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OBSERVATION OF THE TURBULENT TRANSITION OF A FIBRE SUSPENSION IN HAGEN-POISEUILLE FLOW

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ABSTRACT

The focus of the present work is an experimental study of the transition to turbulent flow of papermaking fibre suspensions in a cylindrical pipe. The suspensions used in this study possess yield stress. With this class of fluid the axial profile in fully developed slow flow is characterized by an unyielded or plug zone. With increasing flow rates the size of the plug diminishes. One of the remaining open questions with these suspensions is the role of the plug during transition.

In this work we characterize the size of the plug using ultrasound Doppler velocimetry (UDV) as a function of flow rate for dilute, i.e. less than 2% consistency, papermaking suspensions in a 50 *mm* diameter, 10 *m* long cylindrical pipe. The plug size was determined through analysis of local spatial and temporal variations of the velocity, strain-rate and the fluctuating component of velocity. With this, we were able to estimate the yield stress of the suspension through knowledge of the applied pressure gradient and find the yield stress to be in the range of 2–10 *Pa*, depending upon the consistency and Reynolds number *Re*. We observe complex behavior with the plug in which we see initially that with increasing velocity, the plug diminishes through a densification-type mechanism in a response to an increase frictional pressure drop. At higher Re, it diminishes through an erosion-type behavior. We estimate the critical Reynolds number Re_c for the disappearance of the plug to be $Re_c \sim 10^5$.

Key words: Turbulent transition, Pipe flow, Non-Newtonian fluids, Yield stress, Viscoplastic fluids, Fibre suspension.

1 INTRODUCTION

The focus of the present work is an experimental study of the transition to fully-mixed, or turbulent flow, of a fibre suspension in a cylindrical pipe. The present work 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 fluids 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. One of the remaining open questions with these fluids is the role of the plug during transition.

Understanding transition flow of a papermaking suspension is difficult. There are a number of classes of flows in the literature which mimic aspects of the flow considered here and insight can be gained by considering these first. We categorize these into three groups which will be summarized below. The major works for category I are for the simplest case of Hagen-Poiseuille flow of a Newtonian fluid. 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, flow is neither laminar nor fully turbulent, and in which 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 $Re = U\,D/\nu$ where U is the average velocity ($m.s^{-1}$), D is the diameter of the pipe (m) and ν is the kinematic viscosity ($m^2.s^{-1}$). 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 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 also 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 value of *f* in laminar pipe flows for Newtonian fluids is $f = \frac{64}{Re}$. 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 (e.g. $u(t) = \bar{u} + u'(t)$). Here, the root-mean-square (rms) of local velocity

$$u_{rms} = \sqrt{\overline{u'^2}} \tag{1}$$

is calculated to measure turbulence strength and

$$I = \frac{u_{rms}}{\overline{u}} \tag{2}$$

for turbulence intensity I. The observation of the velocity and the turbulence intensity at the centerline 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 ([1–6]). Wygnanski and his coworkers ([1; 4; 7]) found that flow disturbances evolve into two different turbulent states called puffs and slugs during transition. 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 [2], for example, reports streamwise vortex patterns near the trailing edge of puffs and slugs. Darbyshire & Mullin [8] indicate that a critical amplitude of the disturbance is required to cause transition and this value depends on *Re*. Toonder & Nieuwstadt [3] 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. [4] 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. [9] expanded on the work of [4] and advance the argument that transition is related with the azimuthal distribution of the stream wise velocity disturbances and 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 propagates downstream but also propagates across the flow, approaching the pipe axis. Hof et al. [5] measured the velocity fields instantaneously over a cross-sectional slice of a puff and showed that uniformly distributed streaks exist around the pipe wall and slower streaks exist near the centreline in a puff. They show that the minimum amplitude of a perturbation required to cause transition scales as the inverse of the Reynolds number, i.e. $O(Re^{-1})$.

