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Short Communication

Scale estimation for turbulent flows in porous media

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HIGHLIGHTS

- Particle image velocimetry is used to obtain time resolved velocity fields.
- Local turbulence quantities are measured within individual pores.
- Pore averaged turbulent kinetic energy production is measured.
- Pore averaged dissipation rates are calculated.
- Results are used to determine pore averaged dissipation scales of turbulence.

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ABSTRACT

The results of an experimental study to determine the smallest, dissipative scales of the turbulent flow in a randomly packed porous bed are presented and discussed. Particle Image Velocimetry was used to obtain time dependent two-dimensional velocity fields within the bed, which were then used to obtain turbulent statistical measures within the flow field. Results are presented for representative pores for a range of pore Reynolds numbers, Re_{pore}, from 839 to 3964, which include integral length and velocity scales and estimates of the Kolmogorov scales of length, velocity and time. The results show an asymptotic region at sufficiently high Re_{pore}, on the order of 2800, where scaling is normalized using the bed pore scales. It is also shown that the turbulent Reynolds number for this flow in the asymptotic limit is on the order of $0.07Re_{pore}$, for the range of pores studied.

1. Introduction

The study of flow in porous media extends over a wide range of disciplines and applications such as gas adsorption, filtration, combustion, catalytic reactors, food processing, nuclear waste management, thermal insulation as well as in groundwater hydrology, oil recovery and others. In many cases the flows in these geometries are laminar, due to low flow rates and small characteristic lengths, however, there are a growing number of important applications were the flow becomes turbulent, (de Lemos, 2012) such as catalytic bed reactors.

Of great importance to understanding these flows and for development of effective models are the length, time and velocity scales at both the large, or integral, scales, as well as the smallest scales. Characteristics of integral scale eddies, which play a critical role in the observed increase of momentum transport, or scalar transport, in turbulent flows, are used to close the Reynolds stress terms and scalar–flux terms using, say, the Boussinesq hypothesis or gradient diffusion hypothesis (Tennekes and Lumley, 1972; Pope, 2000). Information about the smallest, or Kolmogorov, scales in turbulent flows is used to construct effective micromixing models (Fox, 2003), and is necessary to help develop Large Eddy Simulation (LES) models. The spectrum of the variance of scalars such as reactant concentration or temperature, which can be viewed as a measure of departure from uniformity, is dependent on turbulent motion length scales as well as the scalar's molecular diffusivity (Tennekes and Lumley, 1972). Presently our understanding of time and length scales that occur in the turbulent flow fields of porous media is very limited due to the difficulty in obtaining detailed time and space resolved velocity data in such complex flow geometries. Studies involving local measurements of flow fields in porous media and their application to explain mixing or dispersive behavior of randomly closed packed beds are limited to creeping or steady inertial flow regime, and are essentially missing for the high Reynolds number regime.

In a previous study integral scales have been measured and found to have asymptotic values for pore Reynolds numbers greater than approximately 2800 (Patil and Liburdy, 2013b, 2013c). In this paper, time resolved PIV measurements of turbulent porous media flows are used to determine the characteristics of the scales of velocity,

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length and time at the smallest scales versus Repore. The relationships of the integral and Kolmogorov scales with Re_{pore} are given and discussed along with the turbulent Reynolds number, Re_t.

2. Methodology

The experimental test section used in this study is shown in Fig. 1. The test section was constructed from Pyrex® (70 mm × 70 mm × 90 mm long), and filled with 15 mm diameter, D_B, beads also made from Pyrex®. The bed porosity, ϕ was measured to be 0.45, and the bed aspect ratio (width to bead diameter ratio) was 4.67. The flow was driven in a closed loop which is described in more detail by Patil and Liburdy (2013b). A two degree of freedom traversing stage (Parker Hannifin Corporation, Model: 4454) placed under the test section was used to move the bed horizontally perpendicular and along the optical axis of the viewing system. In order to obtain refractive index matching for the PIV measurements an aqueous solution of ammonium thiocyanate (NH_4SCN) was used as the working fluid which was index matched to that of the walls and spheres by adjusting its concentration. An earlier study identifies the effect of refractive index mismatch on the particle detection, and resultant errors in PIV measurements (Patil and Liburdy, 2012). In the current study the difference of the index of refraction between the solid and liquid phases was kept below 0.0005, the resultant associated error is given below. The liquid phase viscosity was 1.44 cP as directly measured using a viscometer (Cambridge Viscosity, Model: VISCOlab 450). The density was 1.118 g/ml. Results are presented for a pore Reynolds number from, $Re_{pore}=839$ to 3964, based on the porous bed hydraulic diameter, $D_H=\phi D_B/(1-\phi)$ and average pore velocity, $V_{int}=V_{Darcy}/\phi$, where $V_{Darcy}=Q/A_{bed}$, with Q being the volumetric flow rate and A_{bed} the bed cross section.

