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Digital Simulation for the Behavior of the Flow of Non-Newtonian Fluids in Pipelines' Entrance Area

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***Abstract*— In this study, the frictional losses in a pipe due to shear stress produced in a pipe due to viscosity of fluids has been discussed. Pipeline system is a vast network in any industry and minimizing losses through these pipes can contribute a lot. This paper contains flow analysis of different fluids in a pipe entrance. The Computational Fluid Dynamics (CFD) analysis for the flow of non-Newtonian fluid through a straight pipe is presented. Laminar non-Newtonian pseudoplastic power law model has been used for the simulation of non-Newtonian fluid flow through the pipeline, particularly the entrance area. The CFD analysis has been tested from previously published experimental results.**

***Index Terms*— CFD, Pipeline, Channel, Non-Newtonian fluid, Pressure drop.**

***Conflict of Interest*—K. Kahine, A. Hammoud and G. Accary state that there are no conflicts of interest.**

I. INTRODUCTION

Implementation of fluids in many industrial activities often requires their transport in pipeline networks having singularities, pumps and heat exchangers. A good design of these networks requires a precise knowledge of the laws governing the transfer of heat energy loss E (regular and singular).

Fluids with nonlinear [3] behaviour conforming the power law as well as their changing flow parameters are of interest to many industrial sectors; they are nevertheless considerably less studied compared to Newtonian fluids. The consequences of shear thinning need to be identified to a clearer understanding of the structure of the flow.

The assumption that the flow is fully developed in regions where it remains under strong influence of the inlet boundary conditions can seriously underestimate the design of flow systems and incorrectly assume specific velocity profile shapes leading to wrong conclusions in the interpretation of data [10].

Unsurprisingly, determining this length for a range of ducts, e.g., pipe, channel, and annuli, has been the subject of a great deal of attention over the past 100 years or so [9].

A detailed discussion of the inconsistencies and confusion in literature is provided by Durst et al. [9], who conducted a detailed numerical study and proposed nonlinear correlations for pipes and channel for Newtonian fluids.

In this study we are interested in the laminar flow of non-Newtonians pseudoplastics thermo-dependents fluids in a straight cylindrical pipe and between two plates particularly in the entrance area.

The mathematical model is represented by the equations of continuity and conservation of momentum. The rheological behaviour is given by the power law of Ostwald of Wale.

It is proposed to determine the structures dynamic and static fields of this flow. We will study the influence of the Reynolds number and shear-thinning characters on the dynamic field and the evolution of head losses.

The development or the use of numerical calculation software is essential to the resolution of such problems. The discretization of the system of equations is performed using the finite volume method that is implemented in digital modelling software "Ansys-Fluent".

II. MATHEMATICAL MODEL

The general equations governing the laminar flow of incompressible fluids are:

(i). Continuity Equation

$$div(\rho\vec{V}) = 0 \qquad (1)$$

(ii). Movement Equation

$$\rho\frac{d\vec{v}}{dt} = -\overrightarrow{grad}(p) + div(\vec{\tau}) \qquad (2)$$

Where $\vec{V}$ is the velocity vector, $\vec{\tau}$ the stress tensor, ρ the density and p the pressure.

The general conservation equations governing the isothermal flow in pipes are written by adopting the system of cylindrical coordinates.

In addition the following simplifications are adopted:

- Stationary flow.
- Incompressible flow (density is constant).
- Axisymmetric flow in cylindrical pipe.
- The radial pressure gradient is negligible.

(iii). Simplified Continuity Equation

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$$\frac{\partial (ru)}{\partial z} + \frac{\partial (rv)}{\partial z} = 0 \tag{3}$$

(iii). Simplified Movement Equation in z Direction

$$\rho u \frac{\partial u}{\partial z} + \rho v \frac{\partial u}{\partial r} = -\frac{dp}{dz} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_a \frac{\partial u}{\partial r}\right) + \frac{\partial}{\partial z}\left(\mu_a \frac{\partial u}{\partial z}\right) \tag{4}$$

(iv). Simplified Movement Equation in r Direction

$$\rho u \frac{\partial v}{\partial z} + \rho v \frac{\partial v}{\partial r} = \frac{\partial}{\partial r}\left(\frac{\mu_a}{r}\frac{\partial (rv)}{\partial r}\right) + \frac{\partial}{\partial z}\left(\mu_a \frac{\partial v}{\partial z}\right) \tag{5}$$

In addition to the following boundary conditions:

(v). Condition of non-sliding at the wall

$$u(r = R) = v(r = R) = 0 \tag{6}$$

(vi). At the axis of symmetry

$$\frac{\partial u}{\partial r}(r = 0) = \frac{\partial v}{\partial r}(r = 0) = 0 \tag{7}$$

For the problem of the establishment length, we have a constant axial velocity profile:

$$\frac{u}{u_m}(z = 0) = cte = 1 \tag{8}$$

Where r is the pipe radius, u the axial velocity, v the radial velocity, μ_a is the apparent viscosity and u_m is the mean velocity.

