Flow Characteristics of Stirred Reactors with Newtonian and Non-Newtonian Fluids

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The flows in stirred reactors have been examined in various papers, for example, those by Sachs and Rushton (1954), Reed, Princz and Hartland (1977), Nouri, Whitelaw and Yianneskis (1987), Nouri (1988) and Hockey, and Nouri and Pinho (1989). The flow visualization results of Hockey et al. (1989), in particular, revealed flow patterns which varied with Reynolds number and non-Newtonian fluid so that the direction of rotation of the main vortices was reversed with a pitch-blade impeller. Variation of discharge angle also was observed by Greene, Carpenter and Casto (1982) and attributed to viscoelastic effects. The experiments performed here quantify this effect and attempt to separate the contributions of effective viscosity and rotational speed.

The flow configuration, fluids and instrumentation are described briefly in the next section, and the results are discussed in the following sections.

Flow Configuration, Fluids and Instrumentation

The stirred vessel and stirring blades are shown in Figure 1, which also identifies the coordinate system used in the presentation of results. Four baffles were used and the impeller blades contained in the system had a thickness of 1.5 mm. The distance of the six-bladed impellers from the base of the tank equals their diameter and is one third of the height of the tank; this is an arrangement commonly used in real mixing vessels. All components are made of clear acrylic (Perspex), and the circular vessel was placed in a rectangular box with the intervening space filled with the same fluid as that in the vessel, so as to reduce refraction.

The impellers are driven by a d.c. motor at speeds up to 2,500 rpm and the maximum variation does not exceed ±0.25% of the tip velocity. The 6.35-mm-diameter shaft gives rise to a precession of up to 0.5 mm but this did not affect the deductions made from the following flow characteristics. An optical encoder is fitted to the shaft, which provides a train of 2,000 pulses per

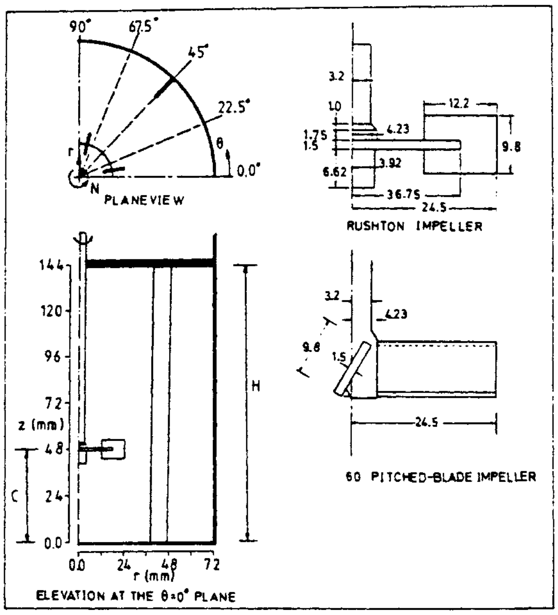

Figure 1. Dimensions and coordinate system.
All dimensions in mm

Table 1. Fluid Properties

	Refractive Index	Density kg/m³	Viscosity Pa · s
Water	1.333	1,000	1.0×10^{-3}
Maltose Syrup	1.39	1,250	38.7×10^{-3}
CMC (0.2 wt. %)	1.34	1,000	$k = 0.044$ $n = 0.75$

revolution to allow recognition of the zero-degree location and measurement of the rotational speed.

Measurements are obtained with water, a mixture of maltose syrup and water and a solution of sodium-carboxmethyl cellulose (CMC) grade 7H4C in water at concentration of 0.2 wt. %. The relevant properties of these fluids are provided in Table 1. No elasticity of a 0.4% CMC solution could be detected by Pinho and Whitelaw (1990) because of very low normal stresses, so that elasticity with the 0.2% solution can also be considered negligible. The power law for pseudoplastic (shear-thinning) fluids can be expressed by $\tau = k(\gamma)^n$, and the effective viscosity is defined as $\mu_e = k(\gamma)^{n-1}$ where k represents fluid consistency and n the degree of departure from Newtonian behavior. The value of n is less than unity for pseudoplastic fluids for which the effective viscosity decreases with increase in shear rate. The variation of viscometric viscosity of CMC solutions is shown in Figure 2, and the values of k and n for the intermediate shear rates are given in Table 1.

The laser-Doppler anemometer used is identical to that described by Nouri (1988). It comprises a 5-mW helium-neon laser, diffraction-grating unit to divide the light beam and to provide frequency shift, a lens located on the axis to collect forward-scattered light, a pin hole, photomultiplier and a frequency counter. The uncertainties associated with the measurements are less than ±1.5% of the mean values and ±2.5% of the rms values and do not affect the important implications of the results.

