Recueil De Mécanique
El Wancharissi University
of Tissemsilt

Research Paper DOI : 10.5281/zenodo.5047291 Open access

Numerical simulation of axial LDPE polymer flow in an extrusion die

Taieb NEHARI

[a]Department of Mechanical Engineering, Institue of Technology. University Center BELHADJ Bouchaib BP 284 RP, Ain Temouchent, 46000, Algeria.

[b]Smart Structures Laboratory (SSL), Institue of Technology,University Center BELHADJ Bouchaib BP 284 RP, Ain Temouchent, 46000, Algeria.

ARTICLE INFO

Article history:

Received 09 August 20

Received in revised form 15 October 20

Accepted 20 October 20

Keywords:

Rheology; extrudate; laminar flow; polymer

ABSTRACT

A numerical study using the finite element method was carried out to determine the rheological characteristics of the LDPE (Lower density Polyethylene) polymer in extrusion through a simple and axisymmetric matrix. This polymer is considered a generalized Newtonian fluid that follows Cross law. The numerical simulation was carried out using POLYFLOW software developed by the firm ANSYS, this calculation code is based on the finite element method, it is specially designed for polymer flows.The Polyflow software requires the GAMBIT code as a preprocessor for finite element meshing. The calculation parameters provided by the Polyflow code are velocity, shear rate, pressure and viscosity. These results are of paramount importance for the design and optimization of the matrix geometry. This study shows clearly that the increase in the outlet diameter of the matrix makes uniform extrusion characteristics.

1 Introduction

In recent years, there has been considerable progress in the field of new materials, particularly polymers. The diversity of polymer properties and their ease of shaping have contributed to the broad development of the plastics industry [1]. However, according to [2] extrusion defects may occur by significantly limiting these processing processes. This crucial industrial problem in the shaping of plastics has given rise to a great deal of research into the flow of molten polymers.

Often engineers are interested in finding optimal shapes of the extruder matrix in order to reduce loads and control the microstructure of the materials to be formed, This is done in order to reduce production costs to a minimum and to obtain a healthy product or with few defects [1]. In extrusion, the matrix design process is very often a test and correction process, and a number of extrusion tests are required before reaching a satisfactory design [3, 2]. A well-designed extrusion matrix should have a uniform output speed to avoid distortion and be able to provide a section within the range of specified tolerances [4].

One of the first techniques to correct or control the flow of material in extrusion dies is by changing the length of the bed bearing or the depth of the bed opening [5]. According to the latter author, by reducing the length of the bearing at a particular point in the opening of the bed, the flow resistance decreases and the flow rate increases. The opposite effect is

---

* *Corresponding* author. Tel: +213552569823
E-mail address: nehari_tb@yahoo.fr

achieved when the length of the bearing is increased. A uniform velocity at the outlet of the bed can therefore be obtained, by changing the length of the bearing. In this sense, profiled dies are used of profiles designed to adapt to the plastic flow.

On the other hand, only the geometric parameters influence the extrusion but also the hydrodynamic parameters. For low flow the extrude is smooth and transparent, the higher the flow defects appear. The influence of the flow on the shape quality of the extrude have been experimentally studied and reported in [6,7]. Depending on the flow rate, extrusion may take different aspects depending on the nature of the polymer. There are generally three main types of defects: shark skin defect, cap defect and extrusion rupture. The shark skin defect is manifested by the formation of scratches on the surface of the extrusion.

In the past, the numerical prediction of polymer extrusion was a large challenge process. However, with the continuous and rapid development of computational means and with the development of new digital techniques, it is now possible to simulate, analyze and optimize the extrusion processes of complex geometries, taking into account the non-linear and viscoelastic behaviour of the molten polymer.

With numerical simulations, the velocity, pressure and temperature inside the extrusion matrix can be obtained, which is otherwise impossible experimentally. The finite element method (FEM) is one of the most widely used methods today to solve partial differential equations of Navier-Stokes governing extrusion.

The objective of this study is to simulate the flow of the melted polymer inside the extrusion matrix for the purpose of designing the extrusion matrix. The design of an output uniform flow matrix is a difficult problem that can be solved using finite element optimization methods.

2 Numerical modeling

This study is primarily concerned with predicting the flow of the LDPE (low-density polyethylene) polymer in the molten state in a single axial symmetrical extruder of well-defined geometry (see Fig.1). Secondly, we are interested in improving this extruder by studying the influence of geometry (inlet diameter and outlet diameter), inlet flow rate and screw rotation velocity on dynamic viscosity, pressure and shear rate. These numerical simulations were conducted for the different influencing parameters, see Table.2. Fig.2 shows the pumping section of the extruder.