The Simulation was done by the software "fluent" using the model of Herschel-Bulkley [5] for $\tau < \tau_0$.

We note that the equation used is Ostwald de Waele, but to solve this problem having our study fluid of this type, we choose to adopt as law behavior the equation corresponding to Herschel-Bulkley fluids in non-Newtonian critical stress. Recall that the model of Herschel-Bulkley is given by:

$$\tau = \frac{\tau_0 + K\left[\dot{\gamma}^n - \left(\frac{\tau_0}{\dot{\gamma}}\right)^n\right]}{\dot{\gamma}} \tag{9}$$

Having τ_0 "the yield stress threshold" equal to zero the preceding equation becomes the Ostwald de Waele equation:

$$\tau = K \times |\dot{\gamma}|^{n-1} \times \dot{\gamma} \tag{10}$$

The consistency K of the fluid is found in terms of Reynolds number Re and the power index n for a cylindrical pipe and in between two plates [4]:

$$Re_n = 8^{1-n}\left(\frac{4n}{3n+1}\right)^n \frac{\rho u_m^{2-n} D^n}{K} \tag{11}$$

$$Re_n = 12^{1-n}\left(\frac{3n}{2n+1}\right)^n \frac{\rho u_m^{2-n} (2e)^n}{K} \tag{12}$$

In this chapter, we have established the mathematical partial differential equations governing the laminar flow of non-Newtonian pseudoplastic fluid and the software used "Ansys-Fluent" is responsible for the discretization and numerical solution.

2. Dynamic Study of Establishment Length

In this chapter we will study the behavior in the entrance area, a non-Newtonian fluid non-complex thermo-dependent flowing in a cylindrical industrial pipe, where the axial velocity profile constantly evolving until it takes its final shape of establishment for laminar flow.

(i). Flow State in the Pipe Line

Consider a pipe fixed to a large-sized tank figure (1). At the entrance of the pipe, the velocity distribution is flat and uniform. During the flow along the pipe, the fluid particles adjacent the walls are braked gradually causing the particles adjacent to the axis to accelerate so that the flow is conserved.

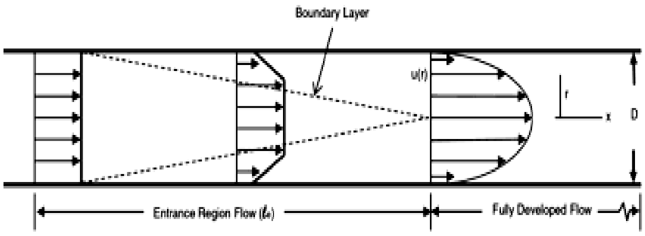

Figure 1: Flow state at pipe entrance

Theoretically for a laminar flow (n=1 & Re<2100) the establishment length $L_{etab.}$ is expressed by [6]:

$$\frac{L_{etab.}}{D} = 0.0575Re \tag{13}$$

Where D is the pipe diameter .

(ii). Velocity Profile in the Established Flow

The velocity profile for an established flow can be defined then by:

$$\frac{u(r)}{u_m} = \left(\frac{3n+1}{n+1}\right)\left[1 - \left(\frac{r}{R}\right)^{\frac{n-1}{n}}\right] \tag{14}$$

The theoretical velocity profiles for different index n are shown in the figure 2:

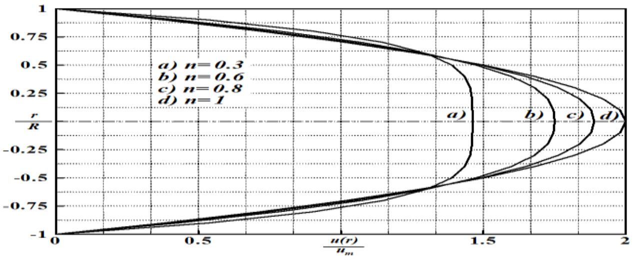

Figure 2: Velocity profile in a cylindrical pipe

(ii). Geometry and Calculation Procedure

The geometry studied numerically is shown in the figure 3 as for the cylinder diameter D = 1 and pipe length L =50D.