In the second category II are pressure-driven non-Newtonian flows. Unlike category I, we find that this literature is less explored, especially with 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, τ. 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 [10] and [11]. This concept has been extended by [12] for Bingham fluids. In perhaps the most recent work in this area, Güzel and his co-workers ([14],[15]), 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.

$$Re_G = \frac{4\rho}{R}\int_0^R \frac{u(r)}{\mu(r)} r dr = \frac{4\rho u_c^2}{R|P_x|} \tag{3}$$

where R is the radius of the pipe (m); u_c is the centreline velocity ($m.s^{-1}$); ρ is the density of the fluid ($kg.m^{-3}$); and P_x is the pressure drop per unit length ($pa.m^{-1}$). With this, they report (see Figure 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 rehology of the fluid.

In recent years there has been a number of increasingly detailed studies of transition of non-Newtonian fluids ([13; 16–19]). One of the key findings in this literature was advanced by [18], 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 [15], the flow profile is asymmetric. In the second stage, with increasing the Reynolds number, turbulent puffs and slugs appear. With viscoplastic fluids, [15] indicates that the plug is present during the second stage of transition and disappears only when the the Reynolds (turbulent) stress is greater than the yield stress.

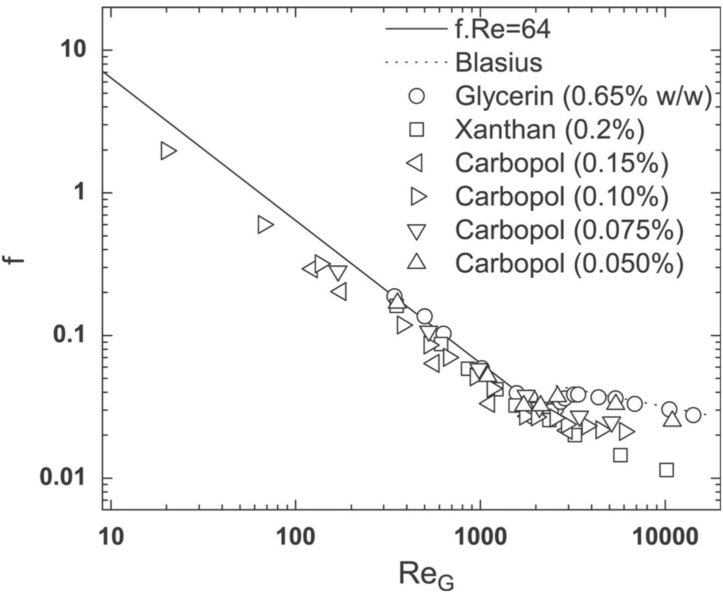

Figure 1. Examination of the deviations of f from $64/Re_G$ for three different classes of fluids. Glycerin represents a Newtonian fluid. Xanthan and Carbopol represent shear thinning and viscoplastic fluids, respectively. Reproduced from [14].

In the third category, we examine transitional flows with papermaking fibre suspensions. Before we discuss the pertinent literature relevant to the motion of this class of material, it is instructive to review the properties of papermaking fibre suspensions. Papermaking fibres are hollow, flexible rod-like particles which have a wide distribution in both length and diameter depending upon species and growing conditions. Papermaking fibre suspensions typically aggregate into coherent networks which possess measurable mechanical strength [20–23]. The reviews of [24],[25], [26], or [27] and the references contained therein summarize our current knowledge of fibre suspension rheology. Although fibre networks may form by surface charges, [28] found that mechanical entanglement rather than colloidal force was the principle source of fibre flocculation. They entangle, bend, and remain networked from frictional forces transmitted by fibres that are locked into bent configurations [29]. [30] confirmed the influence of bending stresses on network strength through stress relaxation experiments. There is some debate in the literature at what is the percolation point for forming networks A number of research groups estimate that at i.e. ~ 5 kg/m^3 there are, on average, 3–4 inter-fibre contacts and the suspension is considered to be networked [29; 31]. Using positron emission tomography, Martinez et al. [32] indicate networking can occur at significantly lower concentration related to aspect ratio of the fibre. Once networked, the suspension takes on the property of a (somewhat) solid structure. In particular compressive stresses on the suspension can be transmitted via the network and the structure has the ability to support itself. If stressed by an external force, the network stress will resist this force until the fibre network deforms or consolidates irreversibly. This physical make-up leads to a complex rheological behavior with the suspensions showing strong non-linear stress/strain-rate relationships.

