



# PRESSURE COEFFICIENT OF HIGH SHEAR RATE NON-NEWTONIAN FLOW IN CAPILLARY PIPE

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## ABSTRACT

*This work focuses on the studies of pressure coefficient ( $\beta$ ) at high shear rate ( $\gamma$ ) of LDPE melt flow experimentally in single pore capillary rheometer and numerically. LDPE melt was extruded at shear rate (300 – 1500 1/s) under different temperatures and die diameters. Pressure coefficients was investigated at constant shear rate due to the 1 and 2 mm die diameters and 150, 170 and 190 °C temperatures. Finite element technique used through ANSYS/ POLYFLOW to check the pressure distribution and pressure drop along the capillary die due to the different temperatures, shear rate and die diameter. The results show that the pressure coefficient ( $\beta$ ) decreased with the temperature, shear rate and die diameter increasing. Shear rate and temperature produced higher and lower effect on the pressure dependence respectively, while the die diameter indicates the moderate effect. The more stability behavior of ( $\beta$ ) obtained at higher shear rate, higher die diameter and higher temperature. Numerical and experimental results indicate a good agreement in pressure drop values and the effect of shear rate ( $\gamma$ ), die diameter and temperature on the pressure distribution.*

**Key words:** Pressure coefficient ( $\beta$ ), non-Newtonian flow, high shear rate, LDPE melt, capillary rheometer and ANSYS / POLYFLOW.

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## 1. INTRODUCTION

The apparent shear viscosity directly depending on the pressure. For example the shear viscosity of polyethylene and polystyrene increased to about more than 12 folds, when the pressure increased to more than 160 MPa. This mutual relationship between pressure and shear viscosity of polymer processes. The need to high quality polymer products and the useful results of numerical simulations prefer applying the reliable pressure behavior in the investigations. Obtaining of exact data in a capillary due to the many techniques used for studying the pressure behavior effect. The pressure coefficient of the polymer melt has usually a value of  $10^{-8} \text{ Pa}^{-1}$  (Coueh and binding 2000)[1]. The effect of pressure on the shear

viscosity of polymer melts has been studied by a number of researchers [2,3,4]. The results exhibit that the increasing pressure of the polymer melt in the die leads to a reduction of the free volume between molecules of polymer melt. As a result of this, the density of the polymer melt increased. Therefore, the shear viscosity of the polymer melts increased with the increase of the intermolecular friction of polymer.

The Barus equation can be used to describe the pressure effect on the shear viscosity[4]. The Barus equation can be expressed as:

$$\eta_s = \eta_p e^{-\beta(\Delta P - P_o)} \quad (1)$$

Where  $\eta_s$  is the shear viscosity (Pa.s),  $\eta_p$  is the shear viscosity (Pa.s) at atmospheric conditions,  $\beta$  is the pressure coefficient ( $\text{GPa}^{-1}$ ),  $\Delta P$  is melt pressure drop (GPa), and  $P_o$  is the pressure at the flow outlet. In this study, the pressure  $P_o$  is considered to be zero and  $\eta_p$  is constant for a given shear rate under given temperature. Then eq. (1) can be changed to:

$$\ln \eta_s = \beta \Delta P + \ln \eta_p \quad (2)$$

Pressure coefficient  $\beta$  is referring to the slope rate of the plot of  $\ln \eta_s$  versus  $\Delta P$ . So eq (2) give predict for affect the pressure on shear viscosity

The  $\beta$  indicates different values according the technique used shear rate (Herrmann and Knapp 1969). The dependence of pressure and temperature coefficient has been found that simple relationship exist between pressure and temperature sensitivity coefficient for individual polymers [5]. The pressure coefficient for the shear and elongational flows order the pressure dependence of the polymer depending on the molecular structure[5]. The pressure coefficient decreases with increasing extrusion rate and arise in temperature[6]. For PP the indirect method based on specific volume measurement can be used instead of the more complex direct measurement of the viscosity under pressure [7].

The authors examined three different polyethylene, a low density polyethylene (LDPE), a high density polyethylene (HDPE) and a linear low density polyethylene (LLDPE) in flow through dies. It was there the pressure dependence of the viscosity. In isothermal simulations, the problem of predicting the pressure for LDPE was solved at very high shear rates reach to  $1000 \text{ s}^{-1}$  [8] by taking into account the effect of pressure on the viscosity on top of viscoelasticity. Thus, it became apparent that both viscoelasticity and pressure were important in obtaining high pressures in agreement with other experiments, as have been reported by number in the reviewer [9-10]. The effect of pressure on the viscosity was found very important. Therefore, it was decided to re-test more carefully experimental and numerical data on LDPE by used many dies at different of (L/D) ratios.

This research investigates the pressure coefficient at constant shear rate of LDPE melt experimentally and numerically in a capillary die according to the shear rate, die diameter and temperature increasing. Direct method used to obtain the ( $\beta$ ) experimentally, while the simulation performed to check the effect of shear rate, die diameter and temperature changing on the pressure dependence and shear viscosity. The effect of shear viscosity behavior with pressure variation, die diameter and temperature were analyzed to obtain the pressure coefficient [8]. The agreement between practical and numerical data were discussed.

## 2. MATERIALS AND METHODS

LDPE grains was used in this work in order to study the effects of pressure coefficient, temperature, and die diameter on LDPE properties. LDPE melts is known to be very sensitive

to temperature and pressure compared with LLDPE and HDPE, so it is the main reason for selected in this study. LDPE supplied by Amir Kabir Petrochemical Company Iran as pellets, commonly used in extrusion process. The properties of the LDPE used in Table 1.