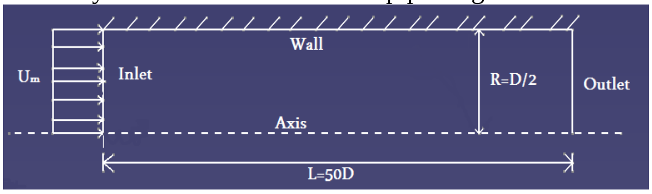

Figure 3: Studied pipe geometry

Meshing of the geometry is done in the software “Ansys” and a 300x50 mesh was used as shown in the figure 4:

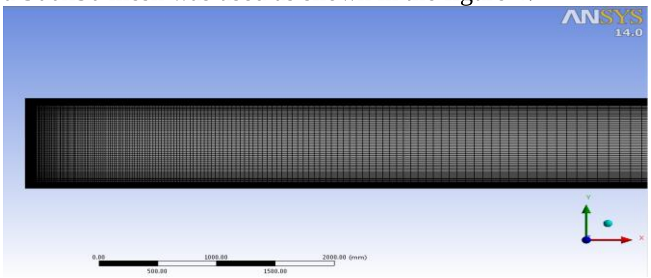

Figure 4: Typical used mesh

The study convergence was set for a value of 10e-6 and the “QUICK” interpolation and the “SIMPLE” algorithm [8] was used as the system configurations and convergence results example are shown below (figures 5 and 6):

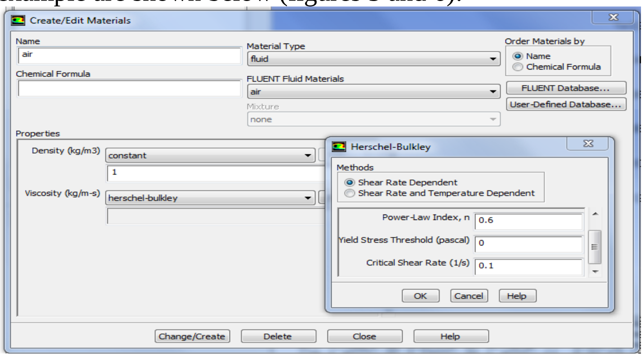

Figure 5: Input parameters

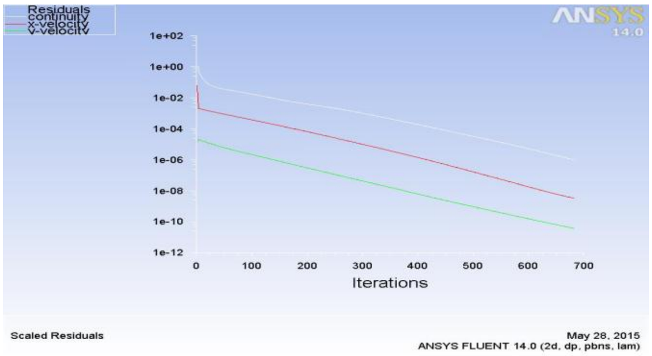

Figure 6: Results evolution

(iii). Variation of the Establishment length as a function of the flow parameters

From our study and as we fixed the number of Reynolds and the structure index n we can find the velocity profile for several positions in the pipe as shown in figure 7:

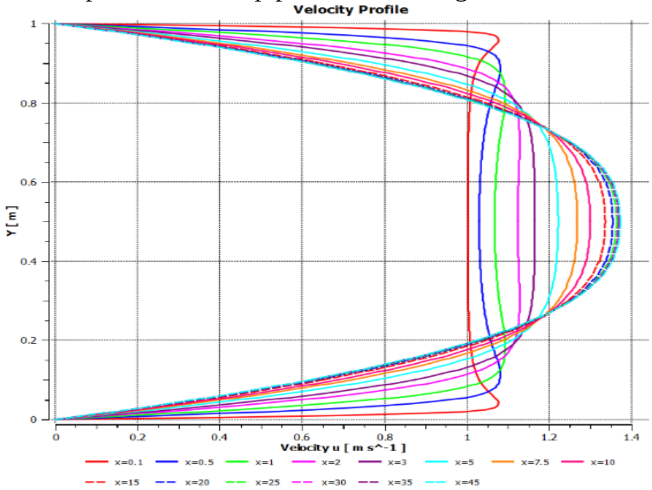

Figure 7: Evolution of axial velocity for Re=250 & n=0.6 for a cylindrical pipe

From the figure 7 it can be found the establishment length was about 13.33 for Re=250 & n=0.6

The influence of Reynolds number in the establishment length was studied by fixing n on 0.6 and varying Re as the results shown in the figure 8:

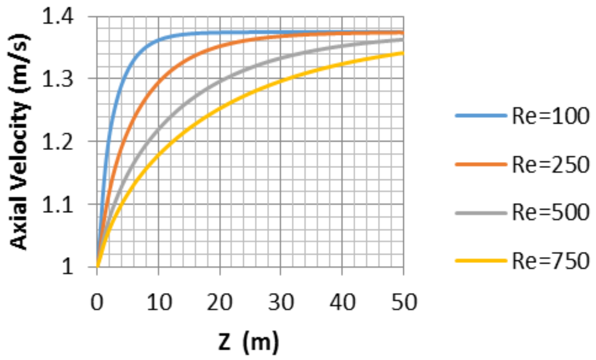

Figure 8: Evolution of the axial velocity for different number of Reynolds

While by fixing Re on 250 and varying n we can find the influence of the structure index on the establishment length as shown in figure 9:

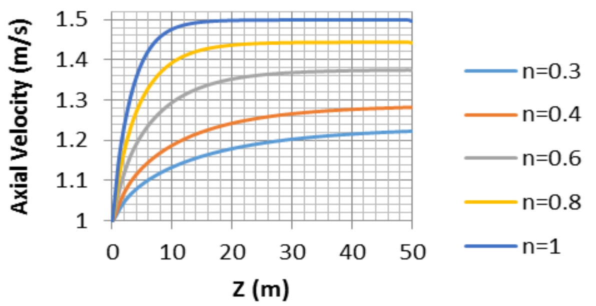

Figure 9: Evolution of the axial velocity for different structure numbers

It is clear that in both cases the axial velocity at the center increases gradually as the fluid advance in the pipe, however, this development does not occur in the same way in both cases studied.

(iii). Search for Correlations

By tracing the evolution of the establishment length as a function of Reynolds number it can be found that the length increases linearly with Reynolds number.
The results of the simulation are grouped in the table 1 and plotted as shown in figure 10.

Table 1

Simulation Results

Reynolds	Normalized Establishment Length (Lest / D)				
	n = 0.3	n = 0.4	n = 0.6	n = 0.8	n = 1
25	1.03	1.33	1.54	1.58	1.59
50	1.88	2.39	2.80	2.95	3.03
100	3.73	4.59	5.42	5.76	5.96
250	9.40	11.34	13.33	14.22	14.69
500	19.13	22.81	26.62	28.36	29.40
750	29.23	34.26	40.12	42.46	43.75

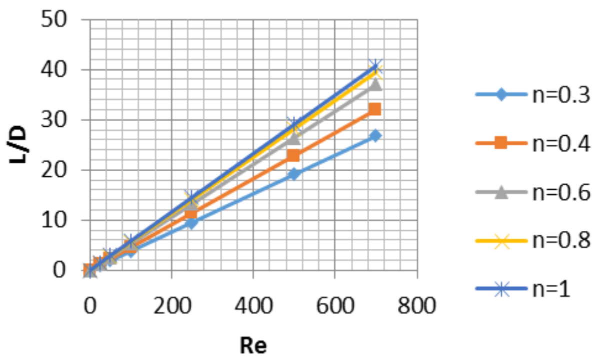

Figure 10: Variation of the establishment length as a function of Re for different values of n

From the results it is shown that the variation of the establishment length is directly proportional to the Reynolds number, forming a straight line passing by the origin for every index n value which can be correlated in the form:

$$\frac{L_{etab}}{D} = a(n).Re_n \tag{15}$$

From our results we can reach to the correlation for the cylindrical pipe:

$$\frac{L_{etab}}{D} = \frac{1}{100}\left(\frac{-0.8678}{n} + 6.71\right) \times Re_n \tag{16}$$

The correlation found in the literature [1] gives the establishment length for a Newtonian fluid for n = 1, then our correlation is in good agreement with [1] with less than 1.7% relative error, which validates the numerical results. This correlation allows to provide the business flow length for various values of the Reynolds number and the index n.
A same study was done for the case of two plates and the correlations were:

$$\frac{L_{etab}}{e} = \frac{1}{100}\left(\frac{-0.265}{n} + 2.57\right) \times Re_n \tag{17}$$

III. Singular Pressure Drop

In this chapter, we will study the singular head losses associated with the flow in the entrance area of a cylindrical pipe and in between two plates.

(i). Influence of rheological parameters on the singular head losses

Influence of fluid's consistency K: To study the influence of the consistency K of the fluid on the pressure drops, it returns to study the impact of the Reynolds number on them [4].

