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Parametric rheology of fluid in constrictive sections

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Abstract - Non-Newtonian fluids play a vital role in Industrial applications like paints, polymers and Food processing. In this study two food ingredient sample solutions are examined for Rheological shear-thinning behavior, under flow in constrictive pipe section.

Experimental viscosity is determined for the samples, and then compared with liner regression fit. The material data, Power Law viscosity model and pipe section geometry is numerically modeled in CFD to obtain apparent viscosity and velocity variations during the flow. Examinations are also conducted for standard Newtonian fluid with Turbulence and Heat Transfer in a sub version of this study.

Key Words: Shear Thinning, Rheogram, Power law model, Regression

1. INTRODUCTION

The Rheology i.e. study of non-Newtonian behavior of fluids during the flow in these sections forms a crucial part in deciding machinery layout process, design of equipment's and the order in the processing of the food products. Further, design optimization can be carried out to minimize energy losses, and bring better efficiency in the system.

2. RHEOLOGY & SIMULATION MODEL

As opposed to Newton law of viscosity for ideal fluids, Non Newtonian fluids can be expressed using laws like power law, Carreau-Yasuda Model Etc. The approach is to first obtain material characteristics of the given sample. Using a Rheometer , a rheogram plot i.e. stresses (σ) vs. shear rate (γ) is obtained for the given sample.

Power Law Model

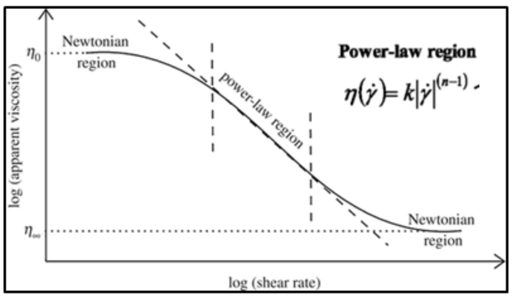

Chart -1: Power Law region

Power law is a viscosity model used to define behavior of time independent Non Newtonian fluids. Power law is used for shear-thinning, weak gels and low-viscosity dispersions. Pseudo plastic fluids show this behavior over a wide range of shear rate; but normally approach a limiting Newtonian behavior at very low and very high rates of shear.

These Newtonian regions are characterized by viscosities η0 on upper bound of graph and η∞ on the lower bound of graph.

Power Law Formula:

Log η = (n-1) log γ + log K	$\eta = K\dot{\gamma}^{n-1}$

γ is the shear rate or (SI unit s−1)
K is the flow consistence index Pas^n

n is flow behavior index and gives us convenient way to compare different materials.
If n<1 fluid is Pseudo plastic, if n=1 fluid is Newtonian, if n>1 then fluid is Dilatant.

In this study liner regression is carried out to obtain best possible fit for the experimental values. Relation between apparent viscosity and shearing rate on a log-log scale is obtained later.

CAD/CFD Model

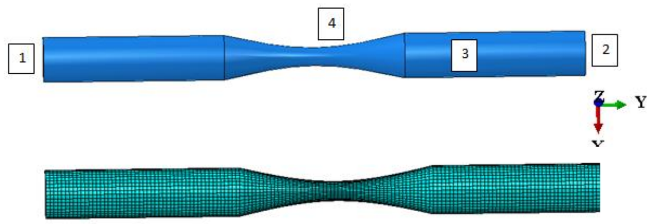

Fig -1: CAD/CAE models

Here, Non-Newtonian flow in a constrictive section is studied to obtain engineering parameters of interest in a particular region for a given sample. The description of the constrictive passage used in the study is mentioned below.

- Total Length: 120mm
- Diameter of inlet and outlet: 10mm
- Diameter at the throat: 4mm
- Length of Converging-Diverging section: 40mm

CFD Model Details

- Total Cell Count : 11929 Hexahedral Elements
- Cell Type : FC3D8 – Linear Formulation
- Total node count : 14592, Model : 3D

Boundary conditions

Two cases are considered for CFD analysis. Refer Fig-1.
For Power Law simulation cases

1. Inlet velocity 0.06 m/s.
2. Outlet pressure : Atmospheric/ Gauge 0 Pa
3. Adiabatic wall – condition of no slip
4. Z symmetry –to mimic other half of the pipe

For Turbulence Model simulation case, considering oil as ideal fluid.