**Table 1**

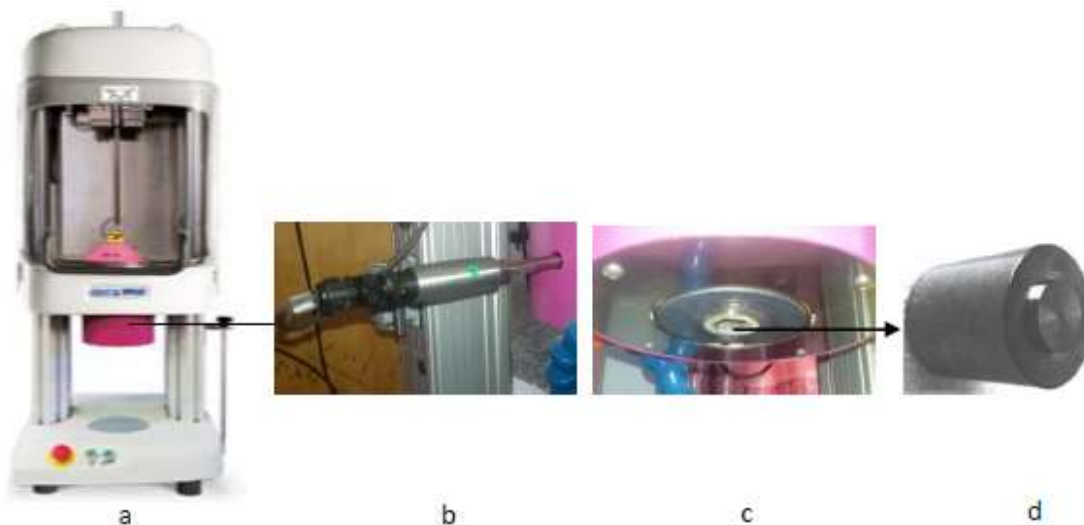
Sample	Melt flow index (g/10 min, 190 °C)	Mw g.mol <sup>-1</sup>	Density g/cm <sup>3</sup> , at 25 °C)
LDPE	2.1	79,200	0.92

### 3. CAPILLARY RHEOMETER TESTING

Capillary rheometer (SR20) was used to determine the pressure through relation between pressure coefficients (Barus equation) depend on pressure transducer temperature and dimensions of die capillary rheometer. The viscosity as a function of the wall shear stress through power law model, and apparent shear rate,  $\gamma_{app.} = 4 Q / \pi R^3$  (300,500, 1000 and 1500 s<sup>-1</sup>) at 150, 170 and 190°C, Q is the volumetric flow rate and D is the capillary diameter, L is the capillary length. In addition, several dies having the different e diameter (1 and 2) mm have been used to determine the effect of pressure on viscosity. The dependence of viscosity on pressure can be assessed, by Barus equation can be used to determine  $\beta_p$ :

$$\beta = \left( \frac{d \ln \eta}{dP} \right) \tag{3}$$

Where  $\eta$  is the viscosity at pressure p.



**Figure 1** Capillary rheometer: (a) - general view, (b) pressure transducer (c) - bottom of barrel, (d) capillary die

### 4. GOVERNING EQUATIONS AND RHEOLOGICAL MODEL

Governing equations of Continuity , Momentum , and power law model fluids which used in study experimental and numerical. The pressure distribution has to be obtained along the capillary length under the following assumptions fully developed flow, isothermal, laminar flow, steady state flow, these are written as:

$$\text{Continuity equations} \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{4}$$

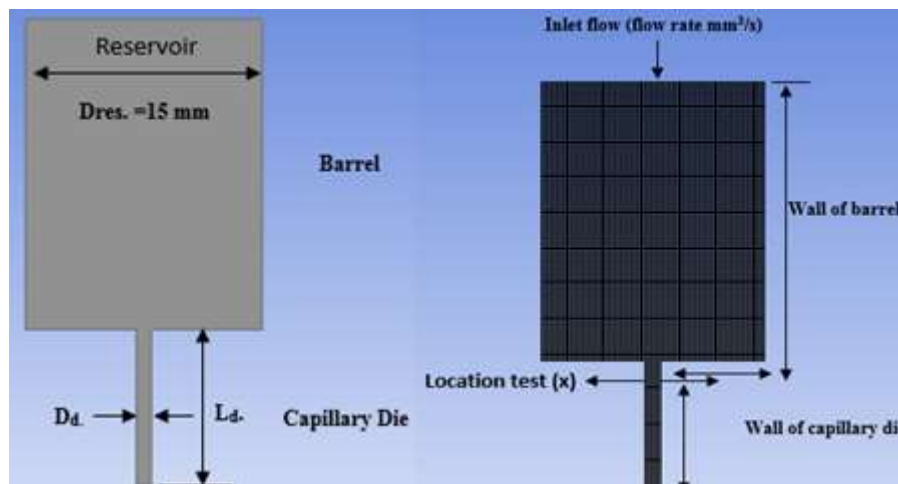
$$\text{Momentum equations } P = mv \quad (5)$$

Where  $t$  is time,  $u$  is the flow velocity,  $\rho$  is fluid density.  $m$  is an object's mass and  $v$  is the velocity.

Power law model was used to check the non-Newtonian viscosity between experimentally and numerically according to the following formula:

$$\eta = k (\dot{\gamma})^{n-1} \quad (6)$$

The finite element numerical technique used by POLYFLOW involves solving the equations non-Newtonian fluid. ANSYS program/ POLYFLOW based on finite element technique was used to simulate the flow in a capillary rheometer [11, 12]. The geometry of the model has been created using ANSYS program (POLYFLOW, 2D planer) in the Figure 2(a) grid generation mesh involved in computing numerical solutions to the equations that describe a physical process, parameter mesh and generate mesh (8260 nodes and 8050 elements) in Figure 2(b).



