Experimental Investigation on Characteristics of Non-Newtonian Fluids

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***Abstract* - The non-Newtonian fluid flow in a pipe has been analysed with reference to the Newtonian fluid using the experimental technique by velocity profiles, wall shear stress and shear rate parameters. The Aqueous Sodium Bentonite solution (Al_2O_3. $4(SiO_2).H_2O$) and Sodium Carboxymethyl Cellulose solution ($[C_6H_7O_2(OH)_2OCH_2COONa]n$) are used as the non-Newtonian fluids and the water is used as a Newtonian fluid, a reference fluid, to do the comparative study of characteristics Similarly by placing the sphere as an obstacle in the flow domain, its effect over the flow has been experimented and analyzed the results using the velocity profiles. Here also, the same Newtonian -water, and non-Newtonian fluids: Aqueous sodium bentonite solution and sodium carboxymethyl cellulose solution are been used. Correspondingly, the wall shear stress & shear rate of the fluids are calculated and plotted against the length of the pipe. The comparative study has been done in reference with the water.**

List of Notations

- τ - shear stress
- μ - absolute viscosity
- u - fluid velocity
- r - radial distance
- $\gamma = (\frac{du}{dr})$ - shear rate
- K - fluid consistency coefficient
- τ_y - yield shear stress
- n - power law index
- τ_w - wall shear stress
- ρ - density of fluid
- υ - kinematic viscosity
- m - constant depending on Reynolds's number
- u_{max} - velocity at the center of Pipe (maximum velocity in a cross-section)
- R - radius of pipe
- D - diameter of the pipe
- d - external diameter of the stagnation probe
- P_o - stagnation pressure
- P_s - static pressure
- C_p - coefficient of pitot tube
- G - acceleration due to gravity
- Re - Reynolds number
- h_s - static pressure head
- h_o - stagnation pressure head
- L_e - hydrodynamic entry length
- g - is acceleration due to gravity

I. Introduction

The flow of fluids through a pipe is important in every day's life ranging from flow of blood in various living species to modern day applications in various industrial operations.

Liquid flows through pipes or ducts are commonly used in heating and cooling applications and fluid distribution networks. The Newtonian and Non-Newtonian kind of fluids flow are generally used in industrial and non-industrial applications and the flow characteristics like, velocity distribution, shear rate and wall shear stress are playing a vital role in the designing of flow systems.

The objective of finding the deviation of non-Newtonian fluid flow characteristics from a Newtonian fluid flow has been carried out. The comparative study for the variation of velocity profile under different size pipes over the length has been done. Introducing the spherical geometry obstacle, the velocity profiles are drawn. The variation of velocity profile for the different size pipes and corresponding shear stress and shear rates variation are been plotted and analyzed.

The various terms associated with different kind of fluids are as follows:

1) Newtonian fluids: Fluids which obey the Newton's law of fluid flow i.e. having a linear shear stress-shear strain relationship are called Newtonian fluids. It has linear dependence of shear stress on shear rate. It is represented by:

$$\tau \propto \frac{du}{dr}$$

or, $\tau = -\mu \frac{du}{dr}$

2) Non-Newtonian fluids: Fluids which do not obey the Newton's law of fluid flow are called Non-Newtonian fluids. They have a non-linear relationship between shear stress and shear strain of the fluid.

They are mainly represented by power law which is given by:

$$\tau = k\left(\frac{du}{dr}\right)^n \qquad (1)$$

$$\Rightarrow \mu = k\left(\frac{du}{dr}\right)^{n-1} = k\gamma^{n-1} \qquad (2)$$

Non-Newtonian fluids are mainly classified into three types:

a) **Pseudoplastic or Shear thinning:** Shear thinning is an effect where a fluid's viscosity i.e. the measure of a fluid's resistance to flow decreases with an increasing rate of shear stress. Examples: Modern paints, polymer melts such as molten polystyrene, polymer solutions such as polyethylene oxide in water, etc.
b) **Dilatant or Shear Thickening:** A dilatant is a Non-Newtonian fluid where the shear viscosity increases with applied shear stress. Example: Modern body armours clay slurry, etc.
c) **Bingham plastic:** Fluids having a linear shear stress-shear strain relationship that requires a finite yield stress before they begin to flow. Examples: Toothpaste, chocolate etc.

Fig.1 shows all these types with respect to shear stress and shear strain variations. All these are represented in fig. 1.