In Hagen Poiseuille flow, papermaking fibre suspensions display a number of features similar to that of viscoplastic fluids. Using non-invasive tools such as NMR imaging or ultrasound doppler velocimetry (UDV), in Hagen Poiseuille flow before transition, a plug is evident in the central portion of the pipe and diminishes in size with increasing velocity ([26; 33–36]). A similar feature has been reported by [37] for pressure-driven flow of a dilute suspension in a rectangular channel.

Transition is quite complex and most authors indicate that it occurs in stages. In early work, Forgacs et al. [38] and Daily & Bugliarello [39] categorized the stages as either plug, mixed, or turbulent. The *plug regime* indicates a coherent plug, i.e. particles with correlated velocities, which are present in all regions of the channel except in the near wall region. The motion of the plug is assisted by a laminar lubricating film of water in the region next to the wall. In the *mixed region*, a plug is present in the central portion of the pipe but in this case, the lubricating film is now turbulent. These authors qualitatively describe that the plug diminishes as the turbulent stress is larger than the yield stress of the suspensions. In the fully turbulent region, the plug is broken-down and the flow becomes turbulent over the entire cross-section of the pipe. Further insights into this behavior are given by Duffy & Titchener [40], Duffy et al. [41]. Of interest is the recent work by Jasberg [42], who measured the thickness of the lubricating layer in the plug regime, using a laser technique, as well as the turbulent characteristics of the flow field in the mixed regime using UDV. Using this data, Jasberg [42] indicates that there are five stages of transition and describes each phase as

(1) plug flow with direct fibre contact with the wall
(2) plug flow regime with lubrication layer
(3) plug flow regime with incipient fluid phase turbulence
(4) mixed flow regime, and,
(5) fully turbulent flow regime

This is shown schematically in Figure 2. In his doctoral thesis, Jasberg [42] opens the possibility that forces such as (inertial) lift or lubrication forces play a significant role in the behavior of the plug, especially in the near wall region.

To summarize the existing literature with papermaking suspensions, we find that transition is quite complicated and occurs in a number of stages. Most authors agree that there are between 3–5 stages. Unlike Newtonian or shearthinning fluids, the early stages of transition are not visible by examining the time dependent velocity fluctuations along the pipe axis; here velocity fluctuations remain at approximately laminar levels. Transition like behavior occurs in regions closer to the wall as there is a significant increase in turbulent intensity levels. For generalized Newtonian fluids, asymmetrical flow profiles are usually the first indication

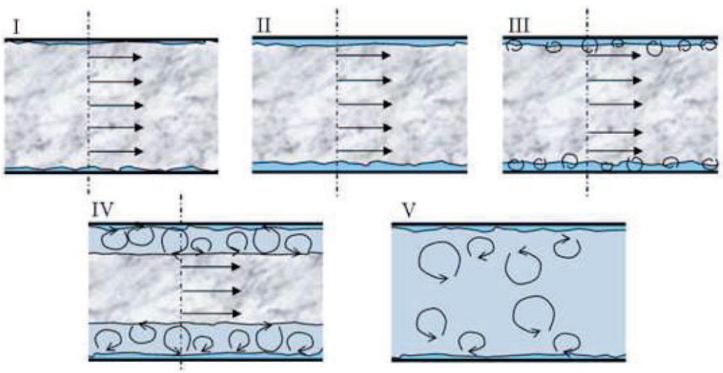

Figure 2. Schematic of the stages of transition. Reproduced from [42].

of transition and most likely a genuine effect of a traveling wave structure, a global mode of instability. This is not reported in the literature for papermaking suspensions. Finally, there is no indications in the literature of the effect of the plug during transition. This is especially evident during the final stages of transition when the plug is small in comparison to the size of the pipe. This is one of the open remaining questions in this literature and serves as the motivation for this study.