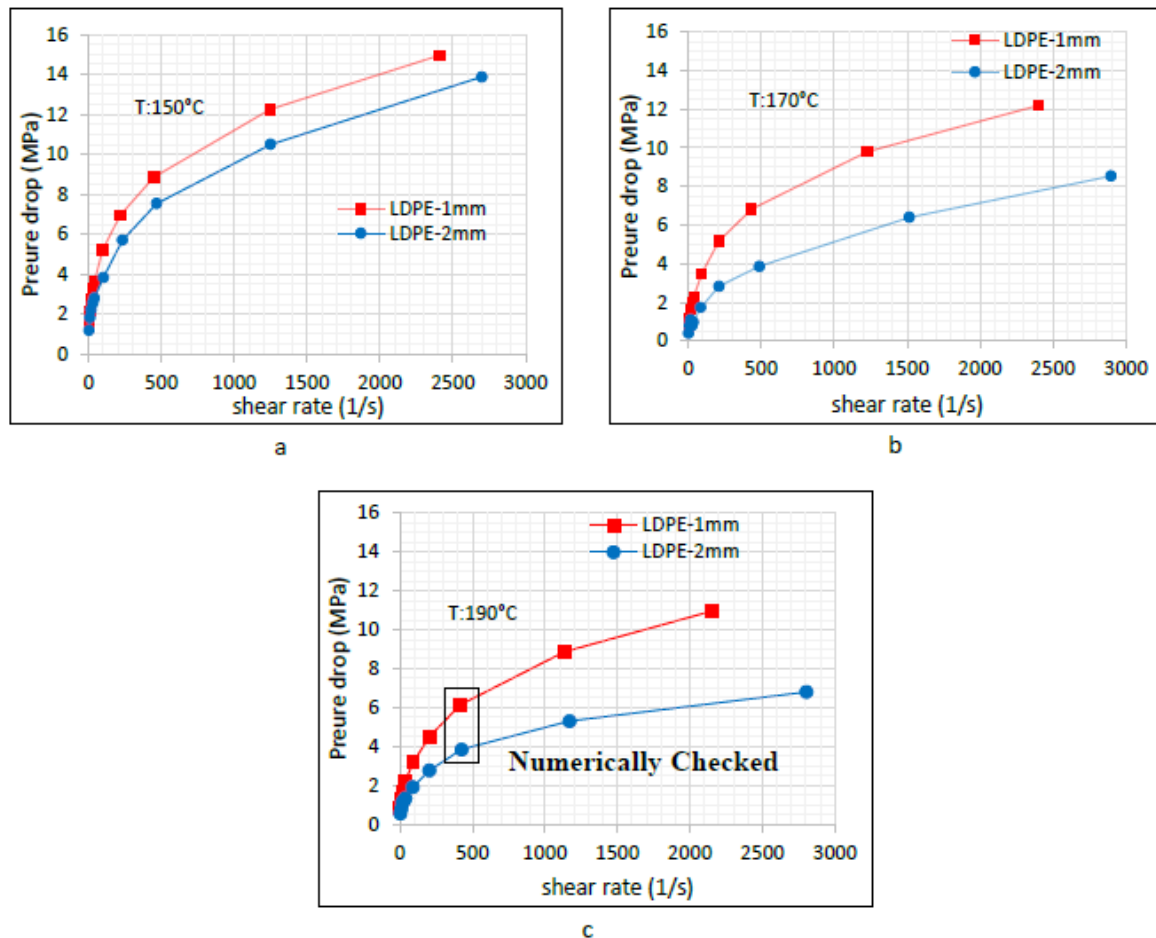
**Figure 2** Schematic of Capillary rheometer: (a) - geometry, (b) - finite element discretization