Flow in a matrix requires the resolution of the continuity equation, and the motion quantity equations for a set of frontier states.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}=0 \tag{2}$$

$$-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}=0 \tag{3}$$

In this study, Low Density Polyethylene LDPE is used because of its availability and lowest cost. The polymer in the pumping zone and in the matrix is molten state (liquid). The characteristics of this material in the molten state are reported in Tab.1.

Table 1 – The characteristics of the polymer LDPE [8].

Density in molten state	ρ=760kg/m3
Viscosity for a shear rate equal to zero	μ_0=85000Pa.s

Normal time	λ =0.20 s

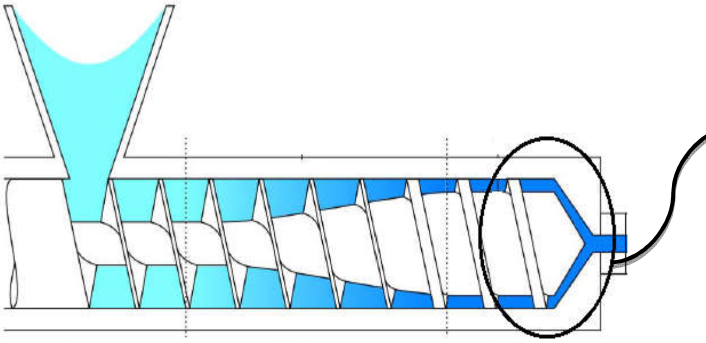

Fig. 1 – Presentation of the extruder

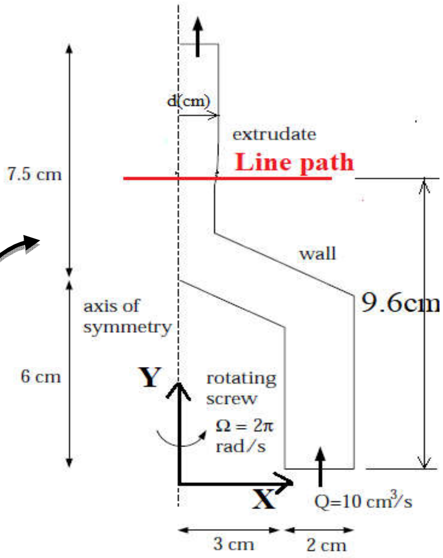

Fig. 2 – Problem description

2.1 Mesh and boundary conditions

The finite element discretization of the structure (pumping-die part) was carried out by GAMBIT software (2007) under version 2.4.6. It is a two-dimensional model; the elements used are of quadratic isoparametric types at 4 nodes. The number of elements used is of 200 elements, i.e 164 nodes (Fig.3b). The grid used is a mesh structure of quadratic elements.

To solve such a flow, boundary conditions of the system must be a priori defined. Fig.3a shows quite clearly and defines the boundary nomenclature of the studied system. Six boundary conditions have been considered:

Boundary 1: flow inlet, Boundary 2: outer wall, Boundary 3: surface, Boundary 4: flow exit, Boundary 5: symmetry axis and Boundary 6: rotating screw.

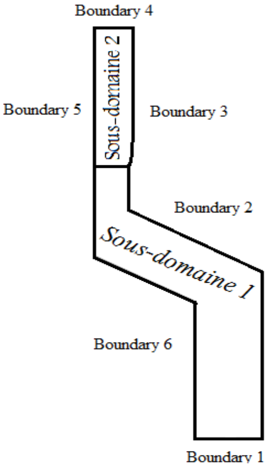

Fig. 3a – Subdomains and Boundary

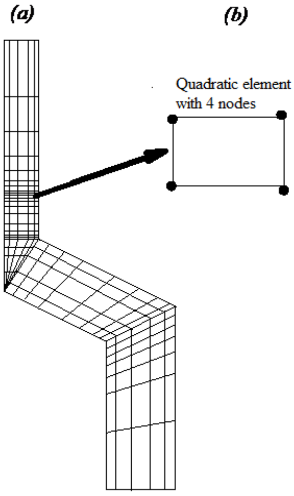

Fig. 3b – Mesh of FEM

3 Results and discussions

In this section, different results from the numerical predictions of the extrusion through the machine (Fig.1) are présented using the Polyflow code.

