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Viscoelastic Fluid Flow in a Sudden Expansion Circular Channel as a Model for the Blood Flow Experiments

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=**Abstract**=

In the current flow visualization studies, the role of non-Newtonian characteristics (such as shear-rate dependent viscosity and viscoelasticity) on flow behavior across the sudden expansion step in a circular pipe as a model for blood flow experiments is investigated over a wide range of Reynolds numbers. The expansion ratios tested are 2.000 and 2.667 and the range of the Reynolds number covered in the current flow visualization tests are 10～35,000 based on the inlet diameter. The reattachment lengths for the viscoelastic fluids in the laminar flow regime are found to be much shorter than those for the Newtonian fluid. In addition it decreases significantly with increasing concentration of viscoelastic fluids at the same Reynolds number. However, in the turbulent flow regime, the reattachment length for the viscoelastic fluids is two or three times longer than those for water, and gradually increases with increasing concentration of viscoelastic solutions, resulting in 25 and 28 step-height distances for 500 and 1,000 ppm ployacrylamide solutions, respectively. This may be due to the fact that the elasticity in polyacrylamide solutions suppresses the eddy motion and controls separation and reattachment behavior in the sudden expansion pipe flow.

1. INTRODUCTION

Flow separation and reattachment through the curved, bifurcated, and tapered ateries is one of the most important and complex fluid dynamic problem, and is of special technical interest in the human cardiovascular system. Since the atherosclerotic lesions and thrombus generation are selective in the appearance of curvature, bifurcation, and variation of cross-sectional area it has been suggested that the fluid dynamics of blood flow through these regions may play a significant role in the initiation and propagation of lesions and thrombus[1−4)]and vortices formed as a result of flow separation are also known to contribute to the enhanced deposition of blood particulates along the aterial wall[5,6)].

Another important problem in the cardiovascular system from the fluid dynamic point of view is encountered in the flow through prosthetic cardiac valves which are intented for use as

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the replacements of diseased natural valves. Since heart valve prosthesis have been used successfully in 1960[7,8], over 90,000 heart valve prosthesis of different types and designs are used annually worldwide at the present time, which is summarized by Shim et al[9]. Although *in vitro* flow dynamic investigations have been carried out, most of them are with Newtonian fluids. Furthermore, in spite of the fact that blood clearly demonstrates a shear-rate-dependent non-Newtonian viscosity, effects of the non-Newtonian viscosity of blood on hemodynamics of large aterial flows with various degrees of atherosclersis and flows through prosthetic heart valves have not been understood well.

Therefore, the main objective to the current study is to investigate the role of non-Newtonian characteristics (such as shear-rate dependent viscosity and viscoelasticity) on the flow behavior across the abrupt expansion step in a circular pipe in the with range of Reynolds numbers by a flow visualization study, which is potentially applicable to blood flow and biological mass transfer in the cardiovascular system.

2. BACKGROUND

In an attempt to better understand the fundamental physics of flow behavior of Newtonian fluid through an abrupt expansion circular channel, several investigators[10-15] have carried out flow visualization tests using various techniques. Macagno and Hung[10] and Iribarne et al[11]. pursued analytical and experimental investigations of the hydrodynamic behavior of laminar flow, respectively. The latter found that the shedding frequency was proportional to the square root of the Reynolds number. Iribarne et al[11]. introduced a non－disturbing flow visualization technique ; they produced colored traces of streamlines by irradiating a photochromic dye with an ultra－violet light from a pulse ruby laser with a frequency doubler. Additionally, a dye injection technique was used by Back and Roschke[12,14] in an abrupt expansion circular channel flow. Also, Feuersteinet al[13]. examined developing flows downstream of tubular expansions for various diameter ratios analytically and experimentally.

On the other hand, corresponding studies of non－Newtonian fluid flow are rarely found[15,16] and are conducted within a relatively low Reynolds number range (i.e.,Re less than 150). Halmos et al.[15] found that for a power－law fluid (i.e., inelastic fluid) the reattachment lengh increase with an increase in the Reynolds number at a constant flow behavior index, n. Also, as the flow behavior index n decreased from 1.0 to 0.65, the reattachment length and the size of the secondary cell increased by 20% percent in the range of Reynolds number ($Re < 150$). The Reynolds number, based on an upstream diameter, varied from 0 to 150 in their numerical calculation, and from 6.7 to 158.8 in the experiments, respectively. Also, the effect of the expansion ratio on the reattachment was numerically studied at $Re = 10$, which showed the trend of increasing reattachment length for increasing values of expansion ratio[15].