## 5. RESULT AND DISCUSSION

### 5.1. Experimental Result

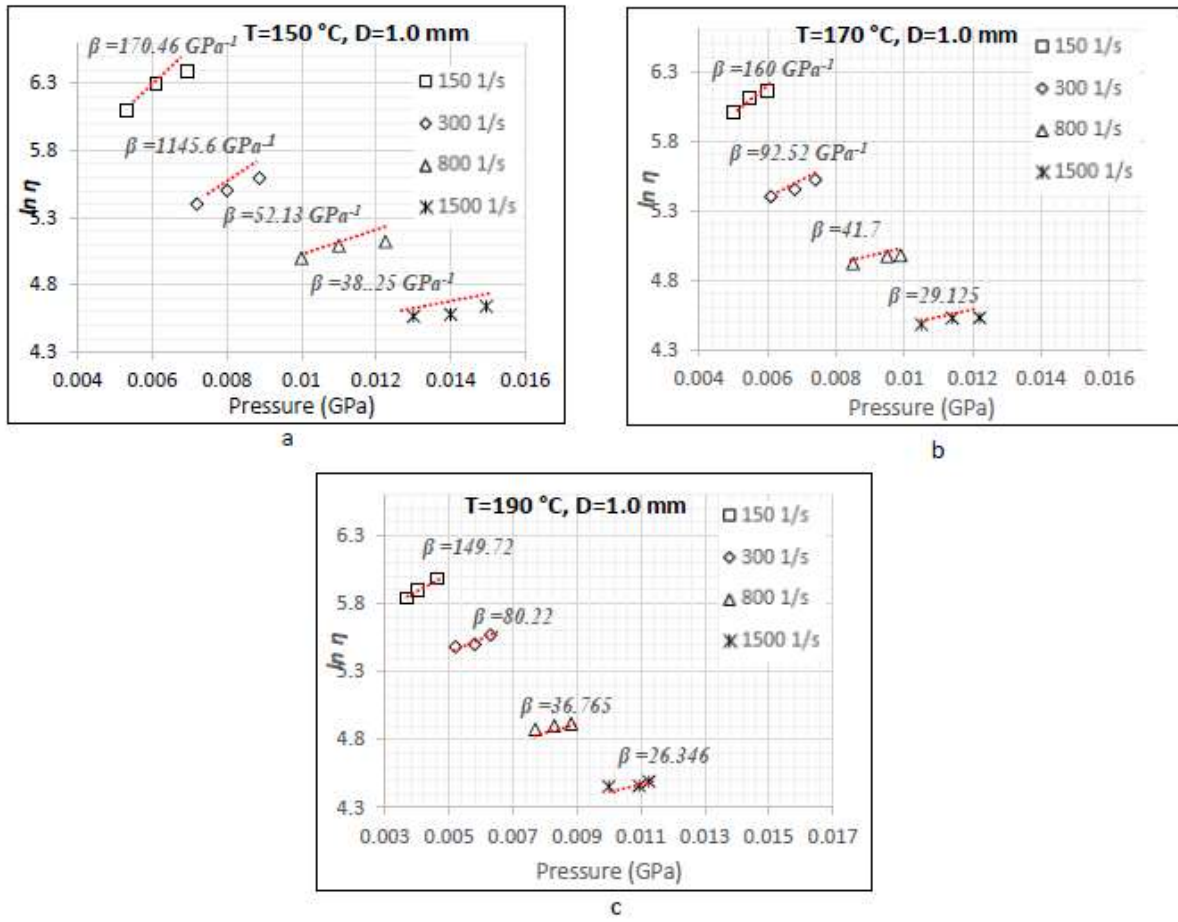
The pressure were measured over the shear rate range through the two dies at different temperatures, as shown in Figure 3. The pressures drops decreased when the temperature increased, and its values in the 1.0 mm are higher than 2.0 mm at the same temperature. The pressure drop values tend to be straight when the temperature is increased at high shear rates. It was clear and easy to understand that the viscosity of the LDPE melt was more sensitive to temperature due to the chains structure. The increasing temperature was attributed to an increase in intermolecular interactions, which affect the amount of free volume available between molecular chains of polymer. Therefore, the viscosity of the LDPE melts decreased, and the flow become easier through the capillary die then the pressure drop decreased. Investigating the effect of pressure on viscosity, previously associated with the Bagley and weissenberg- Rabinowiton correction, which deal with the pressure loses and the non-Newtonian flow of polymer respectively as in research [13]. The pressure drop in a capillary die was tested including the pressure loses at the exit and entrance region and the shear rate  $\dot{\gamma}$  was converted to the wall shear rate  $\dot{\gamma}_w$ . Pressure drop along the capillary die during the flowing of LDPE melt due to the shear rate, temperature and diameter changing were set in figure (3). The pressure drop increases with the shear rate increasing and decreases with the

die diameter and temperature increasing. Moreover, the pressure drop attend to be stable at high shear rate and temperature, while rapid growing in its behavior at low shear rate up to  $500 \text{ s}^{-1}$  was observed. This mechanism of pressure drop behavior was very important in the calculation of pressure coefficient.



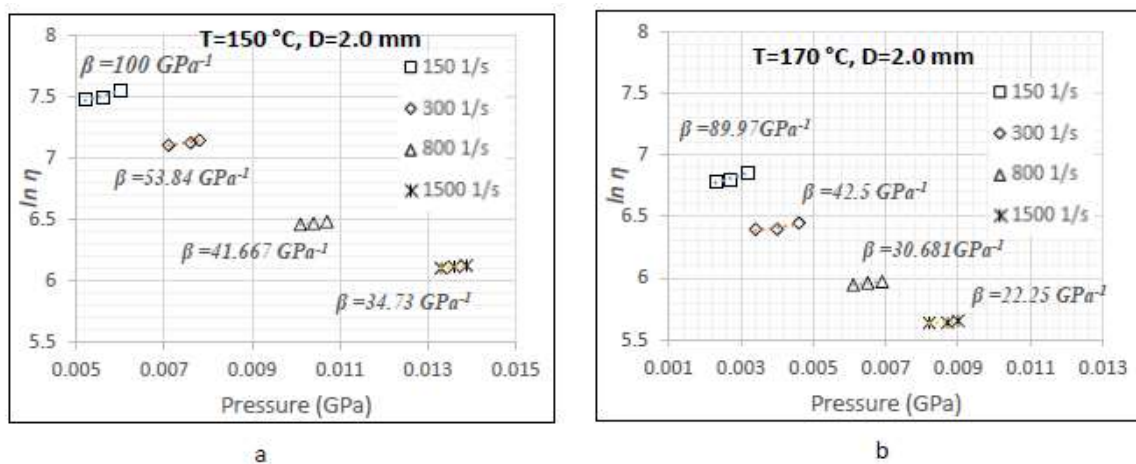
**Figure 3** Pressure drop with shear rate at difference die diameter, a) at  $150^{\circ}\text{C}$  b)  $170^{\circ}\text{C}$  c) at  $190^{\circ}\text{C}$