To better optimize the flow through this machine, we will study the influence of the following parameters (see Tab.2): (I) the diameter of the screw D; (II) the outlet diameter of the die d; (III) the angular velocity ω; (IV) the flow rate Q. First, are presented results of an extruder taken as a reference with following characteristics: Q = 10 cm^3 / s, ω = 2π rad / s, D = 6cm and d = 2cm. The calculations of the velocity, the pressure, the shear stress and the dynamic viscosity were determined at the outlet of the die over a distance of 9.6 cm (line path), see Fig.1.

Table 2–Calculation parameters.

(I) For d=2; ω=2π et Q=10	**(II) For D=6; ω=2π; et Q=10**	**(III) For D=6; Q=10 et d=2**	**(IV) For d=2; D=6; et ω= 2π**
D (*cm*)	d (*cm*)	ω (*rad/s*)	Q (cm^3/s)
6	1.2	2π	10
10	1.6	4π	20
18	2.0	6π	30
-	2.4	8π	40
-	2.8	-	-

3.1 Study of the influence of flow rate (ω=2π rad/s, D=6cm, d=2cm):

The study of the influence of the flow rate (Q=10, 20, 30 and 40 cm^3/s) on the physical quantities for the polymer was carried out in this subsection for =2 rad/s, D=6cm, d=2cm. Fig.4 shows that the increased flow rate increases the pressure of the extrusion. On the other hand, this increase in flow does not change the structure of the flow, which remains uniform and stable as shown in Fig.5, Fig.6 and Fig.7 show us respectively that the flow decreases the viscosity and increases the rates of the shear of the extrusion.

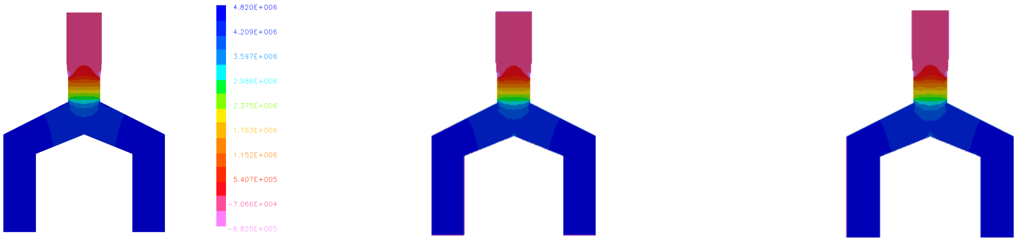

Fig. 4 – Pressure for different flow rates: (Q=20cm^3/s, Q=30cm3/s, Q=40cm3/s, ω=2π rad/s)

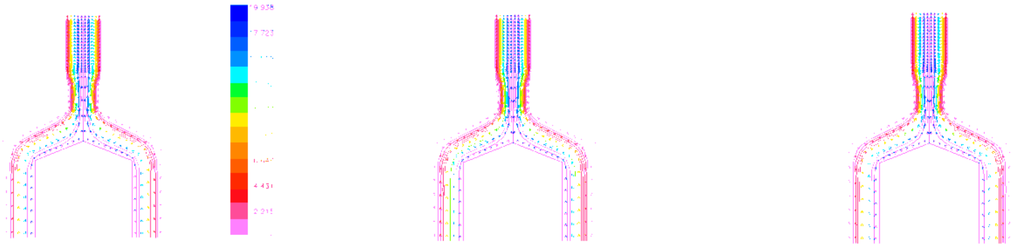

Fig. 5 – Velocity and pressure current lines for different flow rates (Q=20cm^3/s, Q=30cm^3/s, Q=40cm^3/s, ω=2π rad/s)

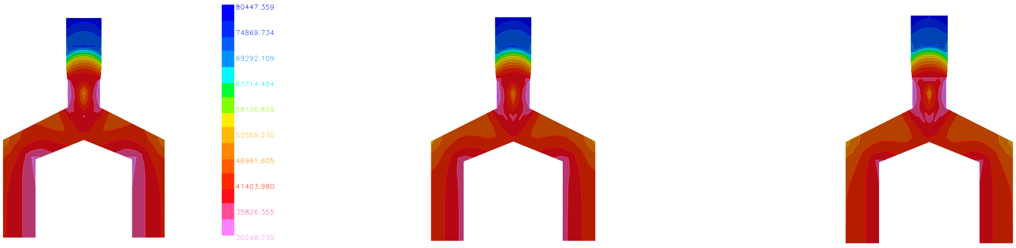

Fig.6 – Viscosity for different flow rates (Q=20cm^3/s, Q=30cm^3/s, Q=40cm^3/s, ω=2π rad/s)