Perera and Walters[16] demonstrated numerically that elasticity definitely reduced the size of the vortex in an abrupt expansion flow. They also found that the elastic fluid had a large recirculating vortex in the sudden expansion flow, while the vortex almost disppeared in the elastic fluid under identical flow conditions, demonstrating the influence of elasticity in the sudden expansion flow.

3. EXPERIMENTAL FACILITY AND METHOD

The flow loop designed for the current flow visualization test consisted of a 200 liter overhead reservoir tank, a centrifugal pump, a calming chamber, a converging section with a conical half angle of 30 degree, a short hydrodynamic entry section, a sudden enlargement circular channel, a converging exit nozzle connected to a 0.953 cm diameter flexible outlet tube, and a 400 liter ground—level reservoir tank. Its schematic features are shown in Fig. 1 (a). A cylindrical polyethylene tank of 55.9 cm in diameter and 91.5 cm in height was used as the overhead reservoir tank, and a calming chamber of 10.2 cm diameter and 15.3 cm length was fabricated with a transparent Plexiglass cylinder. The converging section, with a short entry section, was carefully fabricated in a body from a transparent Plexiglass rod to reduce any flow disturbance. Two separate entry sections in different diameters, which resulted in an expansion ratio (D/d) equal to 2.00and 2.67, respectively, were fabricated to examine the effect of the expansion ratio on the reattachment length.

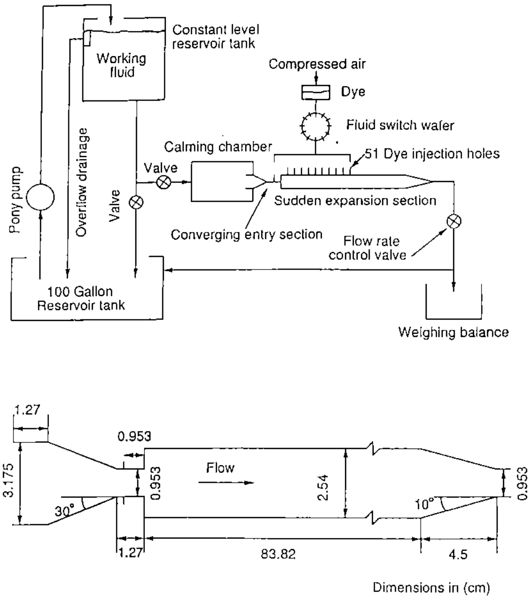

Fig. 1 a) Schematic diagram of experimental apparatus and b) enlarged view of the main test section for flow visualization experiments (expansion ratio=2.667)

A Plexiglas tube of 2.54 cm inner diameter was used for an abrupt expansion section. Figure 1b shows the detailed dimensions and enlarged features of the main test section for the expansion ratio of 2.667. The flow at the entrance of the sudden expansion section is believed to be nearly uniform as the boundary layer thickness is relatively small compared to the tube radius due to the converging and short hydrodynamic entry length.

A total of forty-nine dye injection holes were drilled every one step-height distance along the main tube, where they were located from 2 to 50 step-height positions away from the entrance of the sudden expansion section. The main test section, from the calming chamber to the outlet tube, was kept straight and horizontally fixed to the heavy test bench because it was found that the flow Reynolds number flow. The experiments were carried out under a constant room temperature. For each run, the temperature variaion during the experiment was kept to less than 0.1℃. The mass flow rate was measured by collecting the discharged water over a given period of time.

Water was used to represent a Newtonian fluid and the aqueous solutions of polyacrylamide (Separan AP—273), of 200, 500, and 1, 000 ppm, were used as viscoelastic fluids. The rhelolgical parameter, i.e., the apparent viscosity of viscoelastic fluid, was measured using a capillary tube viscometer, a Brookfield viscometer, and a falling needle viscometer depending on the range of shear rate.

