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CAPILLARY NETWORK MODEL OF POLYMERIC SOLUTION FLOW IN POROUS MEDIA

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Abstract. *Injection of a polymer solution is used in many applications to increase the viscosity of the water phase and therefore reduce the high mobility ratio during oil displacement in a porous media. Experimental evidences have also shown that the viscoelastic behavior of some polymer solution may contribute to a better pore level oil displacement, reducing the residual oil saturation. This pore level behavior is not clearly understood. Modeling viscoelastic flow of polymeric solution in porous media is extremely challenging. The macroscopic flow behavior is directly associated with the extensional dominant flow through pore throats that form the porous media. Accurate models should be able to describe the extensional thickening effect observed in the flow of dilute high molecular weight polymer solutions. The model developed in this work is based on the flow rate-pressure drop relation of polymer solution flow through constricted capillaries that serves as a simple model of the geometry of pore throats. A two-dimensional capillary network model is constructed in order to obtain macroscopic parameters from up scaling of the microscopic behavior. Results show the effect of different rheological parameters on the macroscopic flow behavior.*

Keywords: *polymeric solution; porous media; capillary network model; mobility control; viscoelastic behavior*

1. INTRODUCTION

One of the most used oil recovery method is water injection, due to the available facilities and low cost of this operation. A big challenge of water flooding is the high mobility ratio between the injected water and the formation oil. Another recovery method is used to solve this problem, called Enhanced Oil Recovery, it is the implementation of techniques for increasing the among of oil that can be extract from an oil field. From an engineering perspective, which seeks economic viability and efficiency, the injection of polymeric solution has presented good results.

The prediction of how the flow will behave on the macroscopic scale can be achieved by developing numerical simulations using capillary network models. Firstly, we apply the model using a Newtonian fluid, in this case water was used to obtain the necessary initial features from porous media for an accurate flow description. Then, we apply the model, using a non-Newtonian fluid, to understand the fluid's behavior for a polymeric solution.

Concerning the effects of viscoelastic polymer in the porous media, two mechanisms can increase the oil recovery, one in macro scale and the other in micro scale. In macro scale, the polymeric solution improves the sweep efficiency due to the improved mobility ratio. The microscopic behavior of the polymer is its elasticity, which increases the residual oil recovery.

In the literature, different analyses have been developed to understand viscoelastic effect in polymeric solutions (Smith, 1970; Acharya, 1986). It was realized, over experiments, that, with a critical injection rate, the elastic effect increases the effective viscosity (Mohammad, 1992).

Another characteristic is the viscoelastic effect, which occurs only inside the porous media due to the shear rate (Wang W., 1994). The increase of oil recovery in micro scale is due to the elasticity of the polymeric solutions (Wang D., 2000).

In this work, we use a 2-D capillary network model to obtain the microscopic behavior of the flow of a viscoelastic polymer solution in a porous media. The pore level flow behavior was based on experimental flow rate-pressure relations through a constricted capillary. These results will be compared to a 2-D microchip that serves as a physical model on ideal porous media.

2. CAPILLARY NETWORK MODEL

The capillary network model enables modeling complex porous rock structures for research applications in oil and gas extraction, environmental testing and groundwater analysis(Fatt, 1956).

The network consists of void spaces, called nodes, interconnected by capillary tubes. In this work a two-dimension network was used, as illustrated in Fig. 1.The porous area of the chip has a footprint of 10 x 60 mm. The area is formed by repeating (150 times) a 2 x 2 mm square. The channel arrangement in the square is a grid (8 x 8) of channels which have a near circular cross section (channel depth = 100µm and channel width = 110µm).