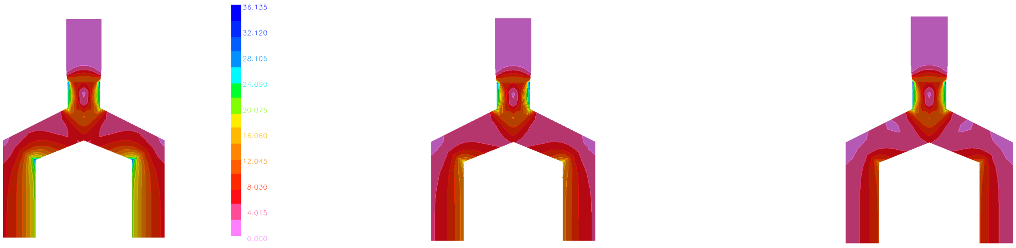

Fig. 7 – Shear rates for different flow rates (Q=20cm^3/s, Q=30cm^3/s, Q=40cm^3/s, ω=2π rad/s)

In the same direction of comparison, Fig.8 shows the velocity, pressure, viscosity and shear rates for different flow rates at the outlet section of the matrix. This figure shows us very interesting results from a technological point of view, and shows us that to have a hard material and low viscosity it is necessary to increase the flow. On the other hand, if you want to obtain reverse characteristics you must work with low flow. According to Fig.8(a), the velocity reaches a maximum value of 3.4 cm/s for a flow of 40 cm^3/s (x=0.8cm), followed by a sharp decrease. According to Fig.8(c), the dynamic viscosity decreases by increasing the inlet flow (Q=40cm^3/s) by 33000.10^{4}Pa.s. The lower the flow rate (Q=10cm^3/s), the higher the viscosity (42000.10^{4}Pa.s).Viscosity is inversely proportional to the input flow. In contrast, the shear rates increases with the flow rate reaching a maximum value of around 70 N/m^2 at a flow rate of 40 cm^3/s.