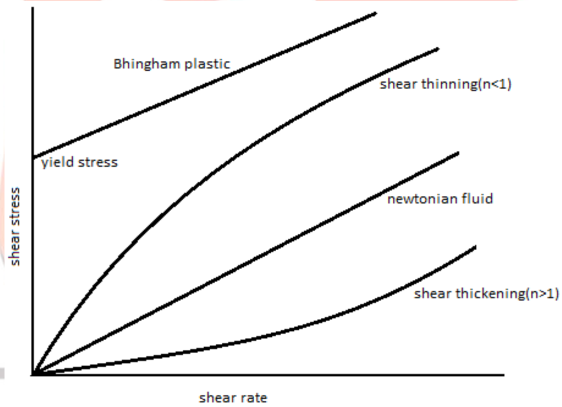

Figure 1: Typical plot of shear stress v/s shear rate for Newtonian and non-Newtonian fluids

II. METHODOLOGY

1. The rise of liquid levels in the stagnation and static probes are used to calculate the stagnation pressure and static pressure. The pitot tube is used to measure the pressure difference.
2. The static pressure is the same at all points along the same horizontal plane in the fluid and is independent of the shape of the container. Static pressure increases with the depth of the fluid and acts equally in all directions. The increase in pressure at a depth is essentially the effect of the weight of the fluid exists above.
3. The total pressure measured at a point is referred to as the stagnation pressure. The stagnation pressure value is obtained when a flowing fluid is decelerated to zero velocity in an isentropic process. This process converts all of the energy from the flowing fluid into a pressure that can be measured.
4. The stagnation or total pressure is the static pressure plus the dynamic pressure. When dynamic pressure measurement is desired, the total and static pressures are measured and then subtracted to obtain the dynamic pressure.

Total pressure = static pressure + dynamic pressure

Therefore,

Stagnation pressure – static pressure

= dynamic pressure (3)

i.e, $P_0 - P_s = C_P \frac{\rho V^2}{2}$ (4)

The stagnation pressure P_0 is given by $P_0 = \rho g h_0$ and static pressure P_s is given by $P_s = \rho g h_s$ and V is velocity in m/s.

$$\rho g h_0 - \rho g h_s = C_P \frac{\rho V^2}{2}$$
$$=> V = \sqrt{\frac{2g(h_0 - h_s)}{C_P}}$$

C_p is evaluated by correlation

$$C_P = 1 + 28.3/Re_P^{\frac{3}{2}} \quad (5)$$

Where, $$Re_P = \frac{\rho V^{(2-n)} d^n}{K} \quad (6)$$

This gives the velocity of liquid at a particular point. But for simplicity we have taken C_p as 1.
The equations 5 and 6 are referred through *M.Ippolito* and *C. Sebatino* (Journals-5).
Assuming the symmetry condition, the value of shear rate is calculated from the velocity profile graph. After knowing shear rate shear stress using the Power law equation 1.

III. EXPERIMENTAL DETAILS

Experimental setup

The Fig.2 shows the schematic sketch of the experimental set up.

1. A 100 liter tank is kept 50cms above the level of the acrylic tube and 50-litre tank is kept on the ground.
2. The flow configuration is made into a closed loop by using a pump.
3. It consisted of a vertical pipe of inner diameter 70mm connected from the larger tank and then this pipe is connected to another horizontal pipe of 60mm inner diameter which is then connected into the transparent acrylic tube through a flow regulator.

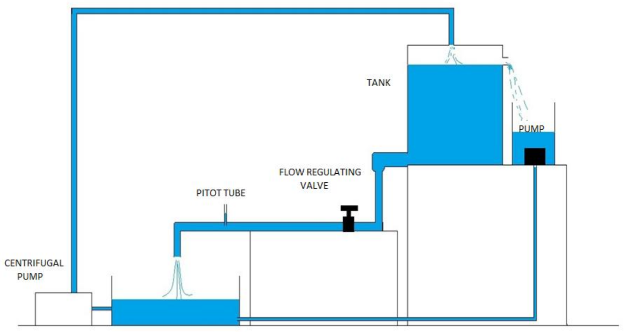

Figure 2: Experimental setup

4. The fluid from the upper tank flow through the acrylic tube and is collected in the lower tank which is then circulated back to the upper tank by the pump.
5. Five holes are made in acrylic tube at an interval of 15cm with first hole made at 90cm from valve opening. Each hole is 1cm in diameter.
6. Two acrylic tubes one with 60mm outer diameter and 50mm inner diameter and another with 50mm outer and 40mm inner diameter are used.
7. Dynamic probe is made of transparent acrylic tube of inner diameter 6mm and outer diameter 10mm. It has a stagnation probe hole of 1.5mm in diameter.
8. A transparent acrylic tube of inner diameter 6mm and outer diameter 10mm is used as static probe. It measures the static pressure head of liquid at pipe-liquid interface.
9. Experiments are done with and without obstacle in the path of the fluid flow.

Obstacle geometry and fixing arrangement

The obstacle has near spherical shape with a diameter of 2.5cm. A mixture of M-seal is taken and is made into a sphere on a thin wire. It is then let to dry. For fixing the obstacle inside the pipe, two holes each of 3mm in diameter are made on a diametrically opposite location on the wall of the pipe. Then the obstacle along with the wire is inserted from one end of the pipe till the region where the holes are made. Each end of wire is then pulled out from the diametrically opposite holes on the wall.

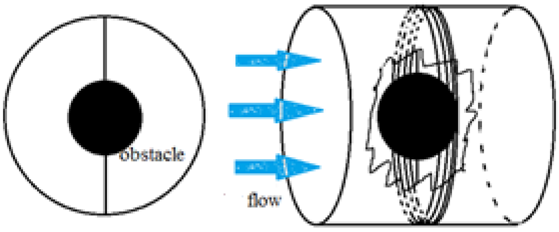

Figure 3: Transverse view and interior view of pipe

The two ends of the wire are then tied on the pipe taking care that the obstacle is located almost exactly at the centre of the pipe and it is shown in fig. 4.