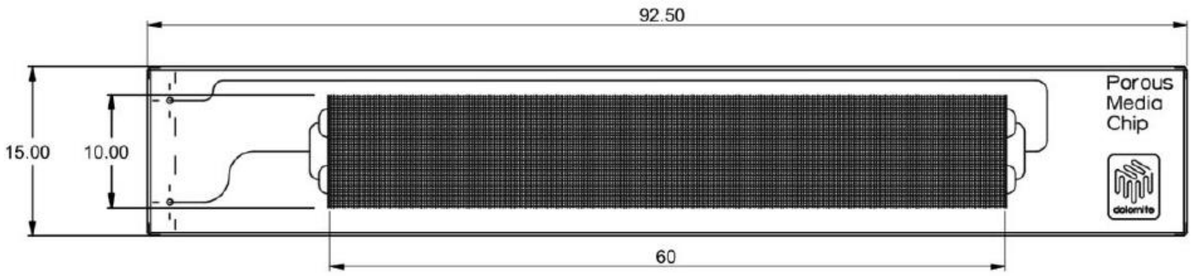

Figure 1. Microchip 2D developed by Dolomite

The network formed by capillaries with throat of 3 different sizes as illustrated in Fig. 2. The channels in the grid have constrictions or pores which are distributed randomly in order to imitate a naturally occurring rock structure. The grid contains 38 type 'a' pores (Ø63 am), 40 type 'b' pores (Ø85 µm) and 50 type 'c' straight channels (Ø110 µm).

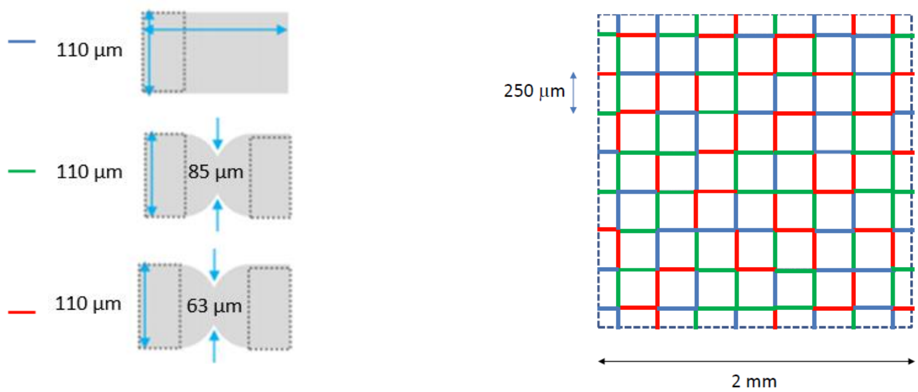

Figure 2. Three different sizes of capillary

Colmenares Vargas (2014) obtained the porosity of the porous media by draining the microchip and weighing it saturated with air and, then, weighing it again, this time saturated with water. Six tests were made and the porosity of the network is 49.95%.

2.1 Flow calculation

The network connectivity is mathematically represented by matrix C, its row represents node's number and its column represents capillary's number

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$C_{\mathrm{ij}} = 0$ – if the capillary j is not connected to the node i;
$C_{\mathrm{ij}} = 1$ – if the capillary j exits from node i;
C_{ij} =-1 – if the capillary j enters in the node i.

When the matrix C is multiplied by matrix C^T, we obtain the following values:

$(CC^T)_{ij}$ = -1, if the note i is connect to node j;
$(CC^T)_{ii}$ =number of capillary connected to node i.

In a network model, the flow rate q_{ij} through a capillary element that connects pores i and j is written as a function of the pressure difference $\Delta P_{ij} = P_i - P_j$,

$$q_{ij} = G_{ij}(P_j - P_i) \tag{1}$$

For a single-phase flow, the conductance G_{ij} is fully determined by the geometry of the capillary cross section and the liquid viscosity.

$$\mathrm{G} = \frac{\pi R_H^4}{8\mu L} \tag{2}$$

where R_H is the hydraulic radium, μ is the water viscosity, in this case, and L is the capillary length.

By applying mass conservation in each node, a linear system of equation (for Newtonian flow) describes the pressure at each node of the network:

$$CGC^T P = q \tag{3}$$

Once the pressure of each node is determined, the total pressure drop for an imposed flow rate can be computed.