The level of the test fluid in the overhead reservoir tank (200 liter) － approximately 2.44m high from the test bench － was kept constant as tap water runs using overflow drainage and a constant flow rate was maintained by gravitational force and by using a flow rate control valve installed in the downstream of the test section. Aqueous solutions of polyacrylamide were directly prepared in the 200 liter reservoir tank and stirred well with a plastic rod to avoid mechanical degradation which might occur if a centrifugal pump was used to pump the fluids up to the overhead reservoir tank. Furthermore the tests were conducted in a once－through mode to assure that the viscosity of the polyacrylamide solution was constant during each test run. Thus, the error due to the change of fluid level in the overhead reservoir tank was inevitable for the Reynolds number calculation. However, the cross－sectional area of the overhed reservoir tank was made large (ID＝110cm) to minimize this error. The maximum error in the Reynolds number calculation due to the above cause was approximately 4.4% at the highest flow rate.

The mixture of 50% test fluid, 50% additive (2% low fat milk plus alcohol) and a small amount of red－colored dye was used as a dye fluid. To reduce the buoyancy effect, the density of the dye was monitored and adjusted using a hydrometer which was readable up to four digits. In order to determine the reattachment point for a given flow rate, dye was simultaneously injected using a fluid switch wager through three tiny holes located one step－height apart at the sudden expansion section. Then the movement of the dye, particularly the direction of the dye movement originationg at three holes was carefully observed. If the dye from the first and last holes moved in opposite directions then the position of the middle hole was assumed to be the reattachment point.

4. RESULTS AND DISCUSSION

4・1 Newtonian Fluids

In sudden expansion pipe flows with an expansion ratio, D/d＝2.667, the dimensionless reattachment length (x_R/h) is presented as a function of the Reynolds number, Re_d, and compared with the data reported by previous investigators [10－14] in Fig. 2. To facilitate the comparison the dimensions of previous sudden expansion geometries and results, together with current data, are briefly summarized in Table 1. In general, the current flow reattachment lengths (see solid circles in Fig. 2) are in good agreement with those from prior investigations in the laminar flow region and in the highly disturbed (or turbulent) flow region. Note that Iribarne et al.[11] and Back and Roschke[12] found the maximum reattachment length to be 25－28 step－heights, while Feuerstein et al.[13] found it to be 113 step－heights at a Reynolds number of 1,090. Roschke and Back[14] attributed this discrepancy to different inlet flow conditions. Also note that the former's inlet flow conditions[11,12] were uniform, while the latter's[13] had a parabolic velocity profiles using a converging nozzle and a short entry tube as shown in Fig. 1(b) However, the current flow loop was designed with a constant overhead tank, together with a gravity－driven flow system in order to minimize any

Table 1 Geometries and results of prior and current investigations in the flow visualization study with Newtonian fluids

Investigator	Geometry		Test Fluid	Inlet Flow Condition	$(x_R/h)_{max}$ at Re	Range of the Reynolds No.
	h/d	h/D				
Macano and Hung (1967)	0.5	0.5	oil	parabolic		1−200
Back and Roschke 20−4,200 (1972)	0.8	0.385		water	uniform	25 at Re=250
Iribarne et al. (1972)	0.49	0.505	water	uniform	27 at Re=350	90−1,355
Feurstein et al. (1975)	0.294	0.185	liquid	parabolic	113 at Re=1090	222−755
current study	0.500 0.833	0.250 0.313	water warer	uniform uniform	bothare>50 at Re=700	30−40,000 28−26,000

disturbance in the inlet flow, which resulted in a greater reattachment length than those observed by Iribarne et al.[11]and Back and Roschke[12].

It should be mentioned that with Reynolds numbers below 660 the shear layer was very sensitive to artificially induced disturbances such as small vibrations in the inlet feed line or from the test bench. During experiments it was observed that, although a longer reattachment length than 30 step−heights could be obtained, a flow field consisting of dye streaks broke down quickly when a small external disturbance was applied to the flow system. Thus it is believed that the maximum reattachment length of Newtonian fluids is much more sensitive to the inlet flow condition than to any other parameter.