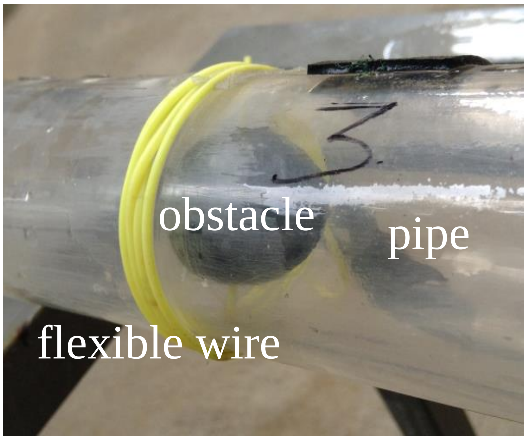

Figure 4: Obstacle fixed inside the pipe

Details of Fluids used

Fluids	% Weight per volume concentration	Density (at room temp.)	Power law index (n)	Fluid consistency coefficient (k)
Water	-------	996.3	1	-------
Aq. sodium Bentonite solution	3.33	1029.6	0.33	0.31
Aq. sodium carboxymethyl cellulose solution	0.4	1000.3	0.56	0.447

The lower density non-Newtonian fluid gives the better pitot tube pressure readings and flow could be ensured. Therefore the Aqueous Sodium Bentonite solution ($Al_2O_3.4(SiO_2).H_2O$) and Sodium Carboxymethyl Cellulose solution ($[C_6H_7O_2(OH)_2OCH_2COONa]n$) are considered and accordingly the size of pipes are determined.

IV. VELOCITY PROFILES FOR THE FLOW WITHOUT OBSTACLE

Velocity profiles at different length for 60mmx50mm pipe.

The velocity profiles at each plane for three fluids are plotted. For 5 planes velocity profiles which are distanced 15 cm between are shown below.

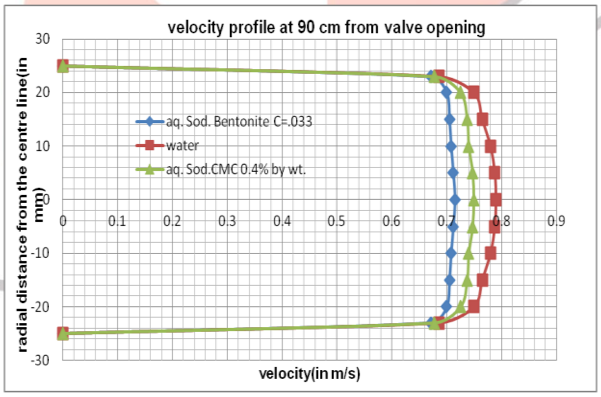

Figure 5: Velocity profile at 90 cm from valve opening.

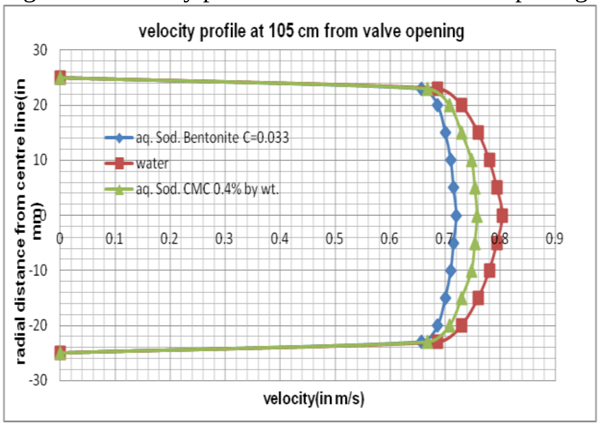

Figure 6: Velocity profile at 105 cm from valve opening.

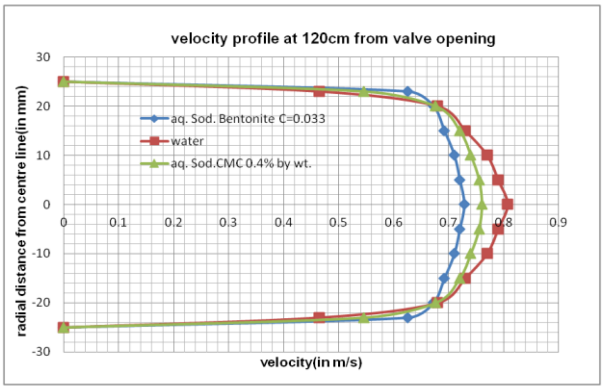

Figure 7: Velocity profile at 120 cm from valve opening.