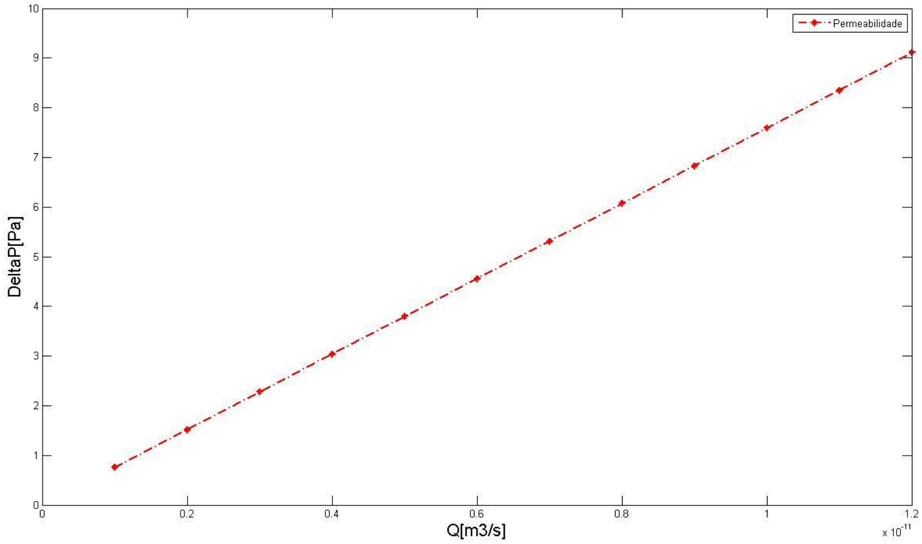

Figure 3. Permeability

The network permeability can be determined directly from the total flow rate and imposed pressure difference using Darcy's law equation:

$$q = \frac{kA}{\mu}\left(\frac{\Delta P}{L}\right) \tag{4}$$

where the water viscosity is $\mu = 0.001003 Pa.s$, L is the microchip length and A is the area. With it, the permeability of the porous media is $k = 79.29D$. The permeability values are similar to an approximate value obtained by Carman (1937) as shown in the Eq. 5:

$$K = \frac{{d_t}^2 . \varepsilon^2}{32} \tag{5}$$

where d_t is the diameter of the throat, ε is the porosity and the permeability is K=71.35D.

2.2 Model for polymer solution flow

For complex fluids, the conductance is not as simply determined. The constitutive equation that relates pressure drop to flow rate in each capillary of the network was developed based on the experimental results for polymer solution flow through a single constricted micro capillary, as described in the following subsection.

The goal of the present analysis is to understand how the rheological behavior of the liquid affects the macroscopic flow through a porous media, i.e. derive a macroscopic correction for Darcy's equation based on the physical mechanisms in the pore scale. The viscosity function of polymer solutions can be described by different generalized Newtonian Model, as Power-law and Carreau-Yasuda.

Power Law

The power-law fluid equation is employed as the constitutive equation, since it is largely used in practice, it is relatively easy in analytical treatment and approximately describes the behavior of a different polymeric solutions(Bird & Hassager, 1987). In this model, the viscosity function is written as:

$$\eta = m\dot{\gamma}^{n-1} \tag{6}$$

where η is the Non-Newtonian viscosity and n is the power-law index and $\dot{\gamma}$ is the shear rate, that is a function of the local geometry and flow rate which in a flow through a capillary is written as:

$$\dot{\gamma} = \left(\frac{4q_{cap}}{\pi R^3}\right)\left(\frac{1}{n} + 3\right) \tag{7}$$

where q_{cap} is the flow rate in the capillary and R is the capillary radio.

Applying the Power law model to Darcy law, we obtain the velocity as in equation 8 that will be used on numerical model:

$$u = \left(\frac{k}{m}\left(\left(\frac{4q_{cap}}{\pi R^3}\right)\left(\frac{1}{n} + 3\right)\right)^{\frac{1}{n-1}}\left(\frac{\Delta P}{L}\right)\right)^{1/n} \tag{8}$$

The flow of power law fluid can also be describe by a modified Darcy law. This equation(Pascal & Pascal, 1989) may be written including the rheological behavior as follows:

$$u = \left(\frac{1}{2m}\left(\frac{n\varepsilon}{1+3n}\right)^n\left(\frac{8k}{\varepsilon}\right)^{n+1/2}\left(\frac{\Delta P}{L}\right)\right)^{1/n} \tag{9}$$

where m is the Non-Newtonian viscosity, ΔP is thepressure in the microchip, k is the permeability, ε is the porosity, L is themicrochip length and $n$is a measure of the deviation of the fluid from Newtonian.

