Journal of Non-Newtonian Fluid Mechanics 212 (2014) 28–35

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

journal homepage: http://www.elsevier.com/locate/jnnfm

Fibre suspensions in Hagen–Poiseuille flow: Transition from laminar plug flow to turbulence

A. Nikbakht [a,*], A. Madani [a], J.A. Olson [a], D.M. Martinez [a,b]

[a] Department of Mechanical Engineering, University of British Columbia, 2054-6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada
[b] Department of Chemical and Biological Engineering, University of British Columbia, 2360 East Mall, Vancouver, BC V6T 1Z3, Canada

ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form 8 August 2014
Accepted 11 August 2014
Available online 23 August 2014

Keywords:
Turbulent transition
Pipe flow
Non-Newtonian fluids
Yield stress
Viscoplastic fluids
Fibre suspension

ABSTRACT

The focus of the present work is an experimental study of the behaviour of semi-dilute, opaque fibre suspensions during fully-developed pressure-driven flow in a cylindrical pipe. We measure the instantaneous velocity profiles across the radius R of the pipe, using ultrasound doppler velocimetry (UDV), as a function of the applied hydraulic pressure and concentration (0.75–1.75% (wt/wt)). In total 374 conditions were tested on three different flexible, non-Brownian fibre suspensions. The goal of the work was to gain insight into the role of the plug during transition to turbulence. From the UDV measurements, we estimated the radius of the plug r_p, the yield stress of the suspension τ_y, through knowledge of the pressure drop, as well as the Reynolds stress $\rho\overline{u'^2}$. We find that the yield stress varied non-monotonically with flow rate for each suspension tested. At slow flow, i.e. when $r_p/R \to 1$, we observe that plug densification, i.e. a contraction of the plug created by the growth of a lubricating film at the wall, caused the initial increase in yield stress. Yield stress was found to continue to increase with flowrate and its maximum was reached at $0.4 < r_p/R < 0.7$. With plug sizes smaller than $r_p/R < 0.4$, the yield stress of the plug diminished with increasing flowrate through what we believe to be an erosion-type mechanism. We estimate the critical Reynolds number Re_c for the disappearance of the plug for all cases.

1. Introduction

The focus of the present work is an experimental study of the transition to fully-mixed, or turbulent flow, of fibre suspensions in a cylindrical pipe. The present work, although found in many natural and industrial settings, was initiated from papermaking operations where control of the product quality requires knowledge of the flow state at different velocities. Papermaking suspensions are considered to be shear thinning and possess a yield stress τ_y. With these suspensions the axial profile in fully developed laminar flow is characterized by an unyielded or plug zone. The radius of the plug zone is dictated by a balance between the frictional pressure drop and the yield stress of the fluid. With increasing flow rates the size of the plug diminishes. Among the remaining open questions with these fluids are the role of the plug during transition and the role of the size of the fibres.

Understanding transition flow of suspensions is difficult. There are many previous reports of experiments on different materials (Newtonian or non-Newtonian) which mimic aspects of the flow considered here, and insight can be gained by considering these first. We categorize the papers into 3 groups which will be summarized below.

The first group of papers represent the simplest case that is studies of transition of a Newtonian fluid in Hagen–Poiseuille flow. Since Reynolds' experiment, a large number of experimental and theoretical studies have been conducted to characterize transition. In laminar flow, fluid particles follow straight lines that are parallel to each other called streamlines. In turbulent flow different sizes of eddies are superimposed on the streamlines. Larger eddies carry the fluid particles across the streamlines and smaller eddies create stirring that causes diffusion. The onset of turbulence is not immediate. There is a process of instability that makes laminar flow a turbulent one. In this transitional zone, the flow is neither laminar nor fully turbulent, and the observed pressure drops are intermediate between those for laminar and turbulent flow.

The details of Newtonian transition is still under investigation. From the engineering perspective, it is generally accepted that transition can be predicted using one dimensionless parameter, the Reynolds number $Re = UD/\nu$ where U is the bulk velocity (m/s), D is the diameter of the pipe (m) and ν is the kinematic viscosity (m^2/s). When Re exceeds a critical value, even small disturbances, which always exist in a physical system, can cause instability and transition. From a mathematical perspective, although

* Corresponding author. Tel.: +1 604 822 2813.
E-mail address: abbas.nikbakht@gmail.com (A. Nikbakht).

http://dx.doi.org/10.1016/j.jnnfm.2014.08.006
0377-0257/© 2014 Elsevier B.V. All rights reserved.

hydraulic stability theory is capable of predicting instability of some flow configurations (transient growth or amplification of small disturbances), it is unable to predict transition (i.e. a critical Reynolds number) for pipe flows because the flow is stable at all Reynolds numbers. So nonlinear analysis is a must to be able to have a predictive mechanism in mathematical fashion. For a Newtonian fluid it is known that the Reynolds number above 2100 is generally accepted as the critical value of practical interest to transition.

There are a number of means to characterize the onset of transition. In the simplest case, the relation between pressure drop and velocity is used to identify the flow regimes. The change from the laminar to the turbulent flow regime results in a large increase in the flow resistance. The functional relationships and physical flow patterns are fundamentally different for the two regimes. The Fanning friction factor f can be derived exactly for laminar flow and empirically for turbulent flow. The Fanning friction factor is related to the shear stress at the wall as:

$$\tau = \frac{f\rho U^2}{2} \tag{1}$$

The value of f in laminar pipe flows for Newtonian fluids is $64/Re$. Measuring the friction factor departure from $64/Re$ is an effective way to detect the transition. In addition to this, characterization of the point of transition in experiments can also be based on the statistics of the time-series of the velocity and pressure, because the motion of turbulent eddies, which are random cause fluctuation. Here, the root-mean-square (rms) of local velocity fluctuations u'

$$u_{rms} = \sqrt{\overline{u'^2}} \tag{2}$$

is calculated to measure turbulence strength and

$$I = \frac{u_{rms}}{\bar{u}} \tag{3}$$

for turbulence intensity I. The observation of the velocity and the turbulence intensity at the centreline is a generally accepted method to detect transition for Newtonian fluids.