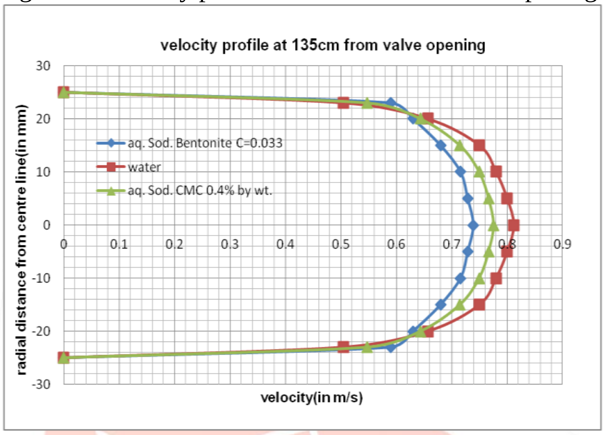

Figure 8: Velocity profile at 135 cm from valve opening.

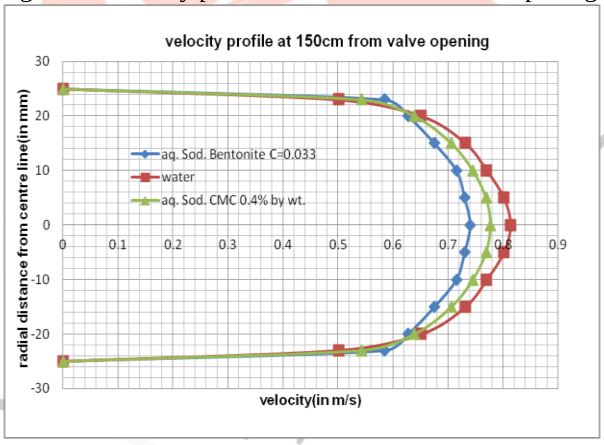

Figure 9: Velocity profile at 150 cm from valve opening.

Graphs shows that the average velocities of water flow through this pipe are 0.702m/s and 0.689m/s for sodium carboxymethyl cellulose and 0.673m/s for aqueous sodium bentonite solution when the flow is fully developed. Hence non-Newtonian fluids are more disturbed only near to the wall with a steep velocity gradient compared to the Newtonian fluid.

Velocity profiles at different length for 50mmx40mm pipe.

Similarly the comparisons between the velocity profiles of the three fluids are shown in sketches from fig 10 to fig. 14 for 50mmx40mm size pipe. At the different lengths the velocity profiles are drawn.

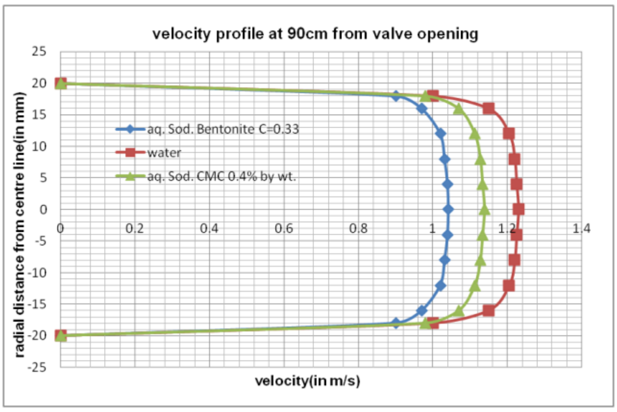

Figure 10: Velocity profile at 90 cm from valve opening.

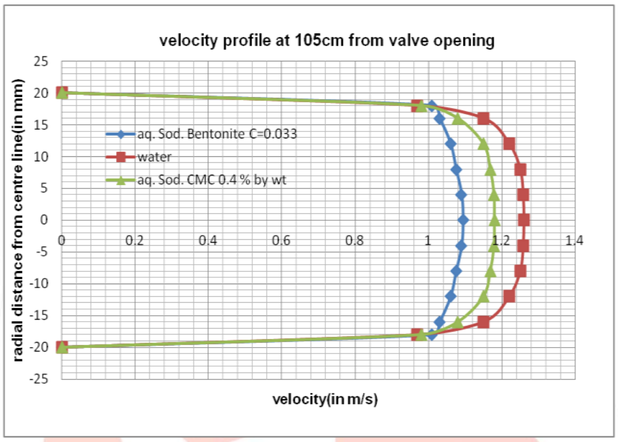

Figure 11: Velocity profile at 105 cm from valve opening.

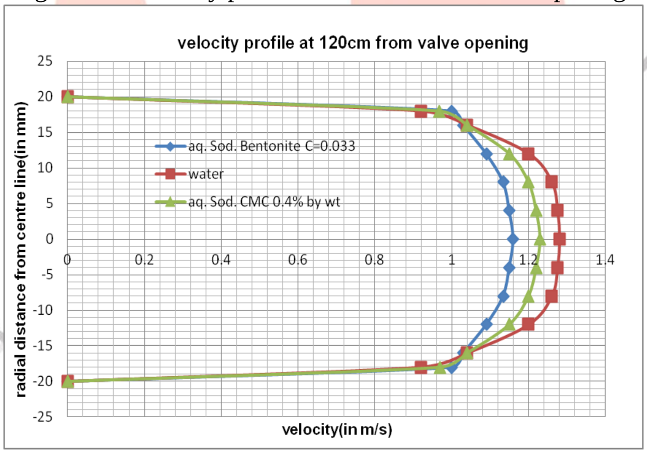

Figure 12: Velocity profile at 120 cm from valve opening.