Carreau-Yasuda(Bird & Hassager, 1987)

A more accurate model to describe shear thinning behavior of polymeric solutions is the Carreau-Yasuda model. This model describes the limiting values of viscosity at how and high shear rates:

$$\frac{\eta-\eta_\infty}{\eta_0-\eta_\infty} = [1 + (\lambda\dot{\gamma})^2]^{\frac{n-1}{2}} \tag{10}$$

where η is the Non-Newtonian viscosity, η_∞ is the upper Newtonian viscosity,$\eta_0$is the lower Newtonian viscosity, $\dot{\gamma}$ is the shear rate, λ is the relaxation time and n is a measure of the deviation of the fluid from Newtonian.

Extensional Viscosity

Another phenomenon associated with polymeric solution is a dramatic resistance to stretching of fluid elements compared to Newtonian fluids. When the solution pass in the throat is required a force to stretch the polymer. It is known as extensional viscosity. The strain rate of the fluid is defined, as shown in eq. 12:

$$\dot{\varepsilon} = \frac{V_1}{L}\left(\left(\frac{D_1}{D_2}\right)^2 - 1\right) \tag{11}$$

where $\dot{\varepsilon}$ is the strain rate, D_1 is the capillary diameter and D_2 is the throat diameter.

2.3 Results

To illustrate the macroscopic behavior obtained from capillary network model, Figure 5.a shows velocity at each capillary and Fig. 5.b shows the predicted pressure field.