1. Inlet velocity 0.12m/s, Inlet Temperature : 50 Deg C, Eddy Viscosity: 0.000837
2. Outlet pressure: Atmospheric [Gauge 0 Pa]. Outlet Temperature : 20 Deg C
3. Wall Temperature – Constant temperature of 20Deg C.
4. Z symmetry –to mimic other half of the pipe.
5. Turbulence – Spalarat Allmaras with Energy Equation.

3. RHEOMETRY

Sample Preparation

The poly gum powder in weighed quantity is mixed into the water in motorized mixer equipment, which continuously stirs the mixture for 10 minutes to get smooth consistent texture i.e. without lumps. The mixture is rested for 30min in a constant temperature water bath at 28 DegC for the sedimentation to absorb and dissolve in water base. Again the mixture is agitated for 10 minutes and sample is ready for further measurements. In case of protein solution, the protein syrup is mixed into the water base at calculated proportion. Motorized stirrer agitates the mixture for 4 minutes. Rest further processes follow the same procedure as the preparation of polygum solution.

The quantities of the samples prepared are outlined below:

Sl No	Sample Name	Quantity	Water base
1	PolyGum solution – additive used : Polygum powder	22 gram	1000ml
2	Protein Solution – additive used : Protein syrup	45 ml	1000ml

Table -1: Sample preparation quantities

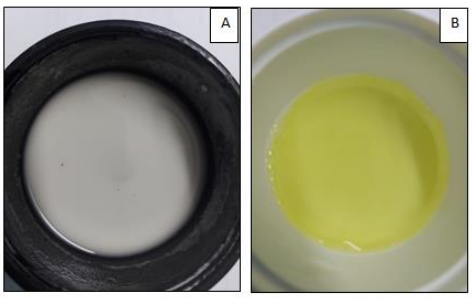

Fig-2: Samples prepared Test sample preparation, A –Polgum Solution, B – Protein Solution

Linear Regression

Using the rheogram of the samples, the experimental data is fit into power law model.