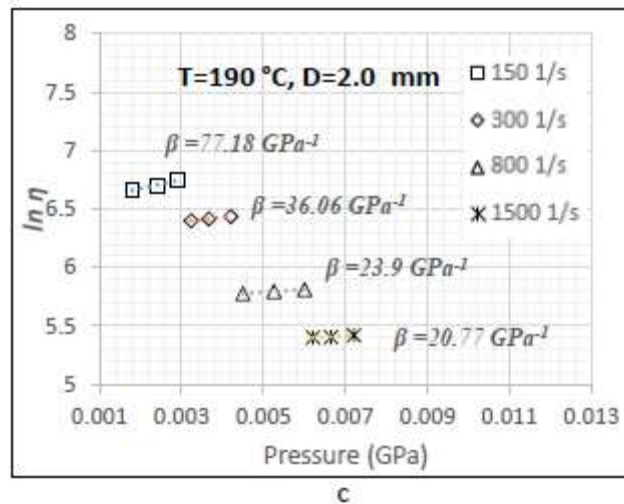
The Pressure coefficient at (constant shear rate) in 1 mm die decreased with temperature and shear rate increasing due to the viscosity decreasing as shown in figure 4. The polymer chains disentanglement and ordered in the flow direction during the shear rate increasing, and the free volume around these chains increases with temperature increasing. The alignment of chains in higher free volume reduces the resistance to the melt flowing. The shear viscosity behavior with the pressure increasing for each shear rate attempt to be stable with the shear rate increasing. The semi stability in shear viscosity obtained lower viscosity difference at higher shear rate and high pressure. This mechanism leads to the decreasing in pressure coefficient with the shear rate increasing. It's clear from the pressure coefficients values, the unstable shear rate range zone occurs between  $150 - 800 \text{ s}^{-1}$ , and semi stable shear rate zone exits between  $800- 1500 \text{ s}^{-1}$ .



**Figure 4** Pressure coefficient behavior of LDPE melt flowing in 1mm a capillary die diameter for different shear rate at, a) 150°C b) 170°C c) 190°C

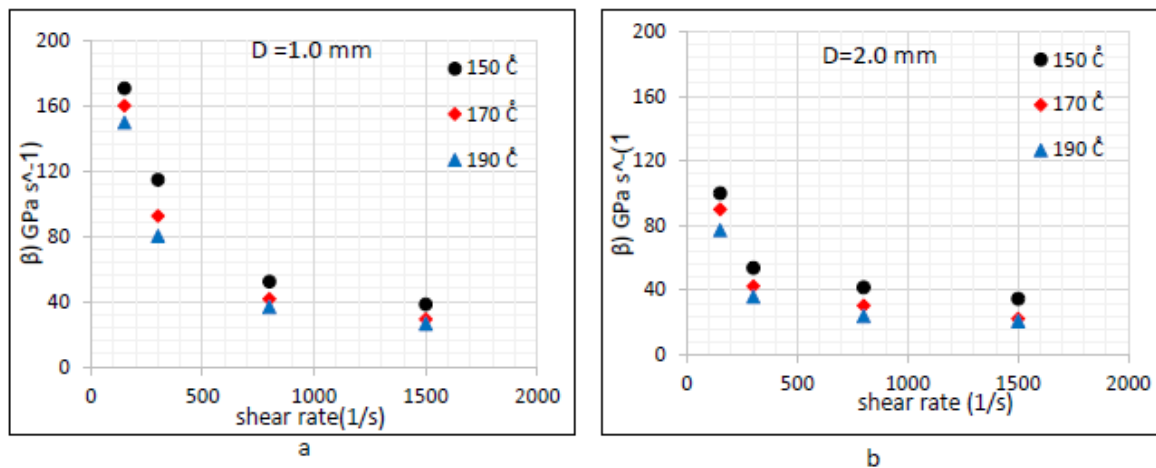
The same behavior in general conducts in figure 5, with lower pressure coefficient values due to the die diameter changing. The shear viscosity verse pressure slope became more stable which produces lower pressure coefficient. Pressure coefficient values obtained a stable zone in the range 300 – 1500 s<sup>-1</sup> range produce semi stable zone.





**Figure 5** Pressure coefficient behavior of LDPE melt flowing in 2mm capillary die diameter for different shear rate at, a) 150°C b) 170°C c) 190°C

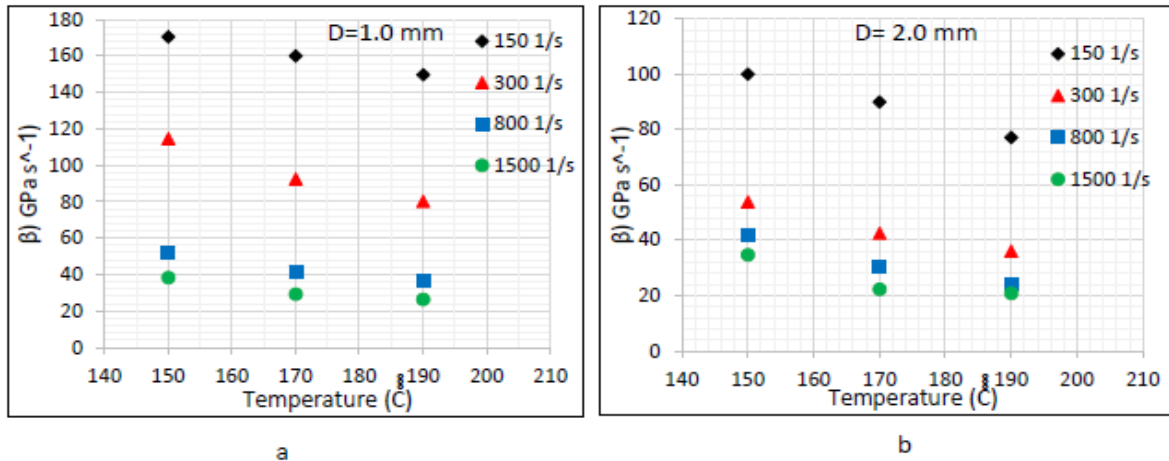
Figure (6a) demonstrates that the pressure coefficient rapidly change with the shear rate increasing in 1 mm diameter for different temperature up to 800 s<sup>-1</sup>. After that the behavior attend to be stable. It was clear that the pressure coefficient decreases with the temperature increasing for both die diameters. Also the pressure coefficient change in 2 mm diameter to about half that in 1 mm diameter. Figure 6(a, b) indicate, that the pressure coefficient showed sever decreasing up to 300 s<sup>-1</sup>, and then the variation become more stable. This result show that the pressure coefficient values in 2 mm diameter was more suitable for our purpose compared with that of 1 mm diameter