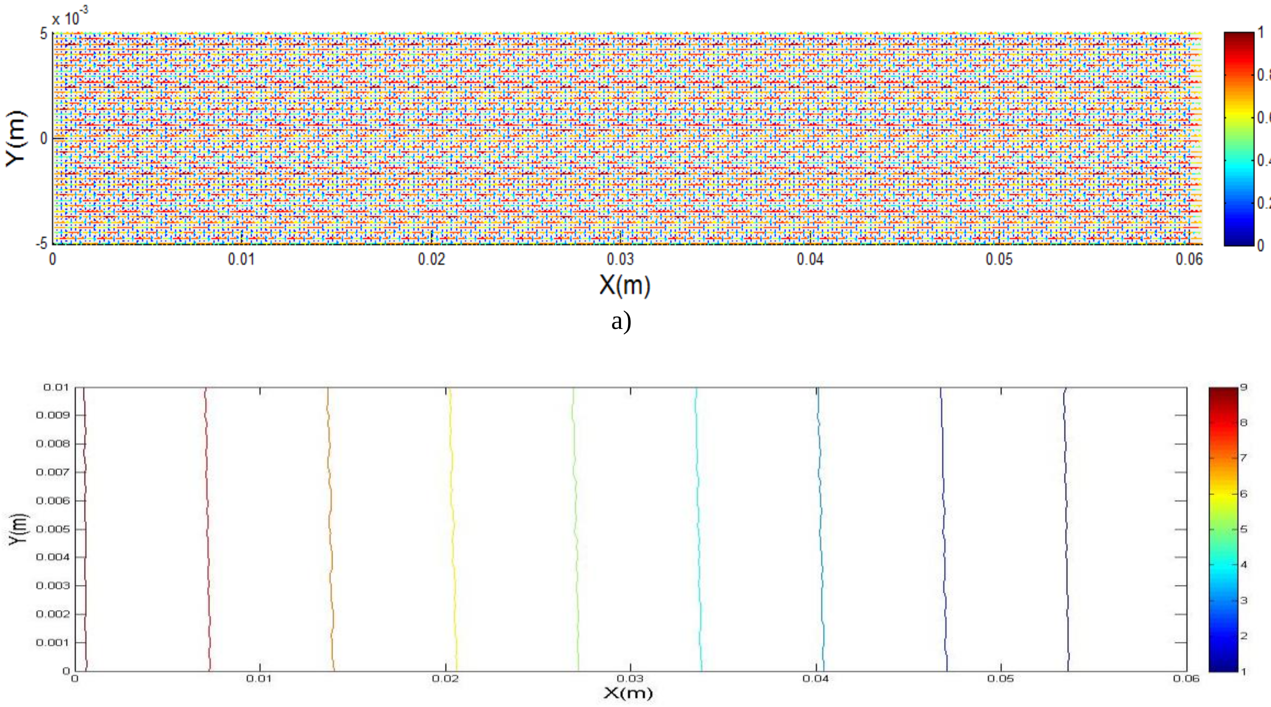

Figure 5. a) Flow rate in each capillary b) Pressure over the microchip

We now observe the behavior of the Non-Newtonian fluid in a porous media. The capillary network model is applied and we variate the flow rate to observe the effect in the in pressure-drop. Capillary network model predictions were obtained for different values of the power-law index: n = 0.7, 0.8, 0.9 and 1. The results are presented in Fig.6. The predictions of the capillary network model agrees with the relation proposed by Pascal and Pascal (1989):

$$q \approx (\Delta P/L)^{1/n} \tag{12}$$

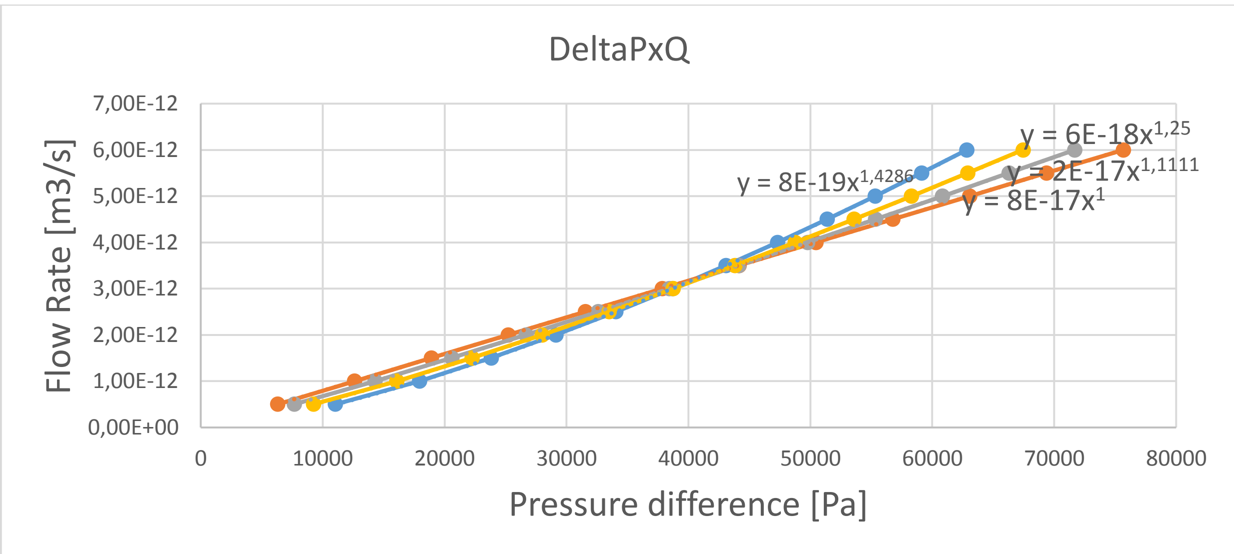

Figure 6. Power Law curves

Figure 7 compares the flow rate-pressure drop relation predicted by the Pascal-Pascal equation and the capillary network model results. The agreement is good, but the Pascal-Pascal relation over predicts the pressure difference for the entire range of flow rate explored for all solutions.

