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Review

Transition from creeping via viscous-inertial to turbulent flow in fixed beds

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This work is dedicated to Prof. Dr. Georges Guiochon on the occasion of his 75th birthday. In particular, U.T. wants to thank him for his prominent role as scientific advisor and mentor, as well as for his friendship over the past decade.

Abstract

This review is concerned with the analysis of flow regimes in porous media, in particular, in fixed beds of spherical particles used as reactors in engineering applications, or as separation units in liquid chromatography. A transition from creeping via viscous-inertial to turbulent flow is discussed based on macro-scale transport behaviour with respect to the pressure drop–flow rate dependence, in particular, the deviation from Darcy's law, as well as direct microscopic data which reflect concomitant changes in the pore-level hydrodynamics. In contrast to the flow behaviour in straight pipes, the transition from laminar to turbulent flow in fixed particulate beds is not sharp, but proceeds gradually through a viscous-inertial flow regime. The onset of this steady, nonlinear regime and increasing role of inertial forces is macroscopically manifested in the failure of Darcy's law to describe flow through fixed beds at higher Reynolds numbers. While the physical reasons for this failure still are not completely understood, it is not caused by turbulence which occurs at Reynolds numbers about two orders of magnitude above those for which a deviation from Darcy's law is observed. Microscopic analysis shows that this steady, nonlinear flow regime is characterized by the development of an inertial core in the pore-level profile, i.e., at increasing Reynolds number velocity profiles in individual pores become flatter towards the center of the pores, while the velocity gradient increases close to the solid–liquid interface. Further, regions with local backflow and stationary eddies are demonstrated for the laminar flow regime in fixed beds. The onset of local fluctuations (end of laminar regime) is observed at superficial Reynolds numbers on the order of 100. Complementary analysis of hydrodynamic dispersion suggests that this unsteady flow accelerates lateral equilibration between different velocities in fixed beds which, in turn, reduces spreading in the longitudial (macroscopic flow) direction.

Keywords: Porous media; Fixed beds; Sphere packings; Darcy's law; Flow regimes; Inertial flow; Turbulent flow; Velocity profiles; Critical Reynolds number; Hydrodynamic dispersion; Zone spreading; Lateral equilibration; Liquid chromatography; Turbulent flow chromatography; Review

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1. Introduction

Turbulence is one of the most important and, at the same time, yet least understood problem in fluid dynamics. It is known that all flows of liquids can be divided into two strictly different types: those referred to as *laminar* flows in which the fluid moves in layers or laminas gliding smoothly over adjacent ones with only molecular interchange of momentum, and their opposite, *turbulent* flows in which all fluid mechanical properties (velocity, pressure, temperature, etc.) fluctuate with extremely irregular spatio-temporal pattern. This complicated structure of turbulent flows affects many properties of liquid transport which differ substantially in the laminar and turbulent cases. The difference between laminar and turbulent regimes is revealed in a number of phenomena which are of great significance for many engineering problems. For instance, the presence of irregular fluctuations of the fluid velocity in turbulent flows leads to a sharp increase in mixing of the fluid, often considered as the most characteristic feature of turbulent motion. In turn, due to a far more efficient radial mixing, the velocity profile in turbulent flow is considerably more uniform than in laminar flow. Based on this fact Giddings in 1965 [1] suggested that "velocity equalization" in turbulent flow through an open capillary is advantageous for chromatographic separation efficiency which he verified experimentally in 1966 [2]. Subsequently, turbulent flow has been studied in gas chromatography [3–6], but did not demonstrate great potential for retained solutes [7].

