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Experimental study of slip flow at the fluid-porous interface in a boundary layer flow

Aswathy Nair K.[a,*], A. Sameen[a]

[a]*Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai - 600036, India*

Abstract

A boundary layer flow over a porous laminated flat plate is analyzed. We model the 2D porous region as an array of circular cylinders kept in the span-wise direction of the flow. The porosity(ϕ) of the models is controlled through the center-to-center distance between the cylinders in the array. Experiments are performed on ϕ = 0.65 and ϕ = 0.80 porosity models for a range of Reynolds numbers, *Re*. The study focuses on the experimental confirmation and quantification of the slip velocity at the porous fluid interface. The stream wise velocity in boundary layer flow is measured using a LDV. The measurements are done at various stream-wise locations with sufficient spatial resolution in the vertical distance. The profiles thus obtained are averaged over a Representative Elemental Volume (REV) to even out the local disparities. The slip velocity is found to increase with increase in porosity and is weakly dependent on *Re*.

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Keywords: Porous media; boundary layer flow; slip velocity; porous-fluid interface

1. Introduction

Flows over and inside porous media have been studied extensively in various fields such as in hydrology and soil mechanics, biomedical engineering, catalyst engineering, thermal engineering, petroleum engineering etc.. However, the physics behind the flow at the interface region of a homogeneous fluid and a porous medium is not completely understood because of the inherent complexity of the interface both in terms of its geometric structure and the flow structure at the interface. Hence, the potential of porous media have been limited by this incomplete knowledge of its flow characteristics, primarily the inter-facial boundary conditions and the inter-facial flow governing equations, which is the motivation for the present study.

The random and complex structure of the porous medium limits the scope of experimental investigations to high porosity and permeability samples. Even so, accurate measurement of velocity inside and at the porous-fluid interface remains a challenge to the investigators since the measurement method should be non-intrusive to avoid any damage to the porous model and perturbation to the flow. Consequently, very few experimental data are available which confirms

* Corresponding author.
E-mail address: ae12s013@smail.iitm.ac.in

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the existence of a significant slip velocity at the porous-fluid interface. Beavers and Joseph[1] were the first to carry out an experimental examination of the flow over a porous, permeable surface to elucidate the inter-facial slip velocity and hence deduce an expression for it. They proposed the *ad hoc* inter-facial boundary condition relating the inter-facial slip velocity and the mean velocities above and below it as,

$$\left.\frac{\partial U_0}{\partial y}\right|_{y=0} = \frac{\alpha}{\sqrt{\kappa}}(U_s - U_D) \tag{1}$$

where α is the slip coefficient which is characterized solely by the structure of the porous surface, κ is the permeability of the porous sample, U_0 is the free-stream velocity above the porous surface, U_s is the slip velocity at the porous-fluid interface, $y = 0$. Darcy velocity, U_D is the mean velocity of flow inside the porous medium calculated as if the fluid were the only phase present in the porous medium, given by the popular Darcy's law[2],

$$U_D = \frac{\kappa}{\mu}\frac{\Delta P}{\Delta x} \tag{2}$$

where μ is the dynamic viscosity of the fluid and $\Delta P/\Delta x$ is the applied pressure gradient in the direction of the flow. By measuring the flow rates above and below the porous-fluid interface of two samples, Beavers and Joseph verified their *ad hoc* boundary condition for the samples considered and concluded that the slip coefficient, α, is independent of the flow properties and is characterized only by the material characteristics of the porous medium. However, they were unable to deduce a unique expression for α and hence the slip velocity, U_s. Taylor[3] proposed a mathematical model to confirm this characteristic of α and experimentally verified it using an ideal porous sample whose κ and α could be calculated independently. Recently, a remarkable experimental work was carried out by Tachie *et al.*[4] to understand the dependence of the inter-facial flow phenomenon with porosity, pore structure and the thickness of the porous layer. They performed PIV measurements in a circular Couette flow generated in the annular space between two concentric circular cylinders with regular arrays of rods lining the inner stationary cylinder. The angular velocity of the outer cylinder was controlled to vary the Reynolds number. The authors report that dimension of the tank was large enough to consider the flow to be essentially rectilinear in the measuring region. They used rods of circular, square and triangular cross-sections, with the same characteristic dimension, to study the effects of pore-structure. The analysis was done for the parameters range of $0.84 < \phi < 0.99$ and $0.05 < Re < 0.2$, where Re is based on tangential velocity of the outer cylinder and characteristic length of the rod. They report that the slip velocity is weakly dependent on the pore structure,thickness of the porous layer and Re. Another interesting result is that it is highly sensitive to the location of the interface. Tachie *et al.*[4] have defined the interface to be at the tangent line connecting the top surfaces of all the cylinders in the top row of the array.