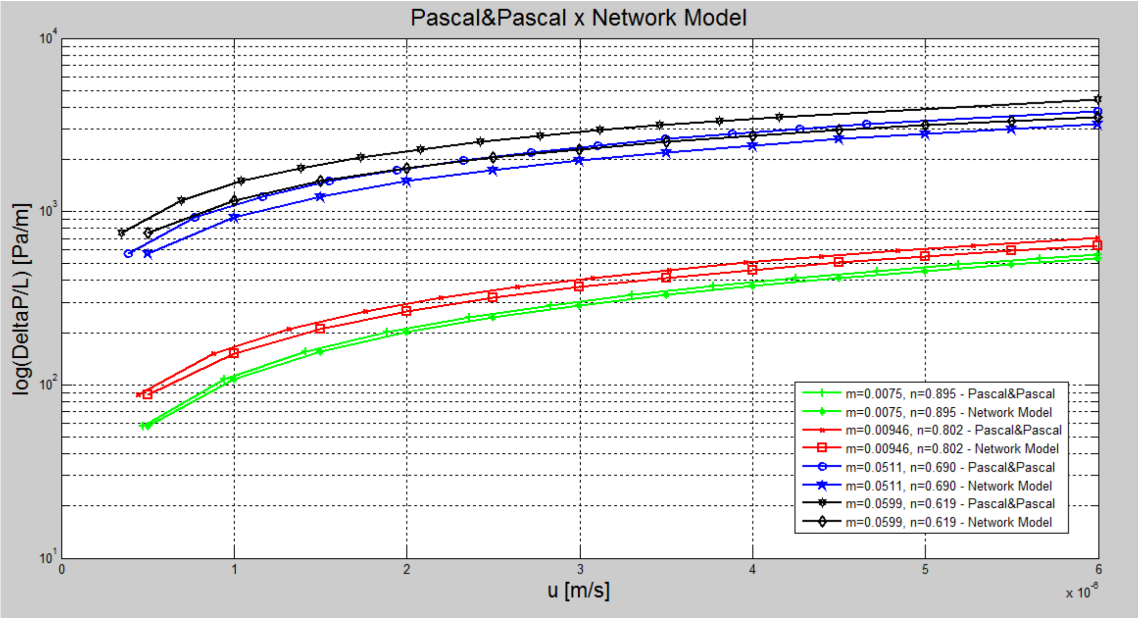

Figure 7. Curves applying Pascal and Pascal(1989) to Power Law curves

Capillary network model can be applied for any viscosity function. As an illustration, predictions for a Carreau viscosity model is presented in Fig. 8. In other words, shear thinning fluids become less viscous with increasing shear rates and so have larger than linear growth with pressure-drop in the flow rate.

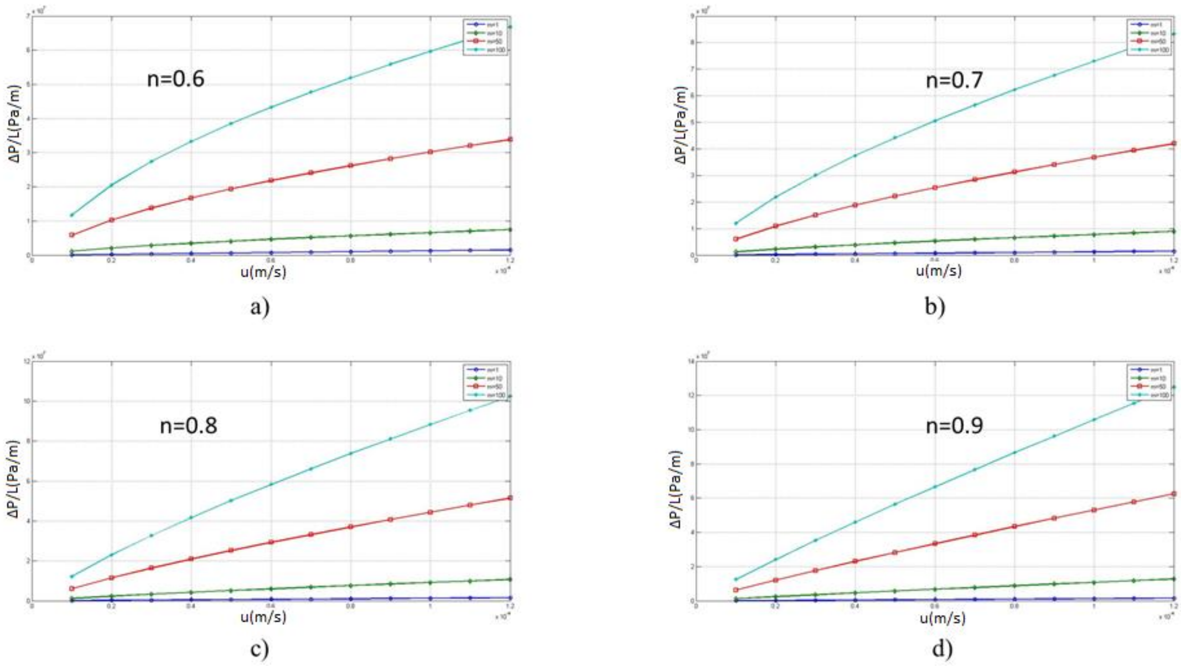

Figure 8. Carreau model: a) n=0.6, b) n=0.7, c) n=0.8 and d) n=0.9. η_∞ is fixed in 1 e vary η_0=1 – 5 – 10 -100.