Given this, in this paper we characterize the size of the plug as a function of *Re*, from slow flow to the point of transition in the hopes of better defining the stages of transition. In §2 we outline the experimental set up, the materials and the UDV methodology. In §3 we give estimates of both the yield stress and the size of the plug and make comments of the behavior of the plug during transition.

2 EXPERIMENTAL SETUP AND PROCEDURES

All results reported are from a test section of straight, smooth pipe 10 m long with an inner diameter 50.8 *mm*, located over 100 pipe diameters from the last disturbance. The setup is illustrated schematically in Figure 3. The flow is generated by a variable-frequency driven (VFD) centrifugal pump from an inlet reservoir of approximately 4 m^3 capacity to an outlet reservoir of the same capacity. The pump can provide a maximum flow rate of 0.1 m^3/s, with water as the working fluid which represents a *Re* number of 2.5×10^6. Laminar flow with water was not achievable in this loop. The test section of the flow channel is comprised of one continuous pipe which was aligned horizontally with the aid of a laser leveling tool.

The measuring system used for velocity profile measurements is pulsed ultrasonic Doppler velocimeter (UDV) (Model 3010, www.signal-processing.com) with a frequency of 8 MHz. The ultrasound transducer has an active diameter of

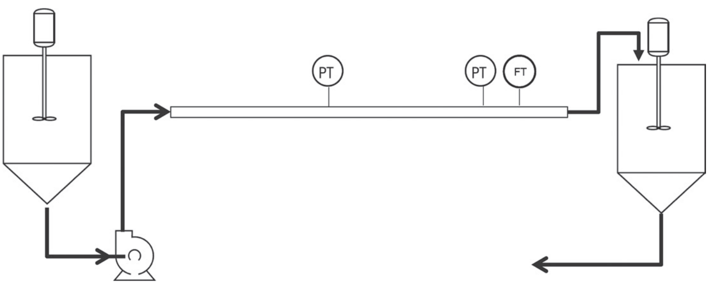

Figure 3. Schematic view of the experimental set up. PT and FT are defined as a pressure and flow transducers, respectively.

5 *mm* and the measuring volume is a thin-disc shape element with 5 *mm* diameter. One thousand instantaneous measurements were used to estimate the average and fluctuating components of the velocity at each radial location.

One differential pressure transducer (*PT*) is located near the inlet and outlet of the flow channel. The accuracy of the transducer is 0.02% of the full scale and they were calibrated with a digital pressure gauge. Pressure readings later reported through our paper are averaged over substantial length of time to increase the confidence in the estimate. Flow rates were estimated using two alternative methods:

(1) Using a magnetic flow meter (Rosemount) installed near the outlet reservoir.
(2) Radial profiles of the axial velocity are measured via UDV and the flow rate is estimated by integration.

Good agreement was found between these estimates.

Four different fluids were tested in this work: one Newtonian fluid (water) and a NBSK papermaking fibre suspension tested at three different mass fractions (wt/wt%). The NBSK pulp had an fibre length of approximately 2.8 *mm* and a coarseness of 0.2 *mg*/*m*. The initial mixing of the suspensions were done in the reservoir and then circulated through the flow channel itself in order to ensure their homogeneity, prior to conducting any experiment. This procedure eliminates, in principle, the initial degradation of the suspensions, i.e. the freeness of the pulp was essentially constant. The detailed test conditions at different flow rates and fiber concentrations are shown in Table 1, where the Reynolds numbers based on water density and viscosity, are listed.

Table 1. The experimental conditions tested. Four series of tests were conducted. In series A, we used water at 23 *°C* as the reference fluid conducted the tests over the entire range of the pump. Please note that it was difficult to achieve laminar flow of this material in this diameter of pipe. In series B-D, we used a NBSK pulp at three different consistencies. and estimated Reynolds number using the density and viscosity of water. The yield stress measurements are estimated using the methodology given below. This will be discussed subsequently

	Fibre Concentration (wt/wt)%	*Q (max) L/min*	U_b *(max) (m/s)*	Re_c	τ_y *(max) (P a)*	*No. Experiments*
A	0	720	1.5	2×10^3	0	20
B	0.5	359	0.7	1.5×10^5	2	12
C	0.75	574	1.2	2.4×10^5	5	14
D	1.0	694	1.4	2.9×10^5	10	18

At this point we turn our attention to the methodology to estimate the plug size r_p and yield stress τ_y. We follow closely the signal analysis routine given by [35] as well as [42]. To begin, we present a representative UDV profile in Figure 4. We estimate the size of the plug using three different criteria, i.e.