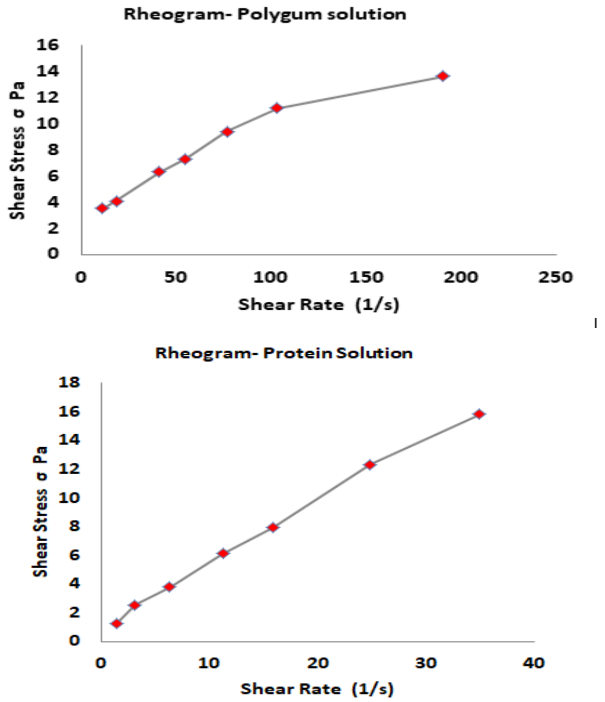

Chart -2: Rheogram Plots for Polgum & Protein Solution

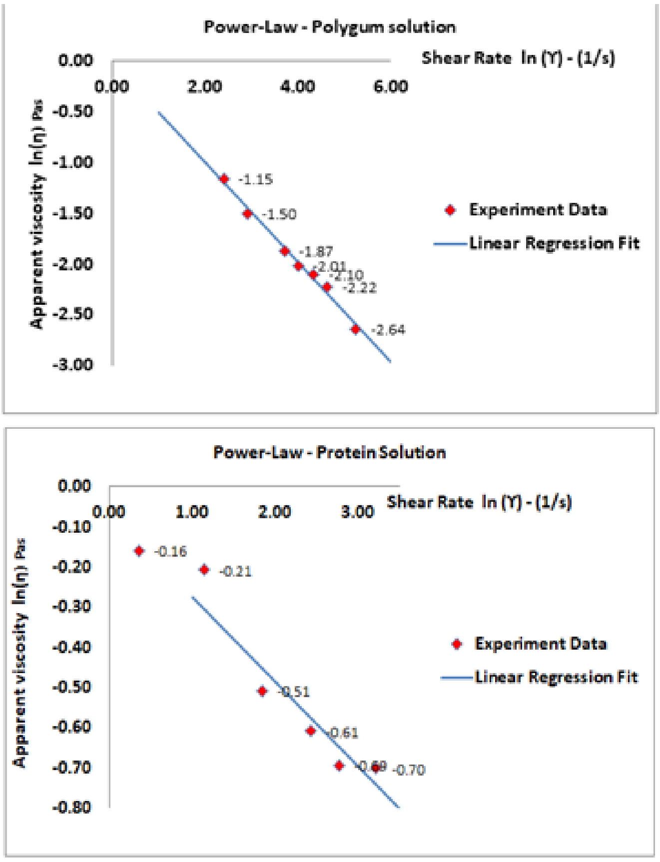

Chart -3: Linear Regression Fit

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Parameters of Best Fit	Values Polygum Solution	Values Protein Solution
Number of XY Pairs	7	7
Equation of Line	Y = -0.4914x-0.01338	Y = -0.211x-0.0638
Slope	-0.4914	-0.211
Y Intercept	-0.01338	-0.0638
X Intercept	-0.02723	-0.3024
Goodness of Fit (R Square)	0.98	0.95
Sy.x	0.058	0.059
Derived values : n	0.51	0.78
Derived Values : k	0.986 [Pas]	0.938 [Pas]

Table -2: Curve fit Summary

Temperature Deg C	Conductivity W/mK	Specific Heat j/kgK	Dynamic Viscosity kg/m s	Density Kg/m3
0	0.15	1798	3.82	
20	0.15	1880	0.85	
40	0.14	1965	0.23	
50	0.14	2005	0.16	
60	0.14	2047	0.08	
70	0.14	2091	0.06	
80	0.14	2130	0.04	
100	0.14	2221	0.01	

Table -3: Material properties of Oil used in turbulent model analysis

4. CONCLUSIONS

Simulation result summary

Fluid	Max App Viscosity [Pas]	Min App Viscosity [Pas]	Percent Decrease viscosity [%]	Max Shear Rate [1/s]	Min Shear Rate [1/s]	Percent Decrease Shear Rate [%]
Polygum Solution	0.69	0.1	85.5	774	66	91.5
Protein Solution	0.69	0.27	60.8	695	62	91.1

Fluid	Max Velocity [m/s]	Max Pressure [Pa]	Max Apparent Viscosity [Pas]	Max Shear Rate [1/s]	Temperature Deg C
Polygum Solution	0.61	901	0.69	774	NA
Protein Solution	0.69	3657	0.69	695	NA
Oil – SA Turbulence Model	1.84	6468	NA	1540	50

