Transition to turbulence in a concentric annular pipe

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In this study the pressure-drop, mean and rms axial velocity data are measured using a differential pressure transducer and a laser Doppler anemometer for the flow of Newtonian and non-Newtonian fluids in a concentric annular pipe (radius ratio κ=0.5) at various Reynolds numbers encompassing the laminar, transitional and turbulent regimes. Three different fluids are utilized; a semi-rigid shear-thinning polymer (a xanthan gum), a polymer known to exhibit a yield stress (carbopol) and a Newtonian fluid (glycerine-water mixture) as the reference fluid. A longer Reynolds number range for the transitional flow regime is observed for the more shear-thinning fluid as determined from the axial rms fluctuation level measured at fixed radial locations. Contrary to what is observed for the Newtonian fluid the higher shear stress on the inner wall compared to the outer wall does not lead to earlier transition for the shear thinning and the yield stress fluids, xanthan gum and carbopol, where more turbulent activity is observed in the time traces at the outer wall region. The mean axial velocity profiles show a slight shift (~5%) of the maximum velocity location towards the outer pipe wall within the transitional regime only for the Newtonian fluid.

Keywords: transition, annular flow, shear thinning fluid, yield-stress fluid

1 INTRODUCTION

The fundamental study of fluid flowing in an annulus within the laminar and turbulent regimes has been the subject of interest since the early work by Rothfus et. al. [1] due to its extensive engineering applications. However, very limited literature within the transitional flow regime especially for the non-Newtonian fluids are available. Velocity profile measurements of a Newtonian fluid were conducted by Rothfus et. al. [1] in a concentric annulus with varying radius ratios (κ=0.162 and 0.650 where $\kappa \equiv R_i/R_o$ with R_i and R_o being the inner and outer pipe radii) at moderate Reynolds number range covering the transitional regime ($1250 \leq Re \leq 21600$). The Reynolds number, $Re(\equiv \rho U_B D_H/\eta)$ is calculated based on the fluid density, ρ, bulk velocity, U_B, hydraulic diameter, $D_H(\equiv D_o - D_i)$ and the fluid viscosity, η. The position of maximum velocity, r_m is found to be the same for laminar and turbulent flow in both annuli. However, within the transitional regime the position is shifted towards the inner pipe. The extent of the transitional regime on the Reynolds number scale was found to be a function of the radius ratio and appeared longer than in circular pipes. Hanks and Bonner [2] performed a theoretical analysis on the stability of laminar Newtonian flow within a concentric annulus. The theory predicts that the inner flow region is the least stable and will undergo transition to turbulence while the flow in the outer region remains laminar. Consequently, the wall shear stress in the inner region will increase significantly due to the change in momentum transport mechanism to a turbulent mode. The increase in wall shear stress would then lead to a shift in r_m to a higher value, towards the outer wall. The r_m value will reach a maximum once the outer flow region undergoes transition to turbulence. Beyond this critical Reynolds number r_m will decrease to a value corresponding to that in turbulent flow. Amongst the limited literature on transitional non-Newtonian fluid flow, Escudier et. al. [3] monitored the axial turbulence intensity of Newtonian and non-Newtonian fluid (xanthan gum, carboxymethylcellulose (CMC) and laponite/CMC mixture) flows at the centre of the annular gap as a means to identify the onset of transitional flow. Although departure from the laminar flow regime was observed on the friction factor, f against the Reynolds number, Re plot, a sudden increase in the normalized axial turbulence intensity, u'/U_B, above the noise level was detected at a slightly lower Reynolds number than what is observed on the f-Re plot for all the fluids studied. The friction factor, f $(\equiv 2\tau_W/\rho U_B^2)$ is calculated from the wall shear stress, τ_W and the Reynolds number, Re $(\equiv \rho U_B D_H/\eta_W)$ is calculated using the viscosity at the wall, η_W. Despite the circumferential asymmetry highlighted by the authors, the mean axial velocity distribution for the Newtonian control case showed a slight shift of r_m towards the outer wall within the transitional regime, a trend which was absent for the non-Newtonian fluid flows.

