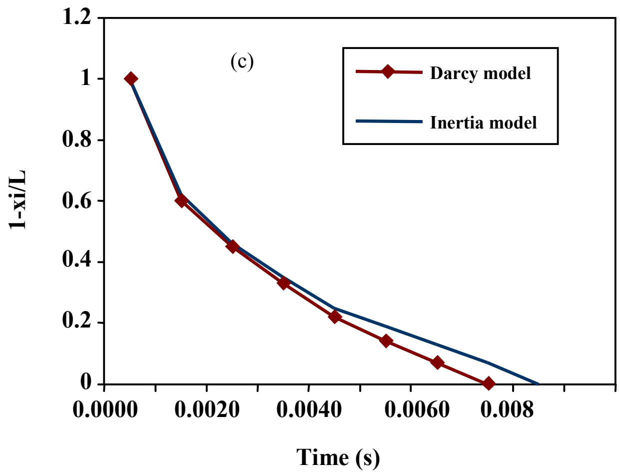


Fig. 5: The experimental in terms of the friction factor f and Re for two different values porosity (ε).

Fig. 6: Comparison of temporal free surface position with and Without inertia terms a) Re_k =0.5, b) Re_k =5, c) Re_k =10.

Nomenclatures

Latin Symbols

F	Forchheimer coefficient (defined as Eq. (15))
f	Function factor
K	Permeability vector
k	Permeability (m^2)
l	Length (m)
p	Pressure (Pa)
Q	Flow rate (m^3/hr)
Re	Reynolds number
t	Time (sec.)
U	Velocity vector
u	Velocity (m/s)
W	An input matrix
x	Local coordinate (m)
y	An input vector

Greek Symbols

Δ	Gradient Symbol
ε	Porousity
μ	Resin viscosity(Ns/m^2)
θ	A parameter vector (defined as Eq.(12))

Subscripts

a	Ambient
i	Inlet
k	Number of intervals

Received: 16th December 2006 ; Accepted : 3rd March 2008

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