**Figure 6** Pressure coefficient vs. shear rate of LDPE melt flowing in a capillary die for different temperatures at, a) 1 mm diameter b) 2 mm diameter

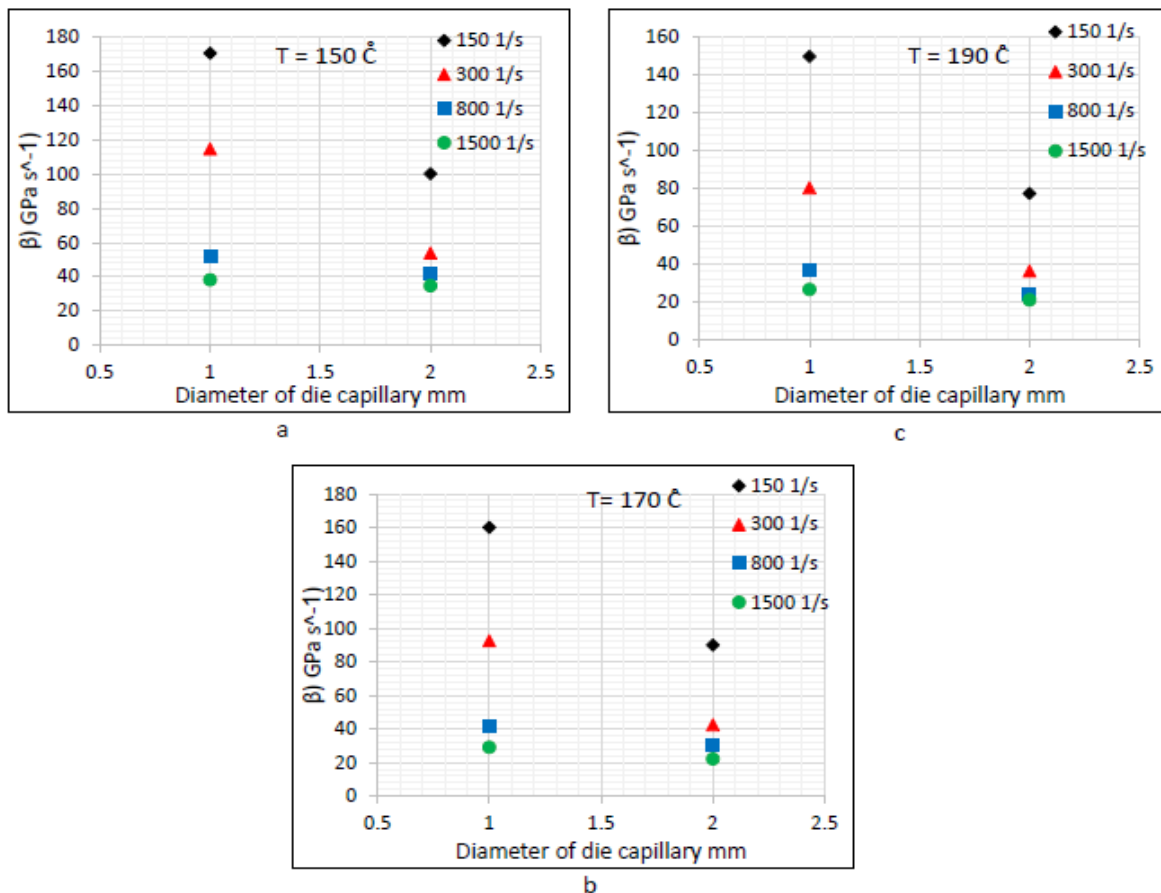
Figure (7) conducts that the pressure coefficient decreases with temperature increasing for different shear rate for 1 mm and 2mm die diameter. The behavior of pressure coefficient indicates higher stability at high shear rate with the temperature increasing for both die diameters. This stability was increased with the decreasing of die diameter.

The Pressure coefficient at constant shear rate decreases with die diameter, shear rate and temperature increasing as shown in figure (8)



**Figure 7** Pressure coefficient vs. temperature of LDPE melt flowing in a capillary die for different shear rate at, a) 1 mm diameter b) 2 mm diameter

At low shear rate a large difference in pressure coefficients between 1 and 2 mm die diameter was observed, while this difference at high shear rate become smaller. Therefore, the pressure coefficients at high shear rate was optimum for many applications. This means that the stability of pressure coefficients will be improved a higher shear rate. In the other side the effect of temperature on the pressure coefficients difference between (1 and 2 mm) die diameter and the stability of pressure coefficient was negligible.



**Figure 8** Pressure coefficient vs. die diameter of LDPE melt flowing in a capillary die at different shear rate at, a) at 150°C b) 170°C c) at 190°C