A large number of theoretical and numerical studies also have been performed to understand the flow at the porous-fluid interface. Brinkman's analytical study[5] was the first to model the flow using a macroscopic model developed from equation 2 by adding a diffusion term to it. However, the numerical studies by Sahraoui and Kaviany[6] and Larson and Higdon[7,8] on 2D porous media, modeled using arrays of cylinders, suggest that the Brinkman model can be applied only to highly porous and permeable media which have scarce applications. Ochoa-Tapia and Whitaker[9,10] provided more insight into the inter-facial flow phenomenon with their theoretical analysis of momentum transfer across the interface. However, a unique relation for the slip velocity could not be deduced and the authors themselves suggest the need for "detailed laboratory and numerical experiments" to arrive at a consistent boundary condition. Breugem *et al.*[11] recently reported a self-similar solution for the developing laminar boundary layer flow over a permeable wall. However, their analysis is constrained by a low value of permeability, κ. More recently, Zhang and Prosperetti[12] numerically analyzed the effect of fluid inertia on the inter-facial flow. They reported the generation of a lift force over the porous layer.

A common characteristic of all the above studies is that they are restricted to high porosity ($\phi > 0.8$) and permeability samples and low Reynolds number flows, which is far from practical. Hence in the present study, samples with moderate ($\phi = 0.65$) and high ($\phi = 0.80$) porosity are studied for a range of Reynolds numbers Re, the definition of which is given in section 3.

The method of averaging of the results[13] forms an important part of the analysis of flow through porous media. The averaging helps to eliminate the local singularities and disparities in the data due to the inherent complex and random structure of the porous media. The concept of a Representative Elemental Volume (REV), which is the smallest volume that enables the use of a continuum approach for porous media flows, thus becomes an indispensable part of the analysis. The REV is analogous to the control volume in a homogeneous fluid flow.

The present study aims to model a macroscopic flow in a porous-fluid domain, formulate a universal expression for the slip velocity at the porous-fluid interface for real porous media and also deduce self-similar solutions for the coupled porous-fluid boundary layer flows for a wide range of *Re*. A spatial averaging of the obtained data is performed in this 2D study.

2. Experimental Analysis

The scope of experiments is restricted to high porosity and permeability models due to difficulty in measurements associated with the inherent randomness and complexity of the structure of the porous medium, as explained in section 1. As a result, most of the experimental studies were carried out on arrays of cylinders which were assumed to model two-dimensional porous media. We follow a similar approach in the present study in which the models for the experiments are fabricated with the porous part formed by square and hexagonal arrays of stainless steel rods. The porous region is placed downstream of an inclined backward facing step to reduce the possibilities of flow separation when flowing past a porous block. The center-to-center distance between the cylinders in the axial and lateral directions determine the porosity of the models and is defined for square and hexagonal arrays as follows with the dimensions as described in Fig. 1,