2 EXPERIMENTAL ARRANGEMENT

A 5.81-m long annular-flow facility as shown in **Figure 1** was utilized. The test pipe comprised of four 1041-mm long, one 625-mm long and one 718-mm long precision-bore borosilicate glass tubes, with an average internal diameter of 100.4 mm. The inner centrebody was made of stainless steel thin walled tube with an outside diameter of 50.8 mm giving a radius ratio, κ=0.506. The fluid was driven from a 500-l capacity stainless-steel tank by a progressive cavity pump (Mono-type, E101). A Fischer and Porter MAG-SM Series 1000 electromagnetic flowmeter was also incorporated in the system. The pressure drop was measured by means of a differential pressure transducer, GE Druck (LPX9381) over a distance of 41.3D_H, starting 75.8D_H downstream of the inlet. Velocity profiles and turbulent fluctuation levels, performed at 104.7D_H downstream of the inlet of the test section, were determined using a Dantec Fibreflow laser Doppler anemometer (LDA) system supplied by Dantec Electronic Ltd, UK. The flowrates obtained from integration of the LDA mean velocity profiles were found to be within 1.5% of the value provided by the flowmeter. A vegetable based glycerine-water solution (40% w/w), supplied by Hays Chemical Ltd was utilized. It has a density of 1070 kg/m^3 and a shear viscosity, measured at 20°C, of 0.00386 Pa.s. The xanthan gum (XG) used in this study was obtained from the Kelco Co. (Ketrol TF) with the molecular weight reported by the supplier to be in excess of 10^6 g/mol while the Carbopol 980 (CB) was supplied by Noveon, France with a molecular weight of 4.00×10^6 g/mol. The carbopol solutions prepared in this research work is neutralized using laboratory grade 2N sodium hydroxide supplied by BDH Ltd, UK. Complete rheological characterizations of the polymers utilized in this study were conducted by Jaafar [4].

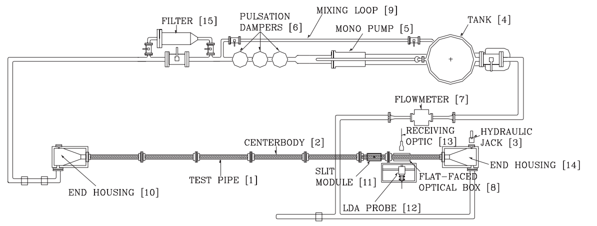

Figure 1: Schematic diagram of the flow loop

3 PRESSURE-DROP MEASUREMENTS AND TRANSITION IDENTIFICATION

In **Figure 2**, a plot of the Fanning friction factor, f against Reynolds number, Re for glycerine, good agreement is observed with the theoretical prediction given by Knudsen and Katz [5] for radius ratio κ=0.5 within the laminar regime. In the high Reynolds number turbulent flow regime, the data agrees well with the empirical predictions by Jones and Leung [6]

$$\frac{1}{\sqrt{f}} = 4\,log(1.343\,Re\,f^{1/2}) - 1.6\ . \qquad (1)$$

A method initially suggested by Zakin et. al. [7] was utilized in an attempt to detect transition from laminar to turbulent flow by plotting turbulent intensities measured at fixed radial locations against the Reynolds number. The axial rms fluctuation component is monitored at non-dimensional radial locations, ξ ($\equiv(r-R_i)/(R_o-R_i)$) of 0.1 and 0.9 with ξ=0.1 being closer to the inner wall while 0.9 is closer to the outer wall. In **Figure 2**, a plot of the axial rms fluctuation component normalized with the local mean velocity, U_{local} against Re for glycerine, a clear demarcation from the laminar regime can be detected where abrupt increases in the values are observed from 2% up to 22% of the local velocities. Two limits of transition could be seen, Re_1 and Re_2, with the first Reynolds number limit, Re_1, identifies the onset of transition seen as a noticeable change in the turbulent activity while the second Reynolds number, Re_2, represents the limit where the maximum value of turbulent intensity is reached. For glycerine, Re_1 is equal to 2100 for the inner and outer wall while the second limit is reached earlier for the inner wall at Re~2900 and for the outer wall Re_2 is about 3100.