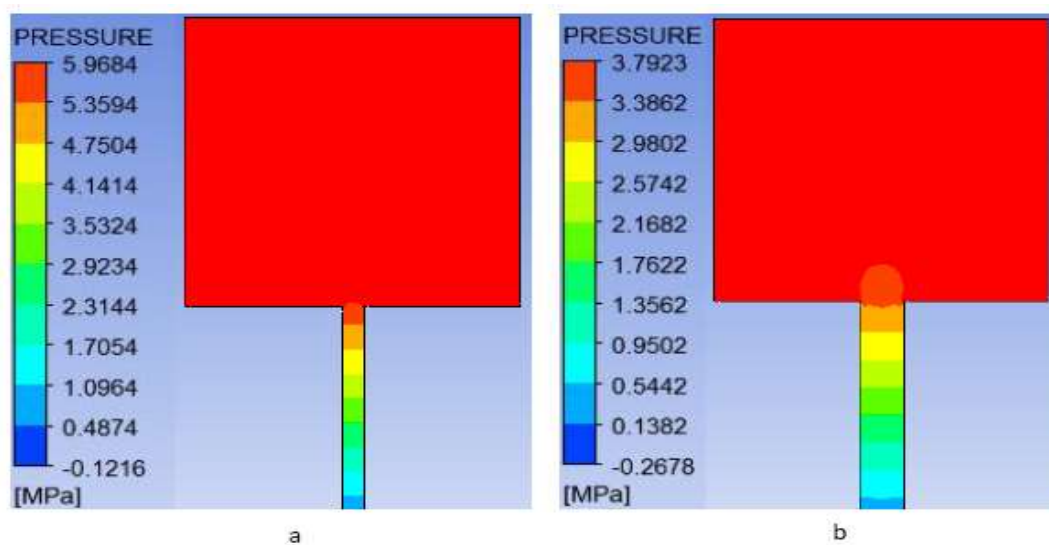


## 6. NUMERICAL RESULT

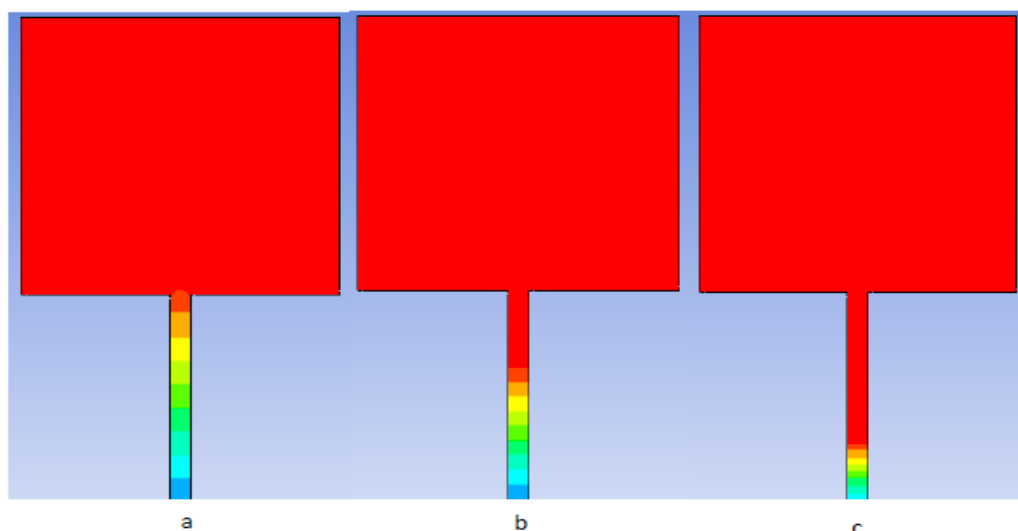
The numerical result exhibits a good agreement with the experimental results, so comparison for pressure drop as in research [14].

The pressure distribution along the capillary die during flow of LDPE melt was effected by die diameter. It can be seen from qualitative results of that pressure drop reduced with the die diameter increasing from 1 to 2 mm at 190 C and  $500 \text{ s}^{-1}$  shear rate as data present at figure (9). Moreover this figure the pressure drop reduces approximately the same for that obtained at the same experimental conditions in figure (3).

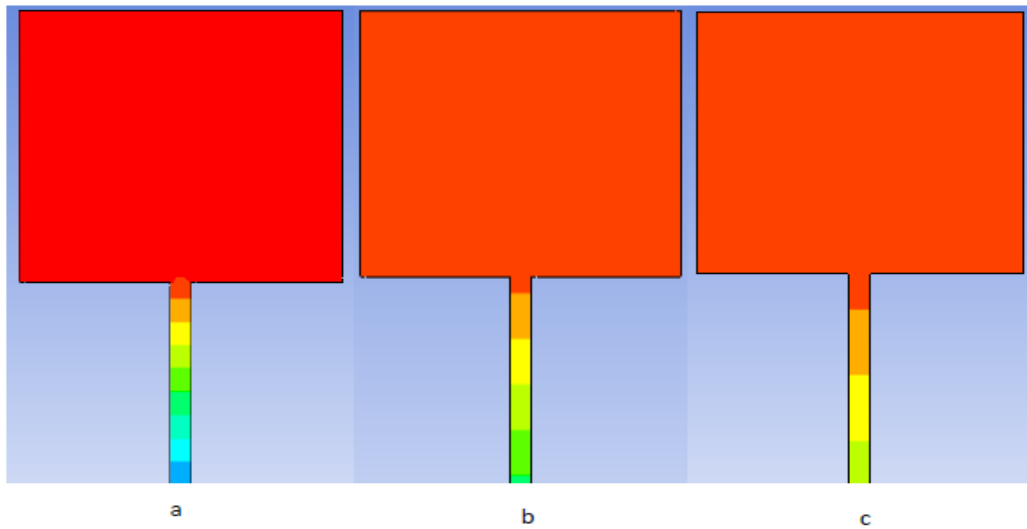
Figures (10, 11) indicate the pressure distribution of LDPE melt flowing in 1 mm die diameter due to the shear rate and temperature increasing. It's easy to say that the effect of shear rate was clearer than that of temperature. These results were comparable with that produced in figure (6a and 7a). Also figure (12 and 13) show the pressure distribution of the same melt with the same shear rate and temperature change for 2 mm die diameter.