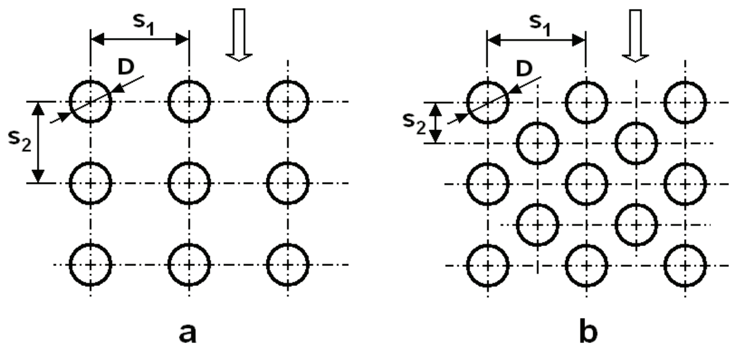


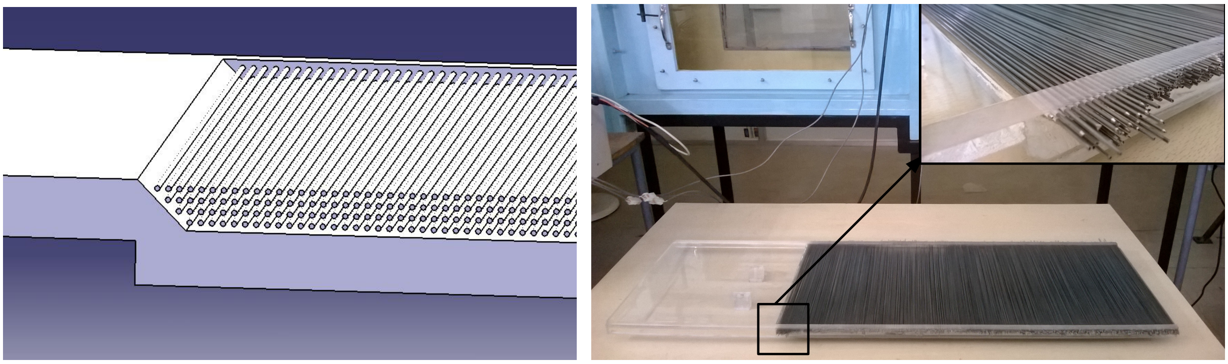
Fig. 1: Schematic of the array of cylinders for (a) square array; (b) hexagonal array. Courtesy: Creative Commons GNU Free Documentation License. The open arrows represent the direction of flow.

$$Porosity,\ \phi = \frac{Total\ Area - Area\ of\ cylinders}{Total\ Area}$$

$$= \frac{(S_1 \times S_2) - (4 \times 0.25 \times \frac{\pi}{4}D^2)}{S_1 \times S_2},\quad for\ Fig.1(a)$$

$$= \frac{(S_1 \times (2 \times S_2)) - (4 \times 0.25 \times \frac{\pi}{4}D^2\ +\ \frac{\pi}{4}D^2)}{S_1 \times (2 \times S_2)},\quad for\ Fig.1(b)$$

The flow phenomenon is studied using a suction-type, open-loop, subsonic wind tunnel facility designed to produce velocities in the range of 0 – 30 ms^{-1} with a $0.5 \times 0.5 \times 2$ *m* test section. A LDV having a probe volume size of 70 μm and stand-off distance of 100 *mm* is used for measurement since it offers the non-intrusive measurement advantage. The LDV can measure velocities in the range of −50 to 600 ms^{-1} with an accuracy of 99.7% and repeatability of 99.9%. The seeding for the LDV is provided by means of a smoke generator which vaporizes a glycerol-water mixture. An automated traverse system is used to position the LDV probe in the required *x* (stream-wise), *y* (vertical) and *z* (span-wise) positions. The data acquisition for the LDV and the traverse movements are controlled through the respective proprietary softwares.



(a) (b)

Fig. 2: (a): 3D model with $\phi = 0.80$; (b): the fabricated model with zoomed in view in the inset.

The cylinder diameter, d, is taken as the characteristic dimension in the direction of flow and the height of the porous layer, h, in the transverse direction of the flow. The cylinder diameter is chosen since it is used to define the center-to-center distance, D, between the cylinders, which in turn defines the porosity of the models. The free-stream velocity U_0 is taken as the characteristic velocity. Presently, two models with porosity value $\phi = 0.80$ and 0.65, with square array arrangement have been analyzed. Fig. 2 shows the 3D model and the fabricated model with $\phi = 0.80$. The model with $\phi = 0.80$ has the characteristic dimensions of $d = 1$ *mm*, $D = 2$ *mm* and $h = 8$ *mm* and that with $\phi = 0.65$ has $d = 2$ *mm*, $D = 3$ *mm* and $h = 12$ *mm*.

3. Results and Discussion

The measurements are taken at various x locations downstream of the step after considering sufficient length for flow development. The spatial resolution for the measurements in the y direction is progressively increased towards the porous-fluid interface. The interface is located at the tangent line connecting the top surfaces of all the cylinders in the top most layer of the array and is denoted by $y = 0$, as mentioned earlier in section 1. The LDV probe volume is positioned at the interface after careful scrutiny. The experiments are repeated over a period of days at random times to eliminate any kind of influence from the surroundings and/or the power supply(since the LDV is susceptible to electromagnetic interference despite its digital filtering circuitry).

We have defined the Reynolds number based on the cylinder diameter, d and the free-stream velocity, U_0. The analysis of the $\phi = 0.80$ model at Reynolds number, $Re_d = 325$ for $U_0 = 5.1\ ms^{-1}$ at $x/d = 300$, where x is the distance along the flow direction with origin at the beginning of the porous region, and mid-span yielded the local velocity profile shown in Fig. 3. Similarly, the local velocity profile for the model with $\phi = 0.65$ at $Re_d = 497$ for $U_0 = 3.88\ ms^{-1}$ at $x/d = 300$ is shown in Fig. 4. The stream-wise velocity, u, is normalized with U_0 and the vertical distance y with the boundary layer thickness, δ_{99} ($\eta = y/\delta_{99}$). The local profiles display a dynamic and variable character since they are highly sensitive to the structure of the porous medium at the measuring location.