Though the existence of two sharply different flow regimes was pointed out in the first half of the 19th century [8], the first theoretical approach to studying turbulence came only with the pioneering works of Osborne Reynolds published in 1883 and 1895 [9,10]. In these studies Reynolds focused his attention, in particular, on the conditions under which laminar flow of fluid in pipes is transformed into a turbulent one and proposed a general criterion for dynamic similarity of flows of a viscous incompressible fluid in geometrically similar systems. Dynamic similarity of flows was proposed to be identified with the coincidence of the Reynolds number, $Re = ud/\nu$, calculated for pipes, where u is the characteristic scale of velocity, d the diameter of the pipe, and ν is the kinematic viscosity of the fluid. The Reynolds number can be also viewed as a parameter expressing the ratio between inertial forces (related to acceleration or deceleration of fluid) and viscous (frictional) forces acting within the fluid. Viscous forces assist in the equalization of velocities at neighbouring points, i.e., in smoothing out small-scale heterogeneities in the flow. By contrast, inertial forces producing mixing of different fluid volumes which move with different velocities result in a transfer of energy from large- to small-scale components and, as a consequence, assist in the formation in the flow of heterogeneities characterizing turbulent flow.

One of the fundamental results formulated in Reynolds' work is that flow will be laminar as long as Re does not exceed a critical value, while for $Re > Re_{\text{crit}}$ it will be turbulent. The first experiments for verifying this criterion and actually measuring Re_{crit} were conducted by Reynolds himself. In these experiments, coloured water was introduced along the axis of a tube (glass pipe) at a smooth inlet connected to a reservoir of pure water. Variation of Re was realized by changing the pipe diameter, flow velocity, and viscosity of the water (via temperature). For small values of Re, the coloured water took the form of a thin jet indicating laminar flow. As Re increased, at the instant of passing through its critical value, the form of the coloured jet suddenly changed. At a rather small distance from the inlet towards the pipe, the jet spread out and waves appeared in it. Further on, separate eddies were formed, and towards the end of the pipe the whole liquid became coloured. It was also found that the value of Re_{crit} corresponding to the transition from laminar to turbulent flow depends on the degree of disturbance in the fluid while entering the pipe. Re_{crit} is the smaller the greater the intensity of the disturbance. Subsequent experimental studies on flow regimes in pipes and tubes have shown that Re in itself is not a unique demarcation criterion for transition to turbulence in open channels [11–13]. For instance, in the case of a tube with a sharp entrance, pushed through the plane wall of the reservoir, the end of the tube creates a significant disturbance and Re_{crit} is about 2800. By contrast, onset of turbulence in flow through a straight pipe can be delayed up to Re_{crit} of 10^5 [13] if special means are employed for damping flow disturbances at the entrance of the tube.

Though the characterization of liquid transport occurring within porous media is of fundamental importance for understanding numerous processes in natural and engineering sciences, the existence of turbulent flow in porous media has been addressed experimentally only in the second half of the 20th century [14–18]. As porous media used in engineering applications and modern liquid chromatography like particulate fixed beds [19] often have small interstitial pores and low hydraulic permeabilities, and because fluid velocity is relatively small, the predominant regime is the laminar flow regime. Meanwhile, high-speed flow may lead to turbulent flow, that is, highly unsteady chaotic flow within the interstitial pore space. In packed beds, viscous and inertial loss terms are additive, an effect completely at odds with the observed flow behaviour in straight pipes. Evidently, something other than simple laminar and turbulent flow takes place in fixed beds. Compared to pipe flow the representative dimension of the largest flow eddy in a porous medium is limited by the pore dimension, usually much smaller than the macroscopic dimension of the system (pipe or column diameter). Investigations of flow through porous media [20–27] allow to conclude that (i) the transition from laminar to turbulent flow is gradual and (ii) Re_{crit} based on average interstitial pore dimensions is several times lower than for flow through a straight pipe.

Another fundamental characteristic of turbulent flow in porous media is the distinction between microscopic and macroscopic turbulence. The only experimental evidence of turbulence in a three-dimensional porous medium is that of microscopic turbulence where turbulent flow was detected by point-wise probes within the pores of the medium, as pointed out by Antohe and Lage [28]; there has been no attempt to volume-average local signals in a representative volume to obtain a signature of macroscopic turbulence. It is possible that by averaging a large number of local (random) signals in a representative ele-