The image data were analyzed using a multi-grid, multi-pass adaptive correlation method. A moving average validation scheme was used to reject outliers. The vectors rejection rate was less than 1%. The total uncertainty is 1.19% in the cross-stream or transverse direction and 1.0% in the downstream or longitudinal direction. The spatial resolution of the measurements results in a vector spacing of approximately 0.2 mm (or 0.0133 D_B). Details of uncertainty are given in Patil and Liburdy (2012) and the magnification error and the methodology used to find the other errors is given in Patil and Liburdy (2013a). Estimation of the local velocity gradient, used to determine local shear rates, was accomplished using a central difference scheme. Assuming nearby vectors to have nearly equal bias errors, the error in the velocity gradient is mostly affected by random error in the velocity measurement. The random error in velocity gradient due to propagation of random error in velocity measurements was estimated to be 4.42 s^{-1} (1.5% of the maximum value) for the highest Re_{pore} case of 3964.

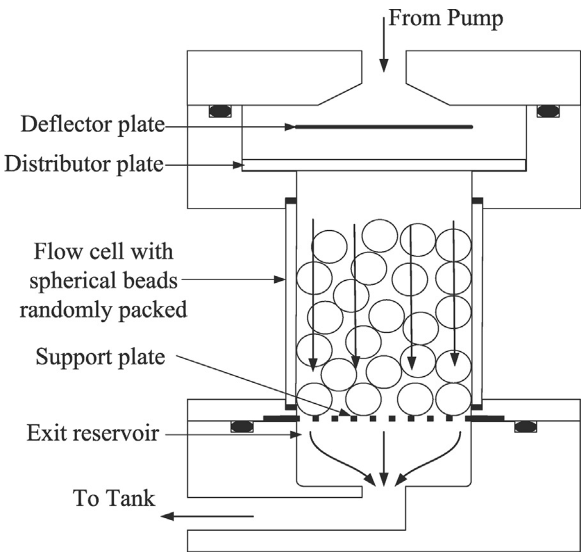

Fig. 1. Schematic of the experimental test section used for PIV measurements.

The number of instantaneous time maps collected for each Re_{pore} at each location was 1600. Approximately 230 of these maps can be considered statistically independent since the temporal autocorrelation function decays to zero past $7\Delta t$, where Δt is the separation time between vector maps, which was 2.5 ms at the highest Re_{pore} condition. Therefore random error of the time averaged mean velocity field estimation is expected to be reduced by an order of magnitude due to the large number of independent realizations of instantaneous velocity field. For similar reasons, pore averaging operations are expected to reduce the random error further by two orders of magnitude.

3. Results

Data were collected in pores near the center of the bed, to reduce or eliminate any direct wall effects of the flow structure. A set of pores were selected based on a detailed study of the affect of pore geometry on the flow characteristics as described by Patil and Liburdy (2013a). In that study major pore types were found based on their mean flow: (i) tortuous channel flow, where the flow resembles a meandering channel flow, (ii) high momentum inflow coupled with impingement onto the solid phase surfaces, (iii) large recirculating regions formed due to flow separation and (iv) jet-like flow caused by inlet constricted flow into the pore. These four pores types are labeled A, B, C and D, respectively in the figures of this paper. Patil and Liburdy (2013b, 2013c) show how the different flow types contribute to overall dispersion based on mean and turbulent flow characteristics. Asymptotic values, at sufficiently high Re_{pore} were found to be remarkably similar among pores.

In order to determine estimates of the smaller scales the integral length, velocity and time scales were used and are given in Patil and Liburdy (2013b, 2013c). The pore averaged turbulent kinetic energy, $\langle k\rangle^f$, was used to determine the integral velocity scale, u_l, normalized by the interstitial velocity, V_{int}, as

$$\frac{u_l}{V_{int}} \approx \sqrt{\frac{\langle k\rangle^f}{V_{int}^2}} \tag{1}$$

The operator $\langle \cdot \rangle$ represents an average over an individual pore; this is in contrast to the averaging used in the Method of Volume Averaging, MVA, which averages spatially over a larger region which includes a number of pores with the solid phase included. Also, in this operation the time averaged values at each location are implied; that is, the time averaged value of the local turbulent kinetic energy, k, is used. The pore area weighted average value for all pores, $u_{l,avg}/V_{int}$, based on the pore area for a given pore was 0.38 with a standard deviation among all of the pores of 0.028.

The integral length scale, l, was determined using the spatial autocorrelation function for the fluctuating velocity fields. For the case of porous media flows the pore averaged spatial correlation function in the transverse direction, $\langle \rho_T\rangle^f$, and longitudinal direction, $\langle \rho_L\rangle^f$, over length s were computed using position data only within the fluid phase. Integration of the autocorrelation function up to the first zero crossing was used as a measure of the transverse and longitudinal integral length scales, L_T and L_L, respectively. The trends show a clear distinction between the longitudinal and lateral length scales, the former being larger by approximately a factor of two at the larger Re_{pore} values. For Re_{pore}