In order to smoothen the disparities in the local velocity profiles, the two-dimensional profiles are spatially averaged over the REV, as mentioned in section 1. A REV of $4d$ was chosen since it was the smallest length that eliminated the local jumps and reverse velocities. The averaging process and the profile obtained are found to be insensitive to REV size if the REV is greater than $4d$. The mean profiles from the spatially averaged data is in concurrence with the available literature[4] on significant slip velocity at the porous-fluid interface. The averaged velocity profile for the $\phi = 0.80$ model is shown in Fig. 5 and that for the $\phi = 0.65$ model is shown in Fig. 6. In all plots the porous-fluid interface is represented by a horizontal solid line. The experimental results presented here suggest that the slip velocity increases with an increase in porosity. This is attributed to the decreasing diffusion of flow into the porous medium due to the denser solid matrix at lower porosities. The measured slip velocity is 40% of U_0 for porosity of 0.80 and 13% for porosity of 0.65. Tachie *et al.*[4] found slip velocity to be 7% for a porosity of 0.99 in the case of Couette flow. Also, in confirmation with their results, the slip velocity is seen to be weakly dependent on Re_d. The dependence of

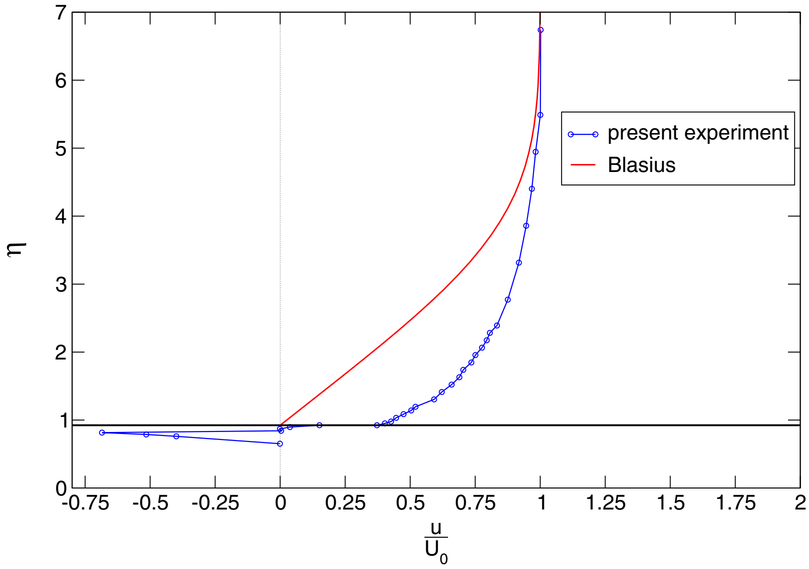


Fig. 3: The local velocity profile for the model with $\phi = 0.80$ at $x/d = 300$ and mid-span for $U_0 = 5.1\ ms^{-1}$ and $Re_d = 325$. The solid line represents the porous-fluid interface.

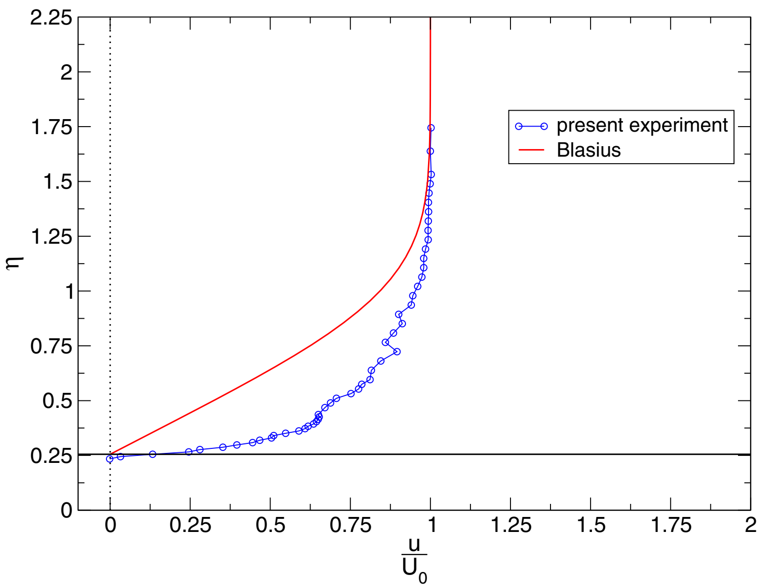


Fig. 4: The local velocity profile for the model with $\phi = 0.65$ at $x/d = 300$ and mid-span for $U_0 = 3.88\ ms^{-1}$ and $Re_d = 497$. The solid line represents the porous-fluid interface.

slip velocity on pore structure and permeability can be ascertained with the results from the remaining models with hexagonal arrangement ($\phi = 0.80$ and $\phi = 0.65$), which will be completed soon.