Using the equation for extensional viscosity, we found the strain rate to calculate how this effect act in the microchip. A shear thickening fluids become more viscous with increasing shear rate and hence have less than linear flow rates. The viscosity effect can be noted in Fig. 9, we show the pressure-drop in the flow-rate to n=0.6 , 0.7 , 0.8 and 0.9 for extensional viscosity. As we can see, a shear thickening fluids become more viscous with increasing shear rate and hence have less than linear flow rates.

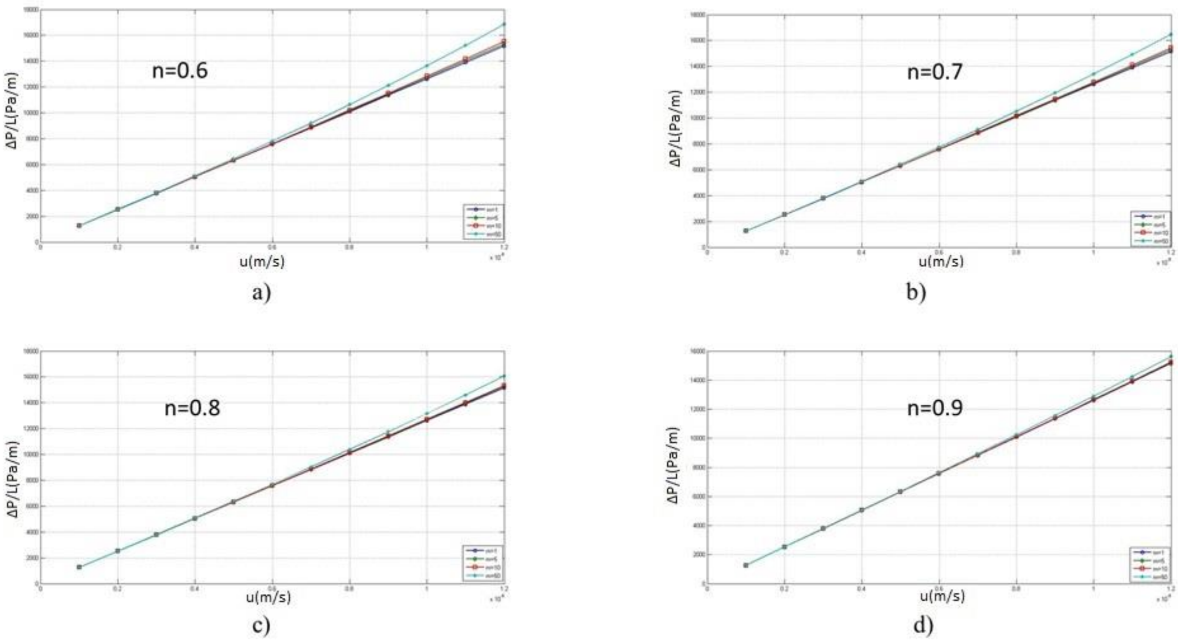

Figure 9. Extensional viscosity model: a) n=0.6, b) n=0.7, c) n=0.8 and d) n=0.9

3. CONCLUSIONS

We have used a pore-network model to predict the relationship between apparent viscosity and flow rate in porous media. The network describes a 2-D microchip used to simulate the throats and pores of a porous media. We have used a capillary network model to study the flow of polymeric solution through a porous media. The network configuration used describes a 2-D microfluidic device that serves as a model of porous media. The macroscopic flow rate-pressure drop relation is determined by combining the non-Newtonian flow at each capillary. The different non-Newtonian behavior were considered: (a) an inelastic, shear-thinning liquid and (b) Boger-type liquid, with constant shear viscosity and extensional-thickening behavior.

The results can be used to derive Darcy-scale equations to describe non-Newtonian flow in porous media.

4. ACKNOWLEDGEMENTS

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