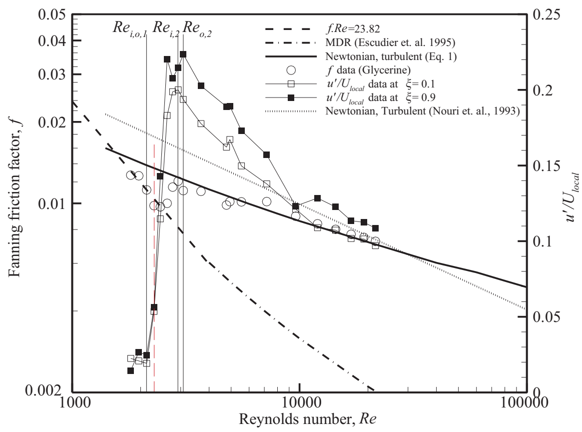

Figure 2: f-Re data for glycerine with u'/U_{local}-Re levels to monitor transition ($Re_{a,b}$ is the critical Reynolds number where a refers to the positions closer to the inner (*i*) or outer (*o*) walls while b refers to the transition stages with 1 refers to the onset of transition and 2 refers to the limit where maximum u'/U_{local}-Re is reached).

Figures 3 and **4** show the friction factor data for 0.07% and 0.15% xanthan gum solutions where within the flow loop operating range all three flow regimes; laminar, transition and turbulent; were clearly encountered. The f-Re and u'/U_{local}-Re data for 0.065% carbopol shown in **Figure 5** also comprises all three flow regimes. In **Figures 3-5**, Re_2 values were found to be higher for the more shear-thinning fluid indicating larger transitional regime on the Reynolds number scale. **Tab 1** lists all the Reynolds number limits as seen from the turbulent intensity activities and also the peak values for the fluids studied. It is interesting to note that these peak values decrease with increasing shear-thinning ability.