(1) $u(r)/u_c > 0.99$, where u_c is the centreline velocity (Method 1)
(2) the shear strain rate, i.e. du/dr, is less than 0.01 (Method 2)
(3) the spatial derivative of the fluctuating component of the signal, u_{rms}, is less than 0.01 (Method 3)

These results are averaged and represent an estimate of the plug size. The uncertainty of the estimates will be discussed shortly. With r_p (m), τ_y (pa) may be estimated from knowledge of the fully developed pressure drop per unit length using

$$\tau_y = \frac{1}{2}|P_x|r_p \tag{4}$$

as given by [35].

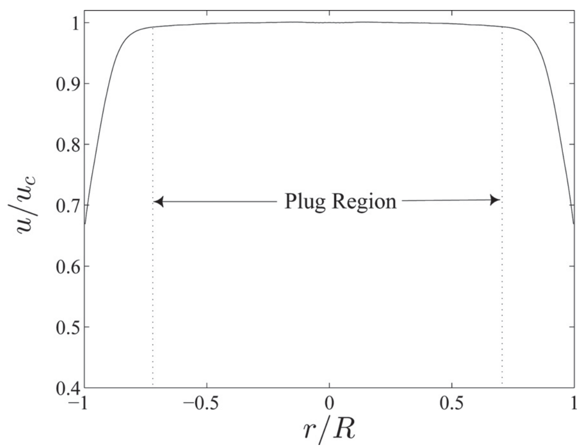

Figure 4. A representative UDV measurement of the local velocity for a papermaking suspension. This example made with a pulp consistency of 0.5% and with Re = 54,000. The dashed horizontal lines indicate the plug region. Outside of this the suspension is yielded.

3 RESULTS AND DISCUSSION

Before proceeding to the main findings of this work it is instructive to examine first the average velocity and turbulent fluctuation profiles as a function of *Re*. We do so by examining representative profiles for one concentration for four different Reynolds numbers, see Figure 5. The first observation that can be made from this figure is that with increasing *Re*, the plug diminishes in size. At $Re = 1.9 \times 10^5$, the plug has completely disappeared. The second observation is that at lower *Re* it is easier to distinguish the plug from the profiles and the uncertainty of the estimate increases with increasing *Re*. To highlight this latter point, we show in Figure 6 where the spread in the different estimates increases with increasing *Re*.

Estimates of the evolution of the plug size as a function of *Re* for all cases tested is given in Figure 7. The error bars in the graphs represent the uncertainty in estimates of plug size using the three different methodologies. What is evident in this figure is that the plug size diminishes somewhat linearly with increasing *Re* over the range tested. Similar findings have been reported by [43], [41], [26] and [37]. We find that the critical Reynolds number Re_c in which the plug size disappears varies with increasing concentration and report that $Re_c \approx 1.6 \times 10^5$ with a 0.5% consistency suspension and nearly doubles to 3.0×10^5 with a 1% suspension.

We know turn our attention to the main findings in this section and estimate the yield stress of the suspension as a function of *Re*, see Figure 8. As shown, non-monotonic behavior is observed in which yield stress of the plug initially increases