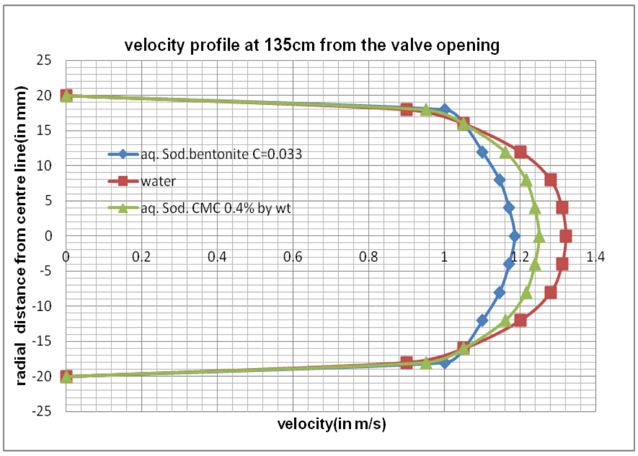

Figure 13: Velocity profile at 135cm from valve opening.

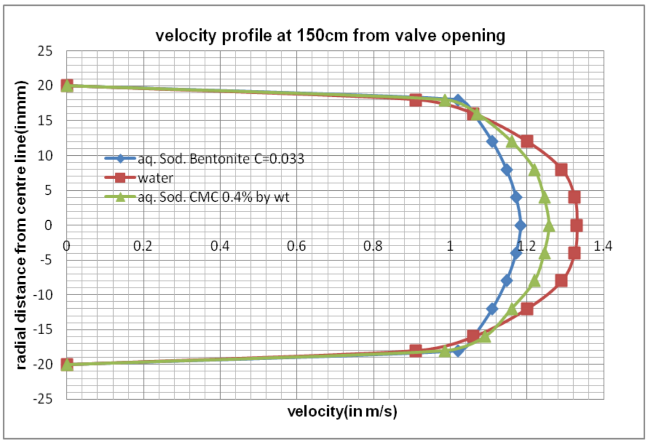

Figure 14: Velocity profile at 150cm from valve opening.

Graph shows that, the average velocity of flow for the water is 1.172m/s, for sodium carboxymethyl cellulose is 1.149 m/s and for aqueous sodium bentonite solution is 1.109m/s, when the flow is fully developed. The trend of variation in velocity profiles is same as that of the 60mmx50mm size pipe.

It is observed that the difference of velocity between water and sodium carboxymethyl cellulose in the central region of the pipe is 0.024m/s and between water and aqueous sodium bentonite solution is 0.063m/s. The average velocity is observed is higher due to the lesser dimension of the pipe and the average velocity of all fluids is about 1m/s.

V. VELOCITY PROFILES FOR THE FLOW WITH THE OBSTACLE

The experiments for the fluid flow with an obstacle have been carried out for the pipe having 40mm inner diameter and 50mm outer diameter. The velocity profiles obtained are shown in fig. 15 to fig. 19 at different planes for all the three fluids.

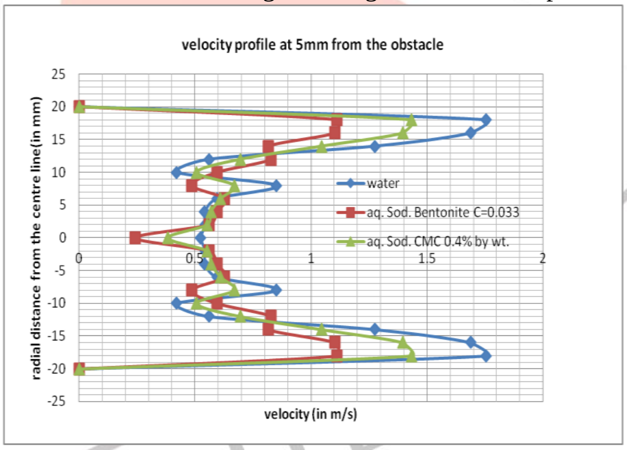

Figure 15: Velocity profile at 5mm from the obstacle.

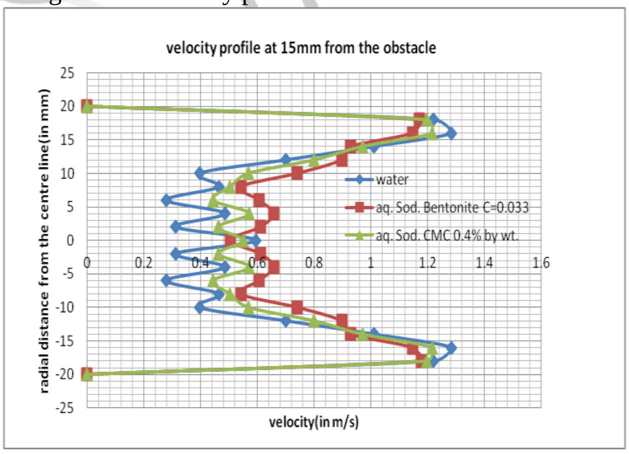

Figure 16: Velocity profile at 15mm from the obstacle.