To examine the effect of the expansion ratio on the reattachment length another series of experiments was conducted with a different expansion ratio, D/d=2,000, and shown in Fig. 3. When the expansion ration D/d was reduced from 2.667 to 2.000 the reattachment length was found to be unchanged both in the laminar ($Re_d < 800$)and turbulent ($Re_d > 2,000$) flows. For the laminar mixing of a stream with uniform velocity u with a fluid at rest the velocity profiles at the mixing zone depend upon a similarity variable[12]. This mixing theory indicates a linear variation of the reattachment length in terms of step−height, h, and the Reynolds number based on the upstream diameter. Note that the so−called configuration factor h/d depends on the abrupt expansion configuration. In the current experiments, the reattachment length was shown to increase linearly with Re_d as shown in Figs. 2 and 3 (note that semi−log graph was used). The effect of the configuration factor on the reattachment lengths for a Newtonian fluid could also be seen in the laminar flow regime (i.e., see open and solid circles in Fig. 3) when h/d varied from 0.833 to 0.500 although the effect seems relatively small. In general, the reattachment length increases with an increasing configuration factor (or expansion ratio) which is consistent with the observation reported for water by halmos et al.$^{15)}$. However, the effect of the configuration factor on the reattachment length was not found in the turbulent flow regime (i.e., Re>2,000) as is demonstrated in Fig. 3

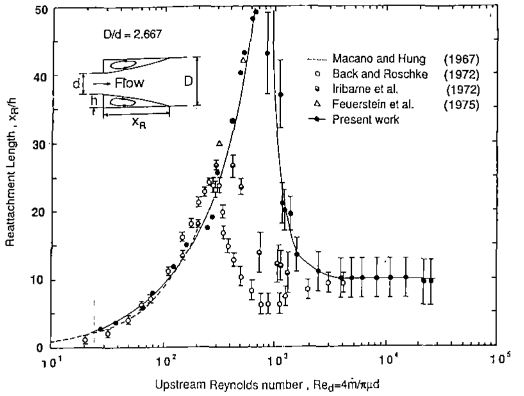

Fig. 2 Reattachment lengths in an abrupt expansion pipe flow with a Newtonian fluid (D/d=2.667, water)

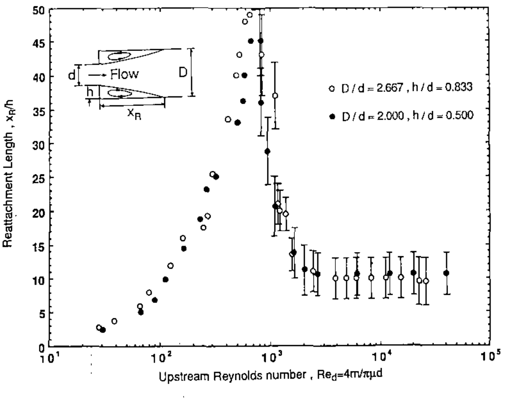

Fig. 3 The effect of an expansion ratio (D/d) on reattachment lengths (water)

4・2 Viscoelastic non－Newtonian Fluids

Figure 4 presents the viscosity data of water and aqueous solution of polyacrylamide (Separan AP－273) measured with the aforementioned various viscometers. The dimensionless reattachment length, x_R/h, for viscoelastic fluids in the case of D/d=2.667 is presented in Fig. 5. It is believed that the boundary layer thickness in the upstream tube is very thin, due to a short entry length, which should result in a very high shear rate at the point of sudden expansion. Therefore the asymptote value of viscosity at a high shear rate, so－called the "infinite－shear－rate viscosity", was used in the calculation of the Reynolds number, Re_a. The results of the reattachment length with Separan AP－273 solutions are significantly different from those with water as demonstrated in Fig. 5. In the laminar region, the size of the vortex in the recirculation zone decreases significantly as the concentration of Separan AP－273 solutions increases at the same Reynolds number, which is manifested by the shortening of the reattachment length as shown in the aforementioned figure.

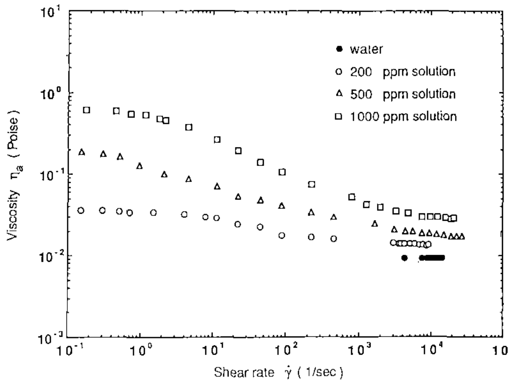

Fig. 4 Apparent viscosity vs. shear rate for polyacylamid (Separan AP－273) solutions