Table -4: Simulation Results summary

Simulation result flow parameters – Contour plots

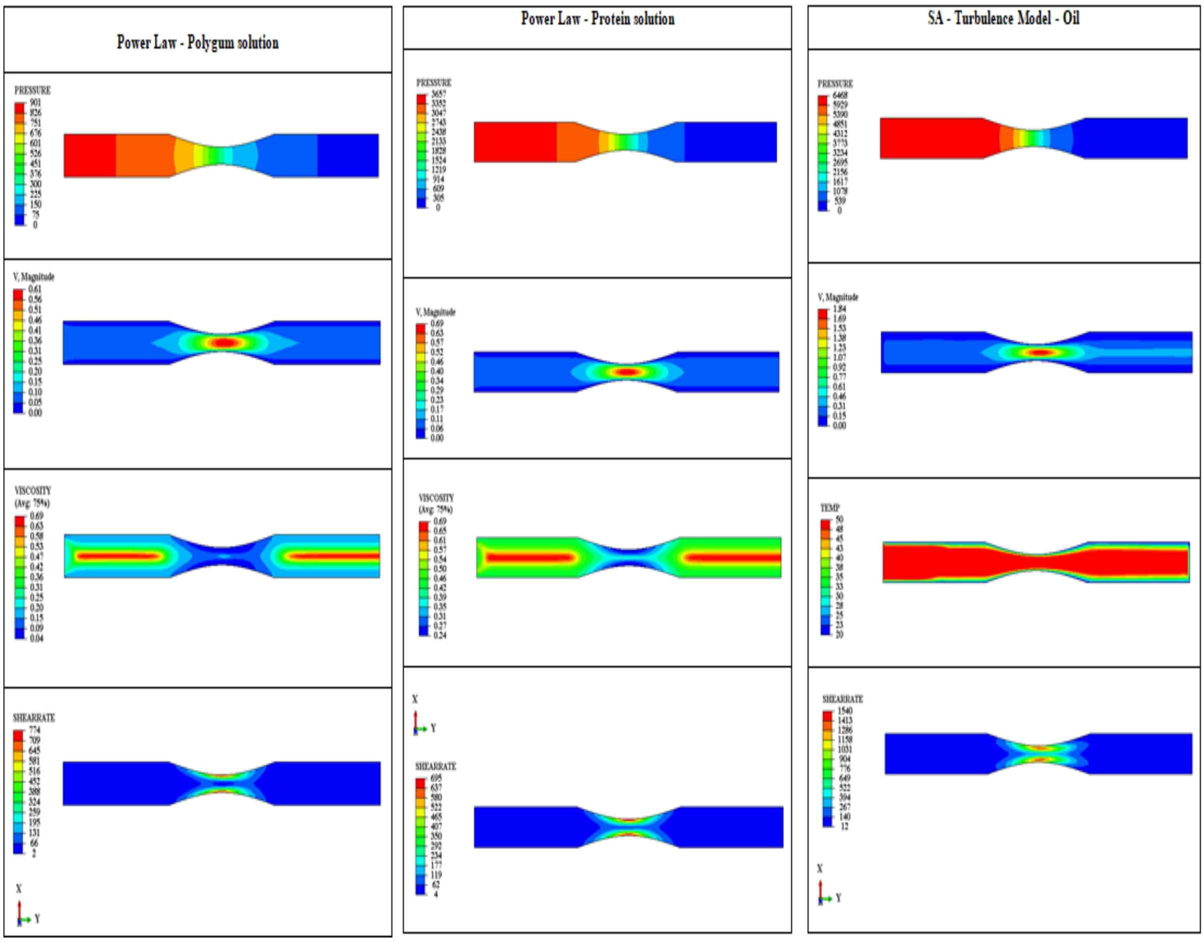
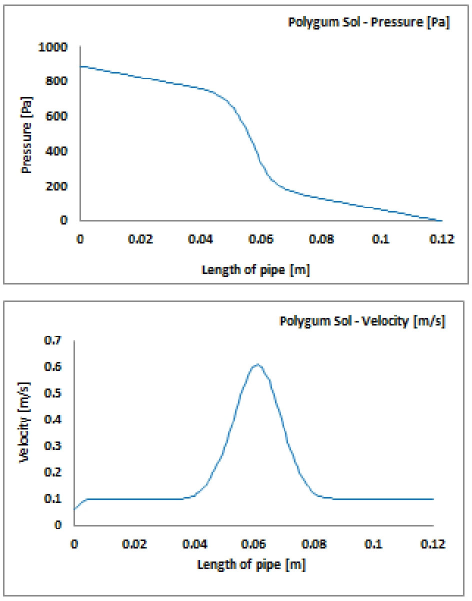
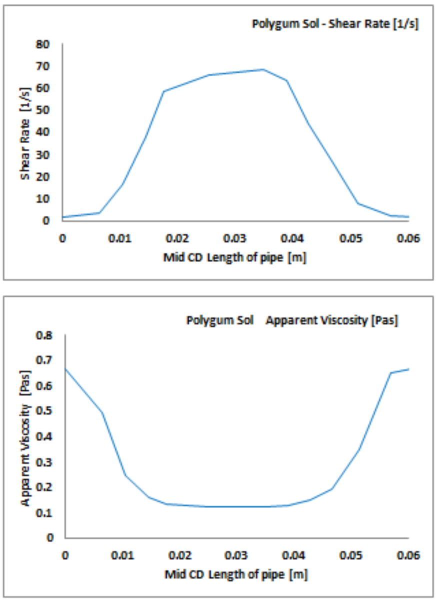


Fig-3: Contour plots of flow parameters.