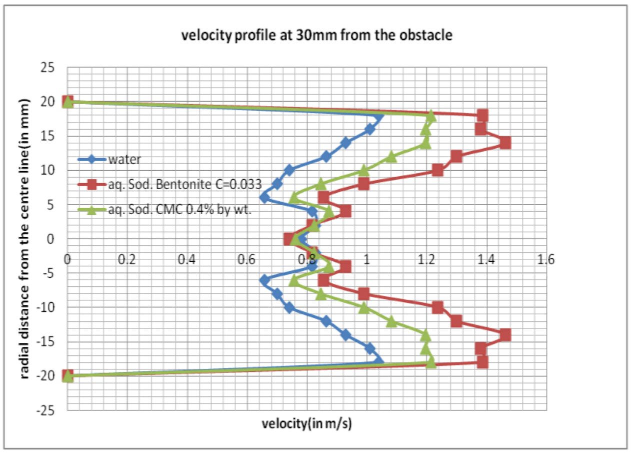

Figure 17: Velocity profile at 30mm from the obstacle.

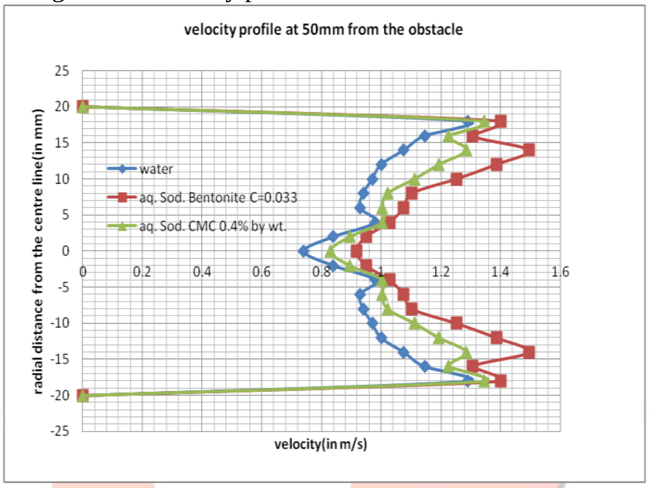

Figure 18: Velocity profile at 50mm from the obstacle.

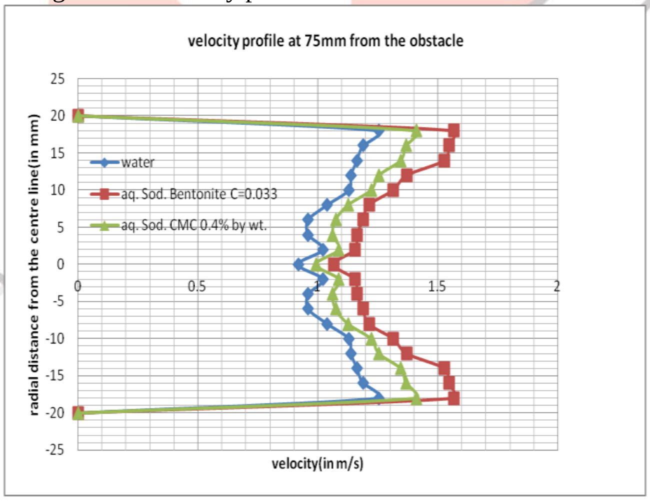

Figure 19: Velocity profile at 75mm from the obstacle.

The velocity variations are more in the radial direction and reduce gradually in the transverse direction. The more variations are observed in a shorter distance after the obstacle as shown in 5mm, 15mm and 30mm planes fig.15, fig16 and fig.17 respectively.

For example, at a distance of 5mm from the obstacle, the velocity of water flowing in the central region is 0.524m/s, for sodium carboxymethyl cellulose is 0.3835m/s and for the aqueous sodium bentonite is 0.243m/s.

The presence of obstacle may create the stagnation condition near the centre of the downstream surface of the sphere. Therefore the eddies formations towards the pipe wall may leads to the waviness in the velocity pattern.

The velocity at central area increases gradually as the test plane distance increases from the obstacle. The higher density fluid velocity at the central zone and near to the surface zone is lesser compared to the lower density liquids in the test planes near to the obstacle.

For example, at a distance of 5mm from the obstacle, the velocity of water flowing in the central region is 0.524m/s, for sodium carboxymethyl cellulose is 0.3835m/s and for the aqueous sodium bentonite is 0.243m/s.

In the transverse direction this nature becomes reverse. The higher density fluid will maintain the higher velocity at all points in radial direction compare to the lower density fluids. For example the velocity of water at a distance of 75mm from the obstacle is

0.918m/s, 0.9925m/s for aqueous sodium carboxymethyl cellulose and 1.067m/s for aqueous sodium bentonite. Hence, farther the distance from the obstacle more is the velocity.

VI. RESULTS AND DISCUSSIONS

Velocity profile variation as a function of density of fluids.

From the above graphs fig. 5 to fig. 14 results shows that, in any plane the maximum velocity increases with decrease in density and vice versa in radial direction.

Along the length of pipe, the maximum velocity of the fluid at different cross-sections increases along the direction of fluid flow. Also as the fluid flows, the maximum velocity of lower density non-Newtonian fluid at each cross-section increases more rapidly than that of higher density non-Newtonian fluid along the pipe.