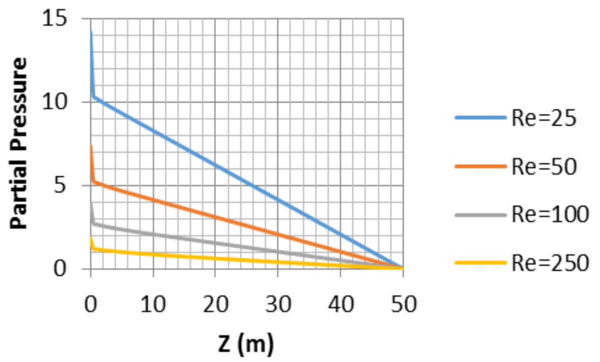

Figure 11: Evolution of partial pressure for different Re number (n=0.6)

Corresponding a zero outlet pressure, as noticed the pressure drop decreases with increase of Re which is as Re decreases the influence of viscosity increases increasing the pressure drop.

Influence of the structure index n:

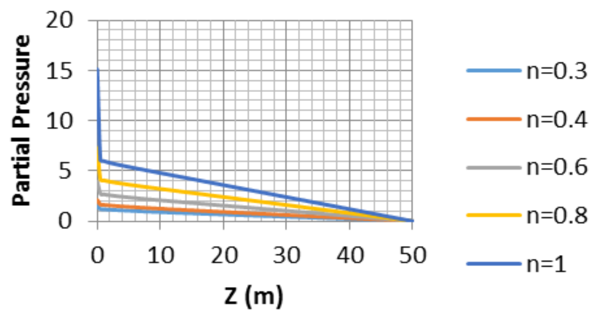

Figure 12: Evolution of partial pressure for different n index (Re=100)

The singular pressure drop increases with the increase in structure index n of the fluid.

(ii). Equivalent Length

Pressure drop Js can be found theoretically [2] to be:

$$J_s = \frac{Cf}{2}\frac{L}{D}\rho 4 u_m^2 \tag{18}$$

This gives the normalized form of the equivalent length:

$$\frac{L_s}{D} = \frac{\varepsilon Re_n}{64} \tag{19}$$

Where ε is the pressure drop coefficient .

(ii). Correlations

Results reached are summarized below:

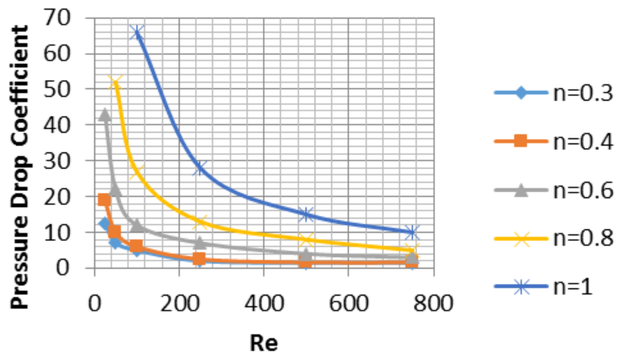

Figure 13: Evolution of pressure drop coefficient for different Re number and structural index n

The pressure drop coefficient can be correlated from the curves in figure 13, and using equation 19 we can find the correlated form for the normalized equivalent length.

For cylindrical pipe:

$$\varepsilon(Re_n, n) = 24.416 e^{5.335n} \times (Re_n)^{-0.305n-0.424} \tag{20}$$

$$(L_e/D) = 0.3814 e^{5.335n} \times (Re_n)^{-0.305n+0.3376} \tag{21}$$

For the two plane plates:

$$\varepsilon(Re_n, n) = 54.559 e^{5.335n} \times (Re_n)^{-0.213n-0.774} \tag{22}$$

$$(L_e/D) = 2.273 e^{5.335n} \times (Re_n)^{-0.2135n+0.2258} \tag{23}$$

Pressure Influence this

IV. Conclusion

The study of the laminar flow of non-Newtonian fluids at the entrance of industrial pipes is a part of a complete overall study necessary for various singularities due to change in directions (elbow) or diameter (expansion, shrinkage, obstacles…) for an effective design of heat exchangers.

Numerical simulations and the use of Ansys-Fluent have shown significant efficacy and brought us logical results of the laminar flow of pseudoplastic fluids in the inlet region of industrial pipes.

A theoretical approach was used in order to obtain the equation for pressure loss and the establishment length. To do so, one-dimensional analysis for the fully developed pressure drop and the establishment length in the two cases was done.

Meshes, was performed to study the influence of grid refinement on numerical predictions. In addition, a technique was used to quantify the numerical results for the total pressure drop (Δp).

After we found the pressure drop coefficient we had made a correlation to find the equivalent pipe length and the establishment length.

This study needs continuity and requires the study of the influence of various peculiarities already mentioned on dynamic and kinetic aspects using the software calculations adopted.

Acknowledgement

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