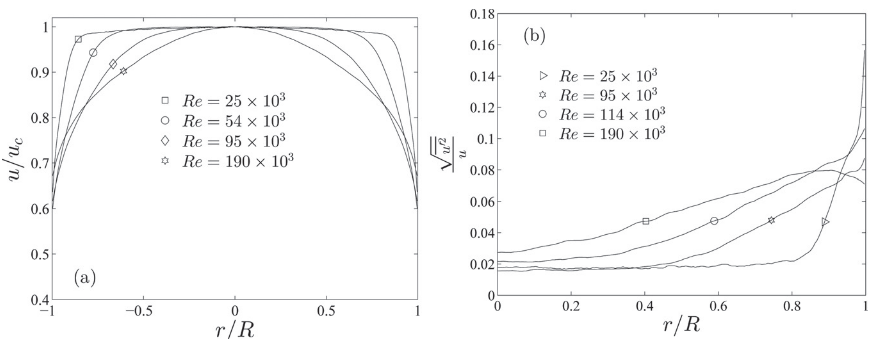

Figure 5. A representative UDV measurement of the local velocity and fluctuating component for a papermaking suspension as a function of *Re*. This example made with a pulp consistency of 0.5%. In (a) the velocity profiles are reported. The fluctuating components are given in (b).

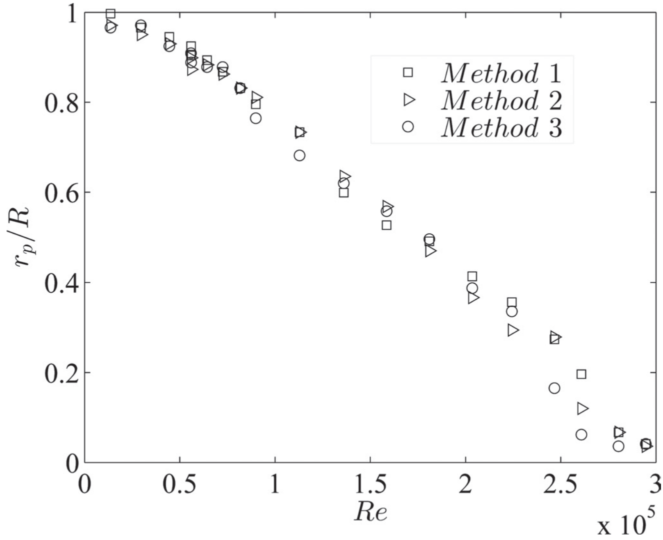

Figure 6. An estimate of the plug size using the three different methodologies outlined in §2. This example is given for Series D in Table 1.

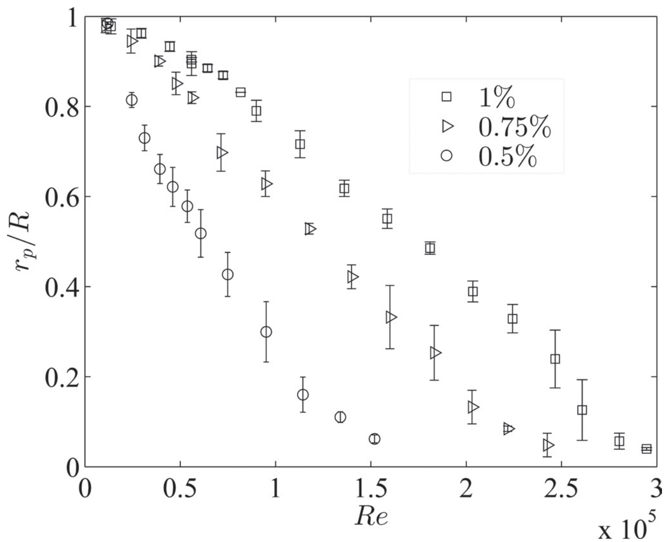

Figure 7. An estimate of the plug size as a function of *Re* for the three suspension consistencies tested.

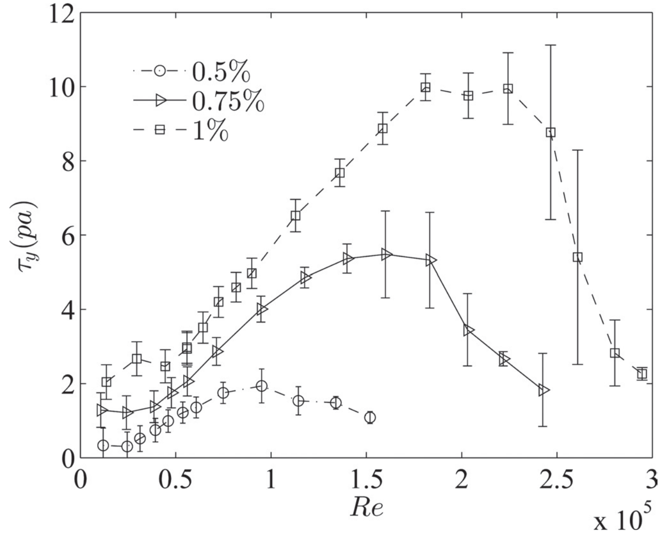

Figure 8. An estimate of the yield stress as a function of *Re*.