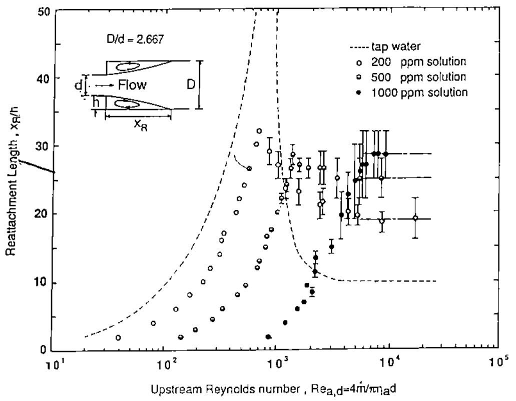

Fig. 5 Reattachment lengths in an abrupt expansion pipe flow with viscoelastic fluids (D/d=2.667, Separan AP−273 solutions)

For the 200 ppm solution the reattachment length increases up to $Re_{a,d}=690$ with increasing the Reynolds number. With a further increase in the Reynolds number the reattachment increasing the reynolds number. With a further increase in the Reynolds number the reattachment point decreases moving toward the sudden expansion step and eventually remains at 18 step−heights at $Re_{a,d}>5{,}000$. For the 500 and 1,000 ppm solutions similar trends were observed as for the 200 ppm solution. In the laminar flow region the reattachment length clearly decreases with the increasing elasticity of viscoelastic solutions, as is manifested by the concentration of Separan solutions. This is consistent with the observation made by Perera and Walters[16], who reported from their numerical calculation that the elasticity definitely reduced the size of the vortex in an abrupt expansion flow. In contrast, in the turbulent region, the reattachment length for the 500 and 1,000 ppm solutionsis found to be 25 and 28 step−height distances, respectively (see Fig. 5), which is much longer than the Newtonian value (10 step−height distances), indicating that the reattachment length increases as the elasticity in the turbulent flow increases.

Fig. 5 presents the effect of the expansion ratio (D/d) on the reattachment length for the 200 and 1,000 ppm Separan AP−273 solutions. For the same flow conditions, when the expansion ratio was varied from 2.0 to 2.667, the reattachment increased by 67% and 50% for the 200 and 1,000 ppm solutions, respectively. This figure clearly shows that the reattachment length for viscoelastic fluid flows increases with the increasing value of the expansion ratio at the same Reynolds number, which is consistent with those for Newtonian fluid flows.

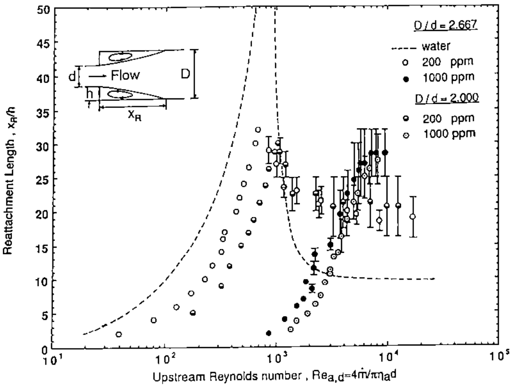

Fig. 6 The effect of an expansion ratio (D/d) on reattachment lengths (Separan AP−273 solutions)

5. SUMMARY AND CONCLUSIONS

In the current flow visualization studies of flow across an abrupt expansion step, the reattachment lengths for a Newtonian fluid, and viscoelastic fluids were obtained as a function of an expansion ratio in a circular pipe, the Reynolds number, and the concentration of non−Newtonian fluid in the laminar flow region. In addition, the reattachment lengths decrease significantly with increasing concentration of viscoelastic fluids at the same Reynolds number. Howerver, in the turbulent flow regime, the reattachment length for the viscoelastic fluids is two or three times longer than those for water, and gradually increases with increasing concentration of viscoelastic solution, resulting in 25 and 28 step－height distances for the 500 and 1,000 ppm polyacryamide solutions, respectively. This may be due to the fact that the elasticity in the ployacrylamid solutions suppresses the eddy motion which extends the region of the separation zone. Subsequently the reattachment lengths are much longer than in the case of water. Finally, in viscoelastic fluid flows through the sudden expansion pipe, the reattachment length may be significantly affected by the inlet velocity profile (i.e., boundary layer thickness)and should be investigated in the future.

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