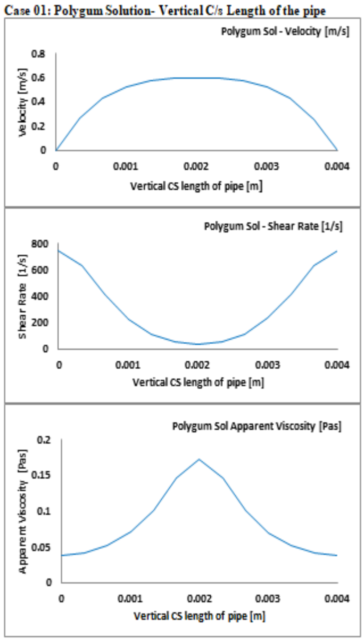
Case 01: Polygum Solution- Horizontal Length of the pipe



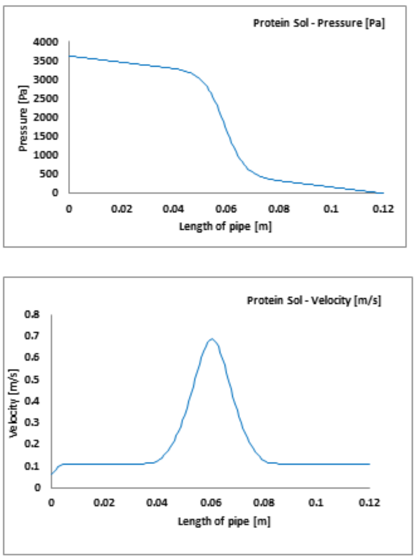
Case 01: Polygum Solution- Horizontal mid CD Length of the pipe



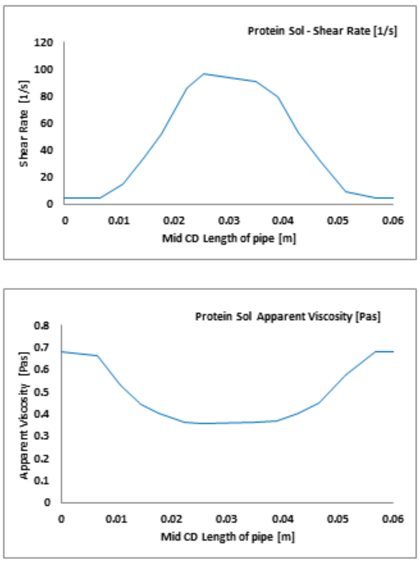
Case 01: Polygum Solution- Vertical C/s Length of the pipe



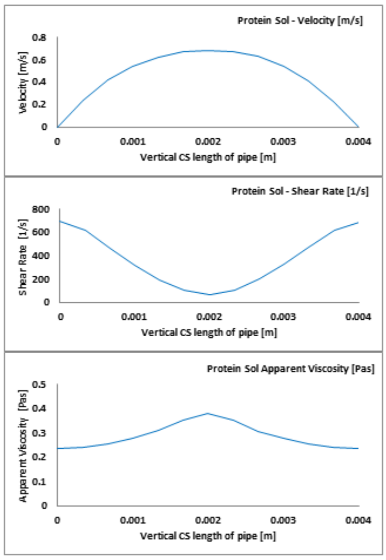
Case 02: Protein Solution- Horizontal Length of the pipe