before diminishing as the plug begins to break. This behavior has not been reported previously. We find that the maximum yield stress occurs at different *Re* for each suspension tested and that transition to turbulence across the entire cross-section of the pipe can only occur after the plug has disappeared. We find that this occurs at Re_c at much higher values than that for a Newtonian fluid in pipe flow and as a result we conclude that the plug retards transition.

For fibre suspensions, the role of the plug region in retarding transition is largely unknown. If one interprets the plug region to be fully rigid below the yield stress then the flow is analogous to that with the plug replaced by a solid cylinder moving at the appropriate speed. As shown by [44], sliding Couette-Poiseuille flow, stabilizes the flow. These authors show that when the sliding velocity is 36% of the maximum Poiseuille velocity, the neutral curves for symmetric mode vanishes and the flow becomes linearly stable. Presumably, since the effective viscosity becomes infinite at the yield surface the flow should be locally stabilized. In the absence of multi-dimensional flow measurement, three possible behaviors may be postulated at transition: (i) transition may occur in the yielded annulus around the plug, leaving intact the plug region; (ii) transition is retarded until the plug region thins to such an extent that the Reynolds stresses (in the annular region) can exceed the yield stress; or (iii) a combination of (i) and (ii). In Figure 9 we present the ratio of averaged Reynolds stress at the edge of the plug

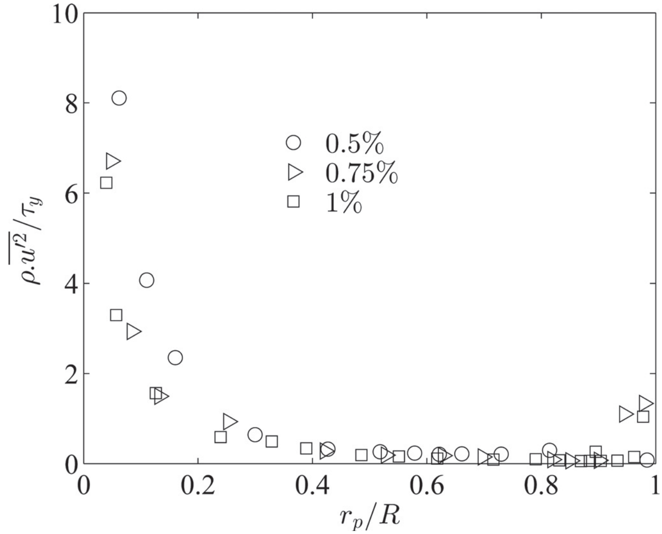

Figure 9. The ratio of averaged Reynolds stress at the edge of the plug to the yield stress as a function of plug size.

to the yield stress as a function of plug size. The first observation that can be made from this figure is that data for all three measurements collapse onto one curve, indicating the possibility of a scaling law. What we see is that initially, i.e. when $r_p/R \to 1$, the values of

$$\frac{\rho\overline{u'^2}}{\tau_y} < 1 \tag{5}$$

and the plug size diminishes somewhat linearly. As the turbulent stress are much small than the yield stress, the reduction in size must result from a response to the network to shear, created from the frictional pressure drop. Duffy & Titchener [40] argue that papermaking fibres suspensions densify under shear. With $r_p \to 0$, $\rho\overline{u'^2}$are much greater than τ_y from which we conclude that the plug breaks apart through an erosion type mechanism. Mih & Parker [43] have indicated this. It is interesting to note that for all three cases tested $\rho\overline{u'^2} \sim \tau_y$ at $r_p/R = 0.2$. This suggests to us that the disappearance of the plug during transition occurs in two steps, i.e. densification in a response to fractional pressure drop followed by erosion when the turbulent stresses are greater than the yield stress.