Results and Discussion

All measurements were made in the zero degree plane, that is between baffles, and are presented in nondimensional form using the impeller tip velocity, V_t, the half-blade width, $h/2$, and the radius of the impeller to normalize velocities, axial and radial distances, respectively. The Reynolds number is based on the rotational speed, impeller diameter and viscosity which, for the CMC solution, was deduced from a characteristic shear rate as suggested by Metzner and Otto (1957) and from the viscosity-

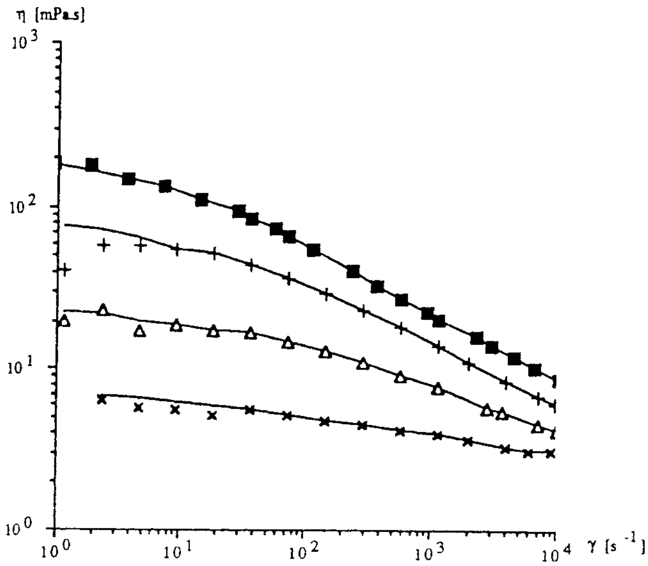

Figure 2. Viscometric viscosity of CMC solutions at 25°C. ×0.1%; △ 0.2%; +0.3%; ■ 0.4 wt. %
From Pinho and Whitelaw (1990)

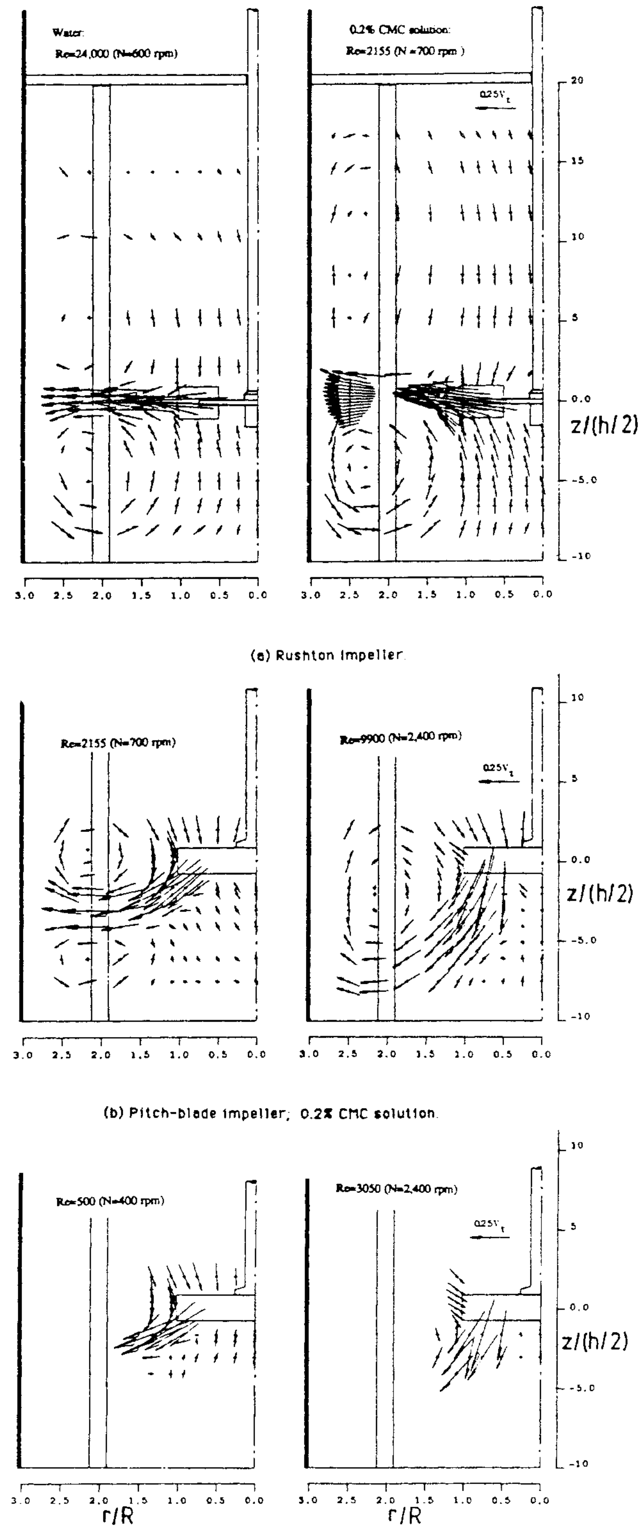

Figure 3. Mean velocity vector in *r-z* plane (θ = 0.0°).