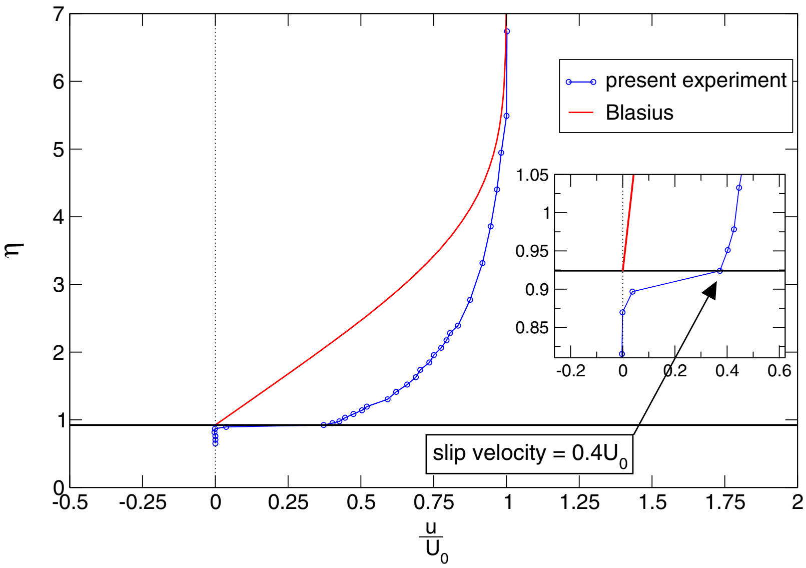


Fig. 5: The averaged velocity profile for the model with ϕ = 0.80, averaged over a length of 4d around x/d = 300 for U_0 = 5.1 ms^{-1} and Re_d = 325. The solid line represents the porous-fluid interface. Inset: magnified view of the profile near the porous-fluid interface.

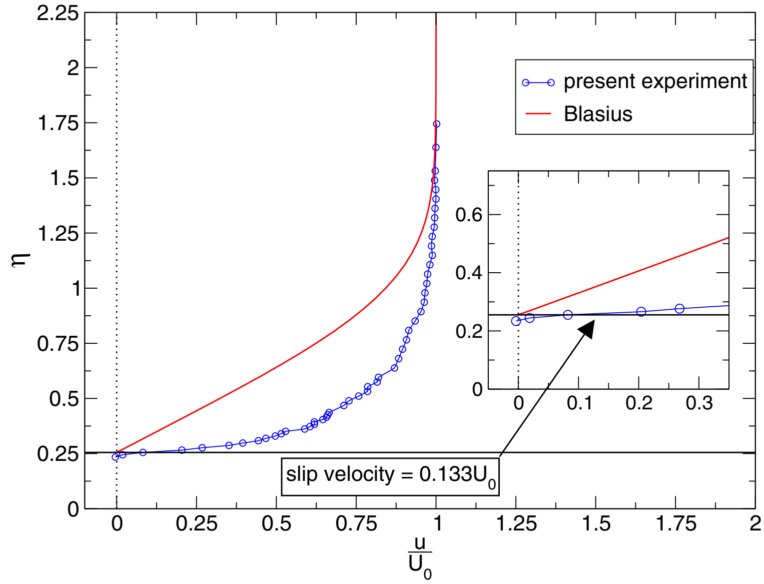


Fig. 6: The averaged velocity profile for the model with ϕ = 0.65, averaged over a length of 4d around x/d = 300 for U_0 = 3.88 ms^{-1} and Re_d = 497. The solid line represents the porous-fluid interface. Inset: magnified view of the profile near the porous-fluid interface.

4. Conclusion

Although, a vast body of literature is available on the porous-fluid inter-facial flow phenomenon, very few address the flow physics at the interface and even fewer have approached it experimentally. A clearer picture of the inter-facial flow phenomenon could lead to better utilization of porous media in fluid flow applications, which was the motivation for the present study. We have experimentally investigated the two-dimensional flow phenomenon at the porous-fluid interface in a rectilinear flow over a porous laminated flat plate. The porous region was modeled from array of circular cylinders with the center-to-center distance between the cylinders defining the porosity of the model. Our results have confirmed the existence of a significant slip velocity at the interface, which is one order less than the mean flow velocity. The slip velocity is found to be marginally dependent on Re_d.

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