Moreover, the difference in the peak velocities of the lower density non-Newtonian fluid and higher density non-Newtonian fluid at each cross-section increases along the length of pipe.

Velocity profile variation as a function of size

The increase in maximum velocity from one cross-section to another along the flow direction for each fluid is more rapid in smaller diameter pipe compared to larger diameter pipe.

The velocity profile of each fluid becomes sharper along the flow direction and also the velocity profile of the fluid with a lower density becomes sharper more rapidly compared to that of the higher density fluid along the direction of flow.

VII. WALL SHEAR STRESS

Shear stress is calculated using the following relationship:

$$\tau = k\left(\frac{du}{dr}\right)^n$$

We already know the values of k and n from table ---and $\frac{du}{dr}$ or shear rate is considered from the velocity profile.

The wall shear stress at different planes for different diameter pipes are been shown in fig. 20 and fig.21 respectively.

- Wall shear stress along the length of pipe of diameter 50mmX40mm

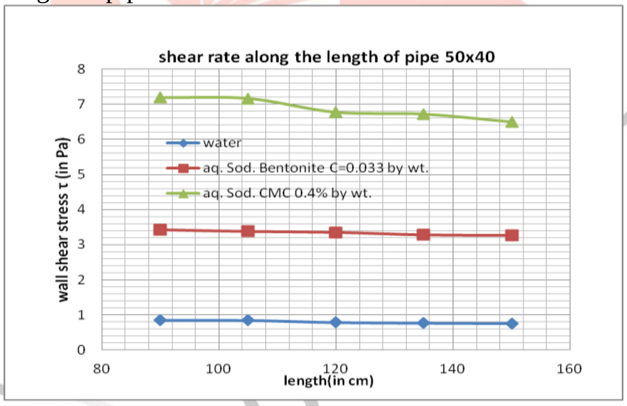

Figure 20: Wall shear stress vs. Length (50mmX40mm).

- Wall shear stress along the length of pipe of diameter 60mmX50mm

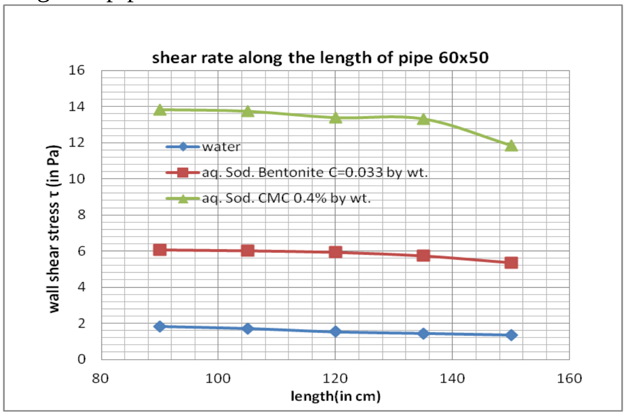

Figure 21: Wall shear stress vs. Length (60mmX50mm).

Figure shows that, the wall shear stress decreases along the length of pipe until it remains almost constant signifying fully developed flow.

For 50mm x 40mm diameter pipe, wall shear stress is almost constant for the last three test section where the flow is fully developed and for 60mm x 50mm diameter pipe, wall shear stress is constant indicating the region of fully developed flow.
The best fitting characteristics equations of shear rate for all the three fluids are;

For 50 x 40mm pipe:
water: y = -0.0081x + 2.5432
aqueous sodium bentonite solution:
y = -0.0113x + 7.1794
sodium carboxy methyl cellulose solution:
y = -0.0291x + 16.721

For 60x50mm pipe:
water: y = -0.0017x + 1.0132
aqueous sodium bentonite solution:
y = -0.0028x + 3.675
sodium carboxy methyl cellulose solution:
y = -0.0121x + 8.3182

The intercepts on the y-axis (i.e. wall shear stress axis) is maximum for aqueous sodium CMC solution for each pipe and water has the least. For non-Newtonian fluids, the fluid with higher density has smaller intercept compare to lower density non-Newtonian fluid. But water which is a Newtonian fluid has intercept smaller than that of both shear thinning fluids. This indicates water has smaller wall shear stress compared to other two non-Newtonian fluids (shear thinning fluids) at higher shear rate and thus shear thinning fluid has a blunter velocity profile compare to that of water.

For different diameters, the intercepts on wall shear stress axis is larger in smaller diameter pipe compared to that of bigger diameter pipe in case of all fluids both Newtonian and non-Newtonian fluids. This indicates a sharper velocity profile for all fluids in smaller diameter pipe compare to that in bigger diameter pipe which is well evident from the velocity profiles shown above.

Also it can be seen that all the characteristic equations of all the fluids have a negative slope or gradient. This signifies a decreasing wall shear stress along the length of the pipe. And water has the least negative slope indicating a very slow decrease in the wall shear stress along the length of pipe compare to shear thinning fluids. And aqueous sodium CMC solution having lower density compares to aqueous sodium bentonite solution has a larger slope indicating a more rapid decrease in wall shear stress along the length of the pipe.