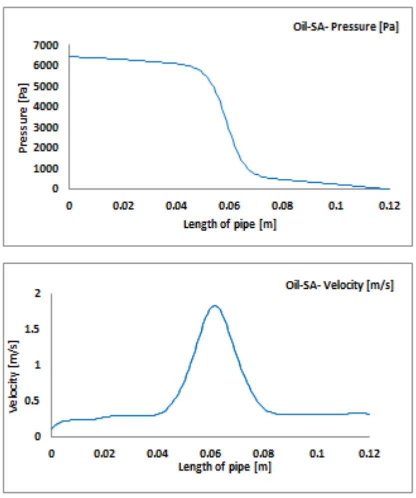
Case 02: Protein Solution- Horizontal mid CD Length of the pipe



Case 02: Protein Solution- Vertical C/s Length of the pipe



Case 03: SA Turbulent Model Oil- Horizontal Length of the pipe



Case 03: SA Turbulent Model Oil- Vertical C/s Length of the pipe

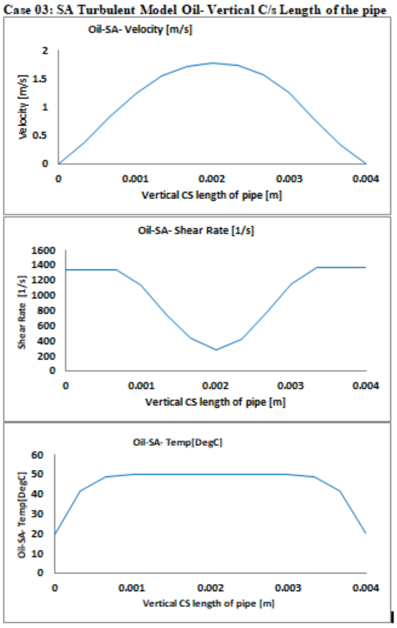


Chart-4: Simulation results flow parameters – Graphical plots

The Rheological data of the samples are experimentally tested and presented in the chart-2.From the linear regression analysis of the Polgum solution, it is concluded that this fluid follows the linear equation Y = -0.4914x-0.01338, with derived values of n=0.51, k= 0.986 Pas, and has R square of 0.98.

From the contour plots Fig-3, for Polygum solution, max velocity of 0.61m/s is observed at constriction. Highest value of Shear Rate is observed at the constriction walls with the value of 774 [1/s]. Consequently, apparent viscosity is minimum at constriction of pipe at 0.1Pas and highest of 0.69 Pas at mid region entry and exit of the pipe. This effect is due to shear Thinning character of the fluid. From Table-4, for the Polygum solution, the percentage decrease in apparent viscosity is 85.5%, and percentage decrease in Shear rate is 91.5%.

The Chart-4, gives the velocity profile and pressure profile for the Polygum solution along the length of the pipe. Chart-4 also gives the constrictive section details of flow. Due to increase in shear rate the apparent viscosity has decreased along the length. Chart-4 gives the flow characteristics along vertical section of the pipe, the velocity profile increases in the mid area of the pipe, and shear rate is highest at the walls and decreases at the center and increases towards the other end of the wall. Consequently, the apparent viscosity is lowest at the walls and increases at the center and decreases towards the other end of the wall.

From the linear regression analysis of the Protein solution, it is concluded that this fluid follows the linear equation Y = -0.211x-0.0638, with derived values of n=0.78, k= 0.938 Pas, and has R square of 0.95. The explanation and analysis follow same logic for Protein solution as above, referring to the Chart-4. The percentage decrease in viscosity is 60.8%, and percentage decrease in shear rate is 91.1%.

Since the percentage decrease of apparent viscosity is 85.5% for the polygum solution it shows higher shear thinning behavior compared to protein solution which has percentage decrease of apparent viscosity of 60.8%.

Above effect, is also due to the fact that flow index n of polgum solution (n=0.51) is lower than protein solution (n=0.78). Hence polygum shows higher shear thinning effects. Fig-3, shows the contour of Turbulence Spallart Allmars Model, Max velocity of 1.84 m/s, and max shear rate of 1540 [1/s] is observed. Equilibrium temperature of 50 Deg C remains constant throughout the flow, this is due to turbulence nature of flow. Chart-4, shows the pressure profile and velocity profile along the length of pipe.

Chart-4 shows vertical cross section profiles. Temperature increases from 20Deg C at walls to 50 Deg C at the mid-section and again drops to 20 Deg C at the walls.

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