shear rate measurements of Pinho and Whitelaw (1990). The effective viscosity should be interpreted with care but does allow comparison of the results with Newtonian and non-Newtonian fluids in a convenient way.

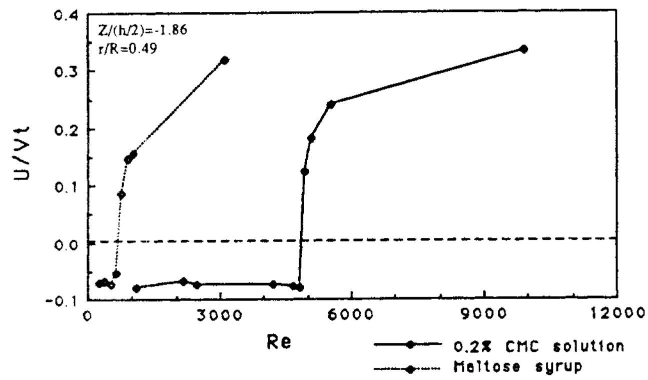

Figure 4. Variation of axial mean velocity as a function of Reynolds number, below the impeller at $z/(h/2) = -1.86$ and $r/R = 0.49$.

The velocity vectors of Figure 3 were obtained from measurements of the axial and radial components of velocity and it is evident that the flow patterns generated by the Rushton impeller are similar for water and the 0.2% CMC solution with the flow induced from above and below the impeller and discharged radially. With the pitch-blade impeller, the flow is induced from above the impeller and leaves it in the downward direction with an angle which varies with Reynolds number. The same trend is shown with the 0.2% CMC solution and with maltose syrup at even lower Reynolds numbers so that the observation is not a result of the non-Newtonian fluid.

The radial profiles of the axial and radial components of velocity confirmed that the jet created by the Rushton impeller was near radial and that Reynolds numbers from 2,155 to 24,000 led to small changes in its angle with axial velocities much smaller than the maximum radial velocity. It is useful to note that the rms of the fluctuations increased with Reynolds number in a manner which would suggest that a Reynolds number of 8,000 is less than that of fully developed turbulent flow rather than that there was any suppression due to non-Newtonian effects. In contrast, the radial and axial velocities for the pitch-blade impeller were of the same order with a sudden increase in the axial velocities below the impeller at Reynolds numbers which, for the 0.2% CMC solution, occurred between 4,690 and 5,090. Inspection of the velocities at the tip of the impeller showed the same transition with a sudden decrease in radial velocity for Reynolds numbers above 4,690. Similar results were obtained with the maltose syrup, but at lower Reynolds numbers.

Figure 4 shows the variation in axial velocity at one radius, for Newtonian and non-Newtonian fluids and as a function of Reynolds number and confirms that the rapid shift to axial flow occurs at a Reynolds number of around 650 with the Newtonian fluid and 4,800 with the CMC solution. The difference can be attributed in part to the drag-reducing characteristic of the CMC solution, as indicated by Pinho and Whitelaw (1990) and, in view of the small variation in turbulence fluctuations, also to the use of an averaged effective viscosity in the definition of Reynolds number.

It remains to explain the variation of the flow caused by the pitch-blade impeller which is evidently due to Reynolds number, a parameter of fluid mechanics, rather than to the particular nature of the non-Newtonian CMC solution. The flat blades of the Rushton-type impeller generate centrifugal forces in the fluid and these are balanced mainly by a pressure field so that fluid is drawn from all directions to provide the radial jet. Differences in the boundary conditions above and below the impeller can cause this jet to deviate from the radial direction and the mechanism is the same no matter what the Reynolds number is. In the case of the pitch blades, the pressure difference from the forward to the rear of the blades varies in the axial direction so that the fluid is drawn preferentially depending on the direction of rotation and tends to direct the fluid in the axial direction. As the Reynolds number is decreased to low levels, there is a tendency for the flow on the suction surface to remain attached with consequent change in the velocity vector relative to the blade and, as the present results show, angles up to 75 degrees from the axial direction are achieved with Reynolds numbers of 500 and 2,155 for Newtonian and 0.2% CMC solution, respectively.

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