There is a large number of works which attempted to characterize flow in this transition region [1,10,20,21,44,45]. Wygnanski and his coworkers found that flow disturbances evolve into two different turbulent states called puffs and slugs during transition [10,45,46]. They observe and describe the evolution of the localized turbulent puffs and slugs in details such as their shape, the way they propagate, their velocity profiles and turbulence intensities inside them. The puff is found when the Reynolds number is below $Re \sim 2700$ and the slug appears when the Reynolds number is above $Re \sim 3000$. Both the puff and slug are characterized by an abrupt change in the local velocity in which the flow conditions are laminar outside the structure and turbulent inside. The puff and slug are distinguished from each other by the abruptness of the initial change between the laminar and turbulent states. It has been reported that for a puff, the velocity trace is saw-toothed whilst a slug has a square form on velocity-time readings.

Since this classic study, a number of works have been reported in the literature attempting to further characterize transition experimentally. Bandyopadhyay [1], for example, reports streamwise vortex patterns near the trailing edge of puffs and slugs. Darbyshire and Mullin [4] indicate that a critical amplitude of the disturbance is required to cause transition and this value depends on Re. Toonder and Nieuwstadt [44] performed LDV profile measurements of a turbulent pipe flow with water. They found that the rms of the axial velocity fluctuations near the wall is independent of Reynolds number. Eliahou et al. [10] investigated experimentally transitional pipe flow by introducing periodic perturbations from the wall and concluded that amplitude threshold is sensitive to disturbance's azimuthal structure. Han et al. [17] expanded on the work of Eliahou et al. [10] and advances the argument that transition is related with the azimuthal distribution of the streamwise velocity disturbances. Transition starts with the appearance of spikes in the temporal traces of the velocity and there is a self-sustaining mechanism responsible for high-amplitude streaks. They indicated that spikes not only propagate downstream but also propagate across the flow, approaching the pipe axis. Hof et al. [20] performed an experimental investigation of the transition to turbulence in a pipe. Although they did not measure any velocity field, they introduced a scaling law which indicates that the amplitude of perturbation required to cause transition scales as $O(Re^{-1})$. Draad et al. [5] proposed several scaling laws and also Peixinho and Mullin [34]. Draad et al. [5] examined transition from laminar to turbulent by imposing disturbances to a Newtonian fluid (water) flow in a cylindrical pipe facility. They reported a critical disturbance velocity, which is the smallest disturbance at a given Reynolds number for which transition occurs. They found that for large wavenumbers, i.e. large frequencies, the dimensionless critical disturbance velocity scales according to Re^{-1} , while for small wavenumbers, i.e. small frequencies, it scales as $Re^{-2/3}$. Peixinho and Mullin [34] perturbed the flow using small impulsive jets and push-pull disturbances from holes in the pipe wall. They reported that the critical value required to cause transition scales in proportion to Re^{-1} for jets and the threshold scales as $Re^{-1.3}$ or $Re^{-1.5}$ for push-pull disturbances with the precise value depending on the orientation of the perturbation. These experimental and numerical studies for Newtonian fluids within the last few years have improved our understanding of the transition to turbulence.

The second (much smaller) group of papers (Group 2) report investigations of pressure driven flow of general non-Newtonian fluids (including some viscoplastic fluids). Non-Newtonian fluids have been generally treated in similar fashion to that of a Newtonian fluids. In order to make use of standard Newtonian theory a value for the viscosity of the fluid is required. Usually defining a unique value for viscosity is meaningless for a non-Newtonian as the viscosity is not constant for a given fluid and pipe diameter. It must be evaluated at a given value of shear stress. There have been a variety of attempts to generalize the Newtonian approach, discussed above, and examples of this are given in the classic works of Metzner and Reed [31], Dodge and Metzner [6]. This concept has been extended by Govier and Aziz [13] for Bingham fluids. In perhaps the most recent work in this area, Guzel et al. [15,16], also used deviations from the laminar friction factor curve to define the onset of transition. In this case they defined an average Reynolds number Re_G by evaluating the local viscosity $\mu(r)$ in the pipe through knowledge of local velocity field $u(r)$, i.e.

$$Re_G = \frac{4\rho}{R}\int_0^R \frac{u(r)}{\mu(r)} r dr = \frac{4\rho u_c^2}{R|P_x|} \tag{4}$$

where R is the radius of the pipe (m); u_c is the centreline velocity (m/s); ρ is the density of the fluid (kg/m^3); and P_x is the pressure drop per unit length (Pa/m). With this, they report (see Fig. 1) for three classes of fluids that transition occurs when the friction factor deviates from $64/Re_G$ and the critical Reynolds number depends upon the rheology of the fluid.

In recent years there has been a number of increasingly detailed studies of transition of non-Newtonian fluids [5,11,33,35,36]. One of the key findings in this literature was advanced by Peixinho et al. [33], who show that transition for the yield stress fluid takes place in two stages. In the first stage, transition is characterized by local velocity profiles that deviate from the theoretical laminar solution without any observable differences in the u_{rms} of the signal. In some cases, like that reported by Guzel et al. [15], the flow