VIII. SHEAR RATE

Shear rate along the length of pipe of diameter 50mmX40mm.

The shear rate is calculated from the velocity profile manually.

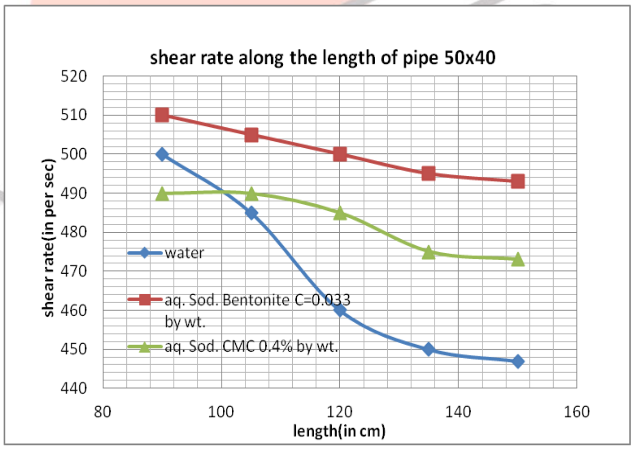

Figure 22: Shear rate vs. Length (50mmX40mm).

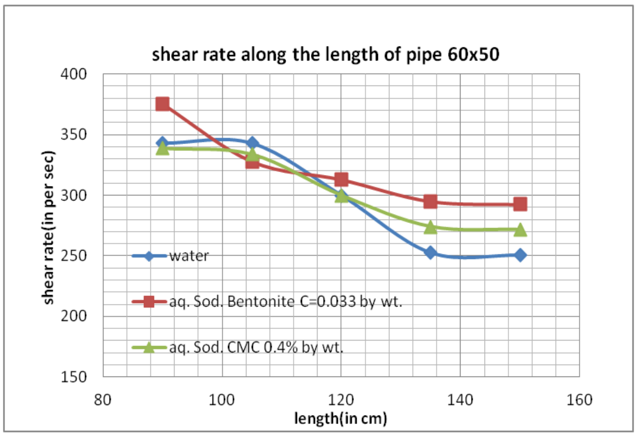

Figure 23: Shear rate vs. Length (60mmX50mm).

The velocity profile of each fluid becomes shaper as the fluid flow continues along the length of the pipe in both pipes of different diameters. As the velocity profile becomes sharper, the effect of wall friction advances more towards the center of the pipe until the pattern of velocity variation across the pipe becomes constant. As the wall friction advances, the shear rate near the wall decreases and after the wall friction advances up to the center of the pipe, the shear rate becomes constant for flow through the rest of the pipe indicating the flow is fully developed.

Also it can be seen from above two figures fig. (22) and fig.(23) that the shear rate decreases as the flow continues along the length of the pipe and the shear rate almost remains constant in the last three test sections for 50mm x 40mm diameter pipe and the last two test sections for 60mm x 50mm diameter pipe indicating the flow is completely developed in these regions.

The best fitting characteristics equations of shear rate for all the three fluids are given below.

For 50x40mm pipe:
water: $y = 0.0004x^3 - 0.1387x^2 + 13.901x + 67.114$
aqueous sodium bentonite solution:
$y = 7*10^{-5}x^3 - 0.0248x^2 + 2.3929x + 441.17$
sodium carboxyl methyl cellulose solution:
$y = 0.0003x^3 - 0.1184x^2 + 13.98x - 43.257$

For 60x50mm pipe:
water: $y = 0.0022x^3 - 0.7894x^2 + 91.539x - 3094.8$
aqueous sodium bentonite solution:
$y = 0.0276x^2 - 7.9552x + 865.29$
sodium carboxy methyl cellulose solution:
$y = 0.0013x^3 - 0.4625x^2 + 52.718x - 1603.7$
Here the polynomial best fitting equations are in the power of 3. The curves are following a similar trend. They decrease from an initial value and become constant as the fluid becomes fully developed.

IX. CONCLUSION

1. The variation in the velocity profiles of non-Newtonian fluid are been found with reference to the Newtonian fluid velocity profile for different diameter pipes along the length. Same has been observed involving the obstacle for the flow.
2. In the flow with obstacle over a length velocity fluctuations are faster in Newtonian compare to non-Newtonian fluid.
3. The increase in maximum velocity in the transverse direction for each fluid is higher in smaller diameter pipe compared to larger diameter pipe.
4. The disturbance by the wall presence is felt significantly near to the wall for the non-Newtonian fluids. But its felt everywhere in the radial direction for the Newtonian fluid.
5. The non-Newtonian fluids are more sensitive to the pressure variation near the obstacle than the far away planes compared to the Newtonian fluid.
6. The variation of shear rate for non-Newtonian fluid is found different than that of Newtonian fluid. At the section near the entrance, shear rate of water which is Newtonian lies between shear rates of the two non-Newtonian fluids. But after the flow is fully developed the shear rate of water is less than the shear rate of both the non-Newtonian fluids.
7. Non-Newtonian fluids have almost linear variation of wall shear stress with respect to the length of the pipe. But the after certain length, there is almost no variation of the wall shear stress indicating a fully developed flow.

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