4 SUMMARY

In this work we measured the instantaneous velocity profiles of fully developed Hagen-Poiseuille flow using a papermaking fibre suspension at three different concentrations. The goal of this work was to develop a better understanding of transition. In particular we were interested in examining the effect of the plug during transitional flow. With the instantaneous velocity measurements, we estimated the size of the plug r_p, as well as the yield stress as a function of the Reynolds number. We find that the plug diminished somewhat linearly, and the yield stress displayed non-monotonic behavior, with increasing Reynolds number. The yields stress was found to vary from 2–10 *Pa*, depending upon the consistency and *Re*. We find that transition region ends at a Reynolds number much greater than that of the Newtonian case and is characterized by the disappearance of the plug. We define this to be the critical Reynolds number and report a value of $Re_c = 1 \times 10^5$ for a 0.5% consistency NBSK suspensions

In what we feel are the main results of this work we find that the plug size scales quite well with the ratio of the Reynolds stress to the yield stress of the suspension, i.e. $\rho\overline{u'^2}/\tau_y$. Through our measurements we estimate that the plug initially reduces in size to overcome the increase in the frictional pressure drop. We find that in this region the yield stress of the suspension increases in this region. With r_p/R less than approximately 0.2, the ratio of the Reynolds stress to the yield stress is greater than unity, and the plug size diminishes through an erosion-type mechanism. We estimate the critical Reynolds number Re_c for the disappearance of the plug to be 1.9×10^5 for a 0.5% suspension. This values increases weakly consistency over the range tested.

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Transcription of Discussion

OBSERVATION OF THE TURBULENT TRANSITION OF A FIBRE SUSPENSION IN HAGEN- POISEUILLE FLOW

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Juha Salmela VTT

Very nice work, Mark. Can you comment on the lubrication layer and do you think there is also some effect of fibre orientation?

Mark Martinez

Yes, I do think there is an effect, but we don't have the ability, in our lab, to measure concentration profile in the pipe, nor the orientation profile.

Paul Krochak Innventia

Very nice work, Mark, and just a comment. You have the ERT (Electrical Resistivity Tomography) setup in your lab, why don't you put that on there and try to measure concentration?

Mark Martinez

Hindsight is 20/20. I do not think, ever, I would have thought that concentration would be varying in a pipe.

Discussion

Paul Krochak

One more question: we are actually doing some rather similar work over at KTH and Innventia. I wonder is there any possibility that you could be just confusing plugs with, say, fibres moving away from the centre or into the centre? Could you imagine that instead of having a plug, could you actually have almost like an anti-plug?

Mark Martinez

I do not understand your question, sorry.

Paul Krochak

Let's discuss it after the session.

Jean-Claude Roux Grenoble Institute of Technology-Pagora (from the chair)

It was an interesting presentation. Concerning the yield stress, have you tried to change the raw material of the fibres, for example, in order to verify this with the new tools that are now available?

Mark Martinez

Yes, we have. This was not presented here, but we have changed both the state of the fibres by refining and the type of fibres.

Jean-Claude Roux

Concerning the forces that you demonstrated from the lubrication layer and densification, have you some ideas?

Mark Martinez

Those are not my ideas, I am just repeating from a PhD student from a number of years ago and from the group in Jyväskylä, Finland. We have put some numbers behind those forces.

Juha Salmela VTT

For example from Jäsberg's work, you can extract lubrication layer thickness, so have you calculated how much densification you need to have to reach the same layer thickness? In the literature there are many correlations between yield stress and concentration.

Mark Martinez

I think from his thesis we could do that but the layers Jäsberg measured are tiny.

Juha Salmela

Perhaps you could actually take this correlation between concentration and yield stress and back-calculate the thickness?

Mark Martinez

Yes, we have done that. We have a size for the plug, and we can get a bulk concentration, we have a yield stress for each one of those concentrations and it does follow a power law relationship, with an exponent of about 2.2 so it follows what other people have measured in different devices.