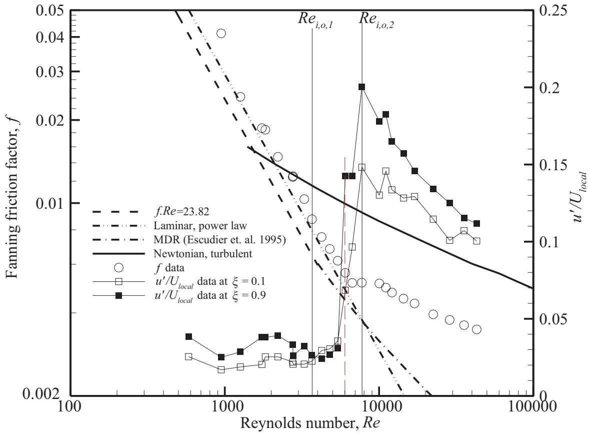

Figure 3: f-Re and u'/U_{local}-Re data for 0.07%XG

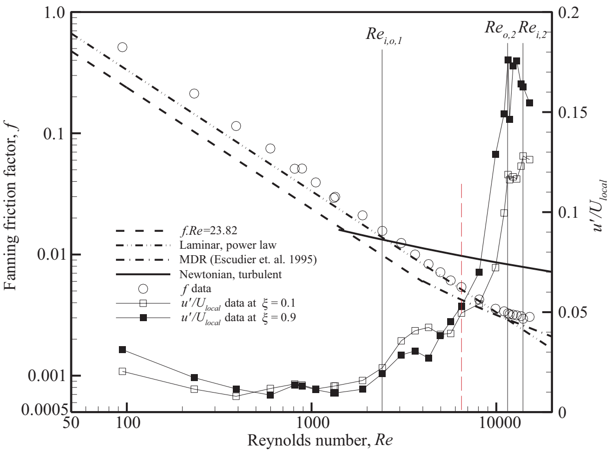

Figure 4: f-Re and u'/U_{local}-Re data for 0.15%XG

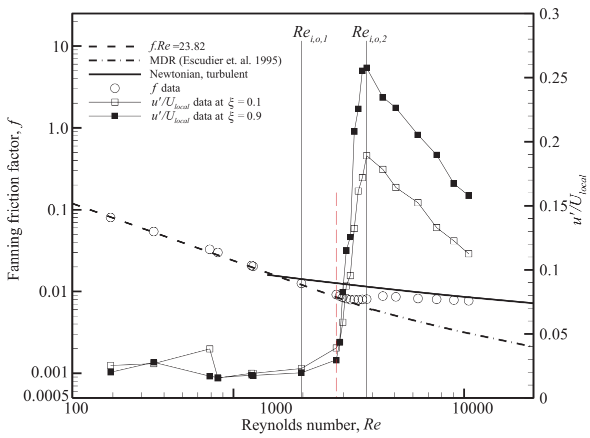

Figure 5: f-Re and u'/U_{local}-Re data for 0.065%CB

For the Newtonian and polymer flows time traces of the axial velocity at ξ of 0.1 and 0.9 for several Reynolds numbers were also monitored for 30 seconds up to a maximum of 90 seconds. Note that the time traces at these two locations were not measured simultaneously.

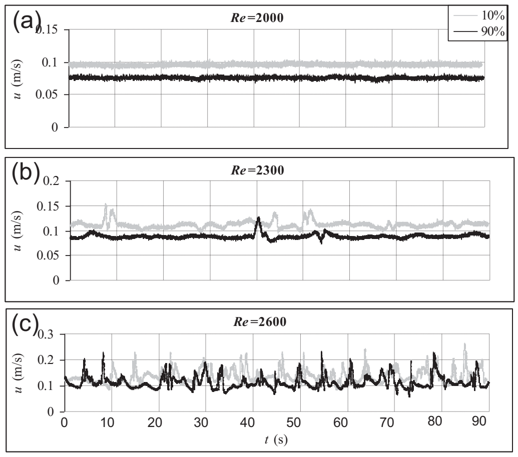

Figure 6: Time series of the axial velocity at ξ=0.1 and ξ=0.9 for glycerine

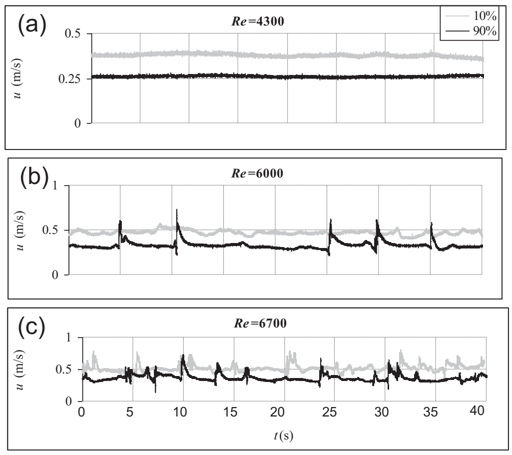

Figure 7: Time series of the axial velocity at ξ=0.1 and ξ=0.9 for 0.07%XG

Figure 6 shows the time traces for the Newtonian fluid, glycerine where the flow is completely laminar for Re=2000 and at Re=2300 spikes are detected at both positions closer to the inner and outer walls. In order to quantify the degree of turbulence at the onset of the transition region a method known as the $\bar{u}$ method [8] is utilized where a time ratio is defined such that:

$$\beta = \frac{\Delta t_{turbulent}}{\Delta t_{total}} \%. \quad (2)$$

$\Delta t_{turbulent}$ is taken as the total time for the spikes. A spike is considered to have occurred within the time trace if the peak velocity is different by more than 15% of U_{local}. At the onset of transition for glycerine (Re=2300), the time ratio for the inner wall was found to be β=26% which is higher than that of the outer wall (β=11%). This observation is in agreement with the behaviour predicted by the theoretical stability analysis by Hanks and Bonner [2]. **Figure 7** shows the time trace for 0.07% xanthan gum at several Reynolds numbers. The velocity data at Re=4300 is essentially steady indicating laminar flow. At Re=6000, the flow close to the inner wall is clearly unsteady with no distinct spikes, however, high amplitude (>50% of local mean velocity) spikes could only be observed for the flow closer to the outer wall. The β values are 15% and 35% for the inner and the outer walls respectively indicating more turbulent activity near the outer wall. At the higher concentration of 0.15% xanthan gum (not shown) similar characteristics are observed with the first trace of turbulence found at Re=6500 with β values of 23% and 31% for the inner and outer walls respectively. The transitional flow study of the yield stress fluid, carbopol at a concentration of 0.065% (not shown) also revealed unsteady flow at Re=2800 with time ratio of 8% for the inner wall and 15% for the outer wall.

4 MEAN AXIAL VELOCITY MEASUREMENTS

Figure 8 shows the mean axial velocity profile for glycerine at several Reynolds number spanning the three flow regimes; laminar, transition and turbulent. The velocity profile within the laminar regime at Re=2000 is in good agreement with the theoretical profile given by Knudsen and Katz [5]. Deviations from the theoretical laminar profile are observed at Re=2600 where a slight shift towards the outer wall in r_m is also observed. As Re is further increased, the shape of the velocity profiles agrees with what would be expected of turbulent flow with a progressively flatter central region. The shift in r_m, however, is not detected and, if any, it is not significant for xanthan gum and carbopol solutions.

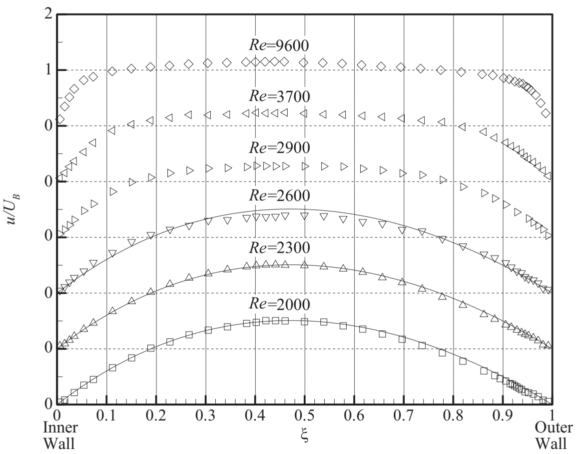

Figure 8: Velocity profiles for different Reynolds numbers including the analytical profile for laminar, Newtonian flow (continuous lines) for glycerine

5 CONCLUSIONS

In the transitional flow studies within the annular pipe larger Reynolds number range of the transitional flow regimes are observed for the more shear-thinning fluid by monitoring the axial rms fluctuation level at fixed radial locations close to the inner and outer walls (ξ=0.1 and 0.9). Time traces of the axial velocity at these radial locations provided further insight of the transitional flow within the annular pipe. The observations indicate that the higher shear stress on the inner wall compared to that on the outer wall does not lead to earlier transition for shear thinning and yield stress fluids as is observed for the Newtonian fluid, glycerine. The mean axial velocity component measured indicates a slightly different behaviour for the Newtonian and polymer flow in relation to the location of maximum velocity. A shift towards the outer wall from a location of ξ=0.44 could be seen within the transitional flow regime only for the glycerine-water mixture. The shift is a consequence of the flow adjusting to the change in momentum transport as suggested by Hanks and Bonner [2].

Table 1: Reynolds number limits and maximum axial rms fluctuation level

Fluid	Re_1		Re_2		u'_{max}/U_{local}	
ξ	**0.1**	**0.9**	**0.1**	**0.9**	**0.1**	**0.9**
Glycerine	2100	2100	2900	3100	0.20	0.22
0.07%XG (n=0.61)	3700	3700	7700	7700	0.15	0.20
0.15%XG (n=0.45)	2400	2400	14000	11600	0.13	0.18
0.065%CB (n=0.81)	2000	2000	3800	3800	0.19	0.26

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