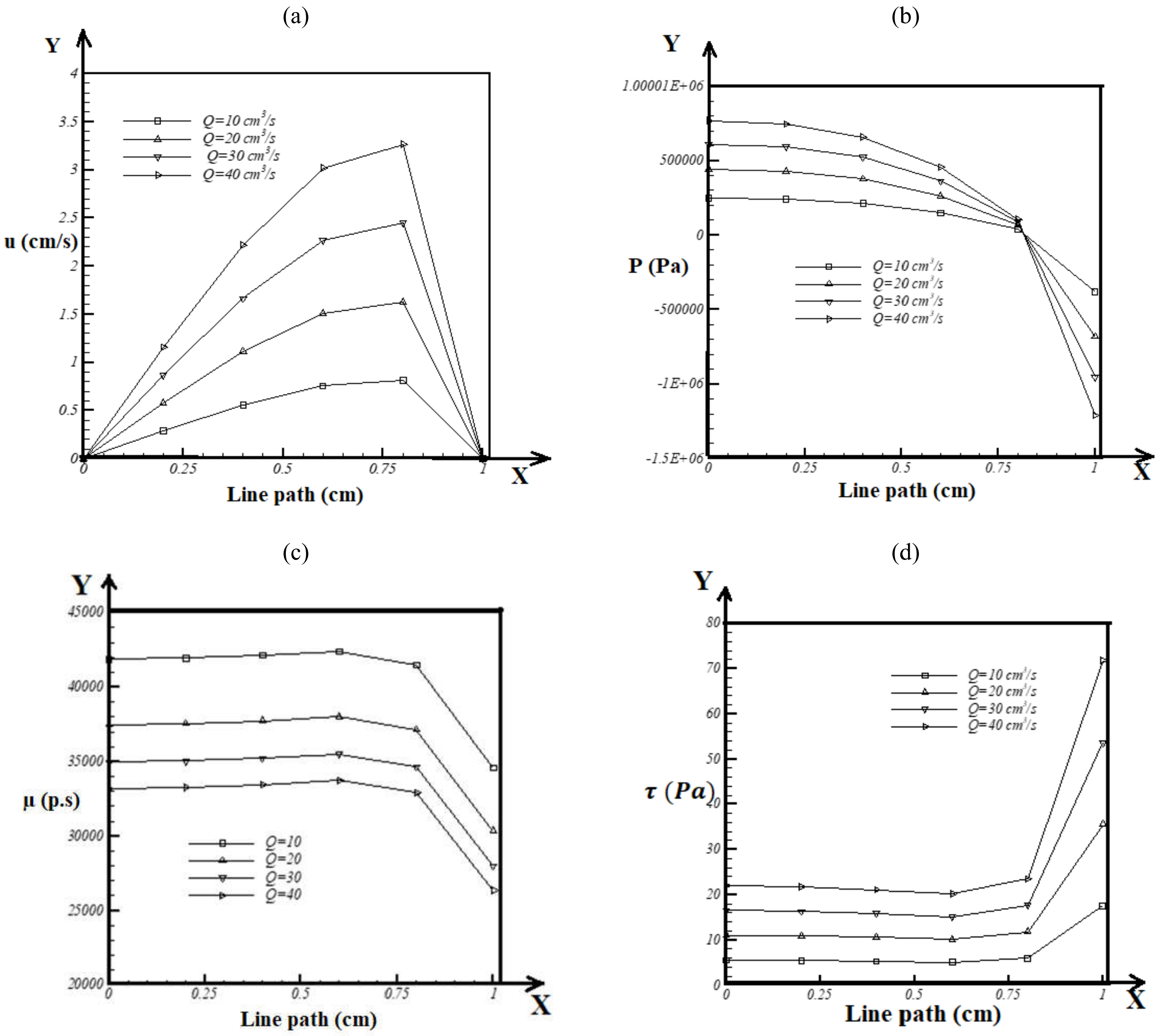

Fig. 8 – Effect of flow rate on the distribution of the extrudate characteristics at the outlet of the matrix following line path: (a) longitudinal velocity ; (b) pressure ; (c) viscosity et (d) shear rate, for (D=3cm, ω=2π rad/s)

3.2 Study of the influence of the outlet diameter ($Q=10cm^3/s$, $D=6cm$ et $\omega=2\pi$ rad/s):

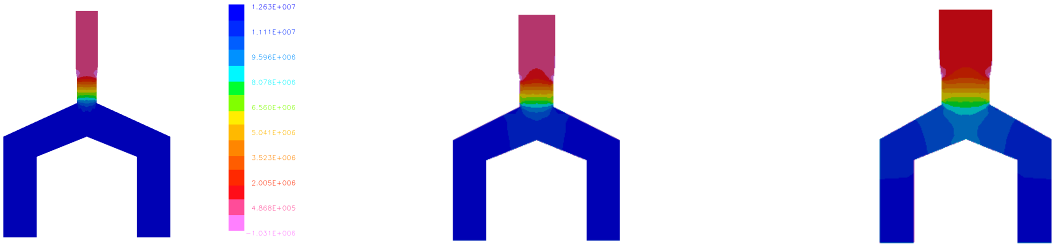

Fig. 9 – Pressure for different diameters : (a) d=1.2cm ; (b) d=2cm ; (c) d=2.8cm avec $Q=10cm^3/s$

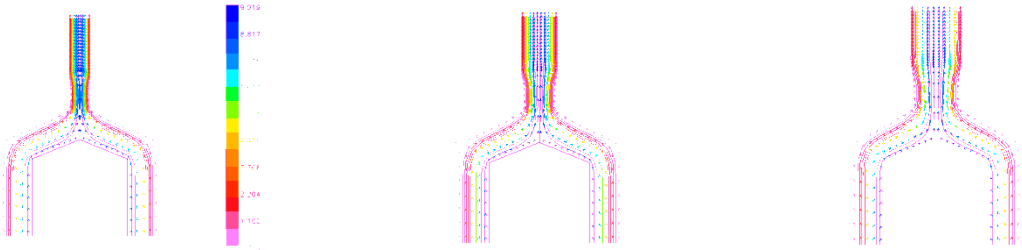

Fig. 10 – Velocity and pressure current lines for different diameters : (a) d=1.2cm ; (b) d=2cm ; (c) d=2.8cm avec $Q=10cm^3/s$

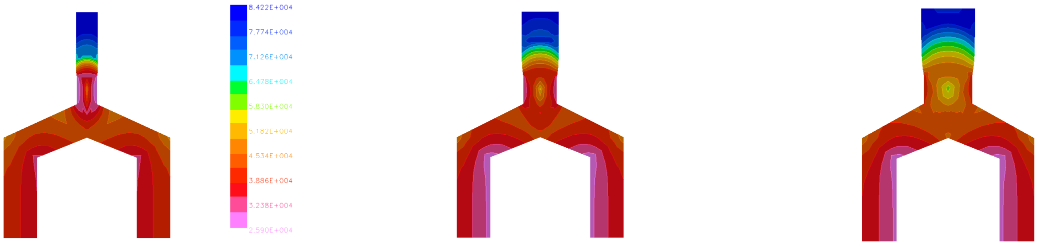