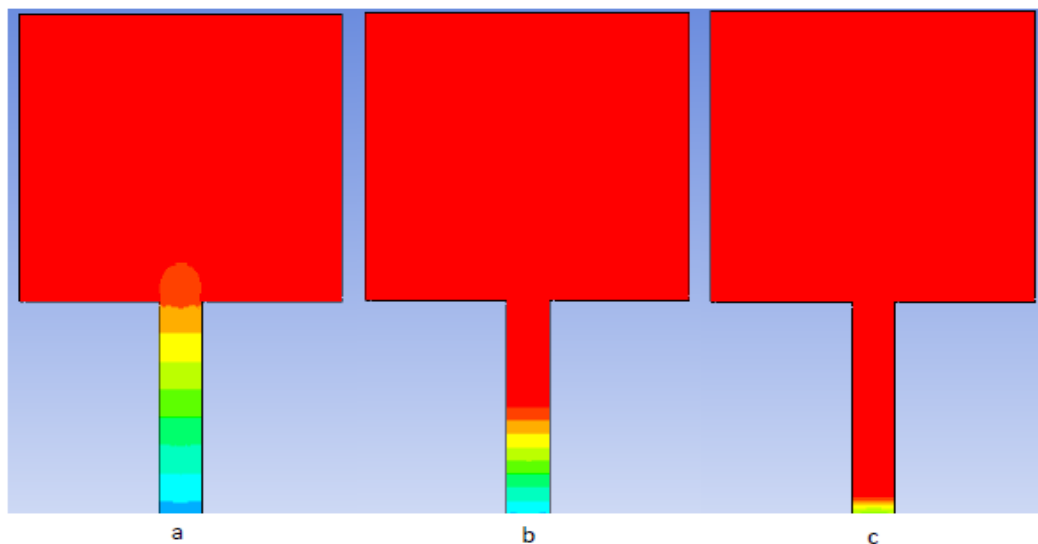
**Figure 9** Pressure distribution of LDPE melt flowing in a capillary die at 190 °C and  $500 \text{ s}^{-1}$  shear rate for a) 1 mm b) 2mm.



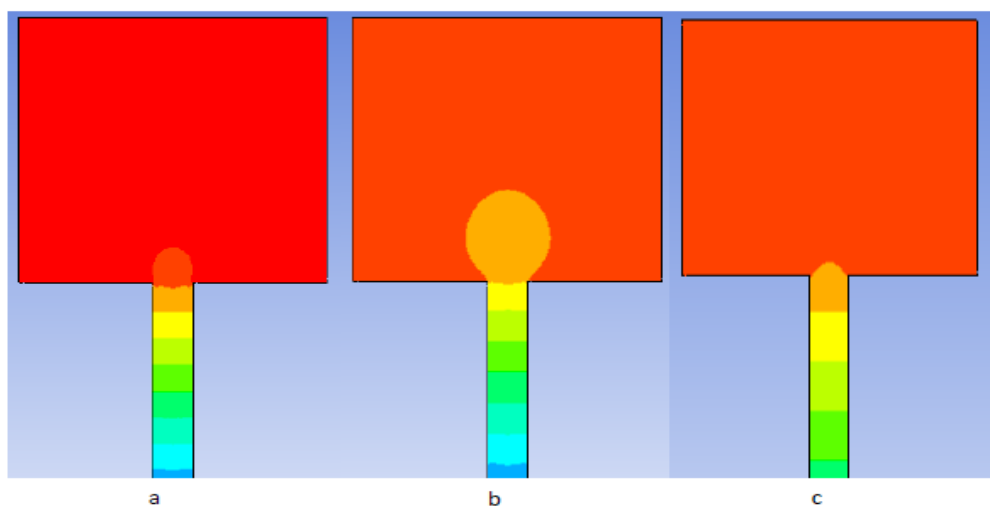
**Figure 10** Pressure distribution of LDPE melt flowing in 1 mm die at 190 °C for: a)  $500 \text{ s}^{-1}$  b)  $1000 \text{ s}^{-1}$  c)  $1500 \text{ s}^{-1}$ .



**Figures 11** Pressure distribution of LDPE melt flowing in 1 mm die at shear rate  $500 \text{ s}^{-1}$  for: a)  $150 \text{ }^\circ\text{C}$  b)  $170 \text{ }^\circ\text{C}$  c)  $190 \text{ }^\circ\text{C}$ .



**Figure 12** Pressure distribution of LDPE melt flowing in 2 mm die at  $190 \text{ }^\circ\text{C}$  for: a)  $500 \text{ s}^{-1}$  b)  $1000 \text{ s}^{-1}$  c)  $1500 \text{ s}^{-1}$ .



**Figure 13** Pressure distribution of LDPE melt flowing in 2 mm die at shear rate  $500 \text{ s}^{-1}$  for: a)  $150 \text{ }^\circ\text{C}$  b)  $170 \text{ }^\circ\text{C}$  c)  $190 \text{ }^\circ\text{C}$ .

## 7. CONCLUSIONS

Pressure dependency of LDPE viscosity through pressure coefficient was investigated experimentally and numerically at constant shear rate due to the shear rate, die diameter and temperature increasing. The purpose of this work is to find out the more stable behavior of pressure coefficient with these parameters.

It can be concluded from this research that the pressure coefficient of LDPE melt flowing in a capillary die was decreased with the shear rate, die diameter and temperature respectively. This because of the slop of the shear viscosity reduced then the shear viscosity difference decreased and the pressure difference increased. The pressure coefficients showed a good stability at high shear rate (800 -1500 s<sup>-1</sup>) for shear rate, temperature and die diameter increasing. In the other hand the numerical result, also visualized that the shear rate indicates higher effect on the pressure drop than die diameter and temperature. Finally a good agreement was observed between experimental and numerical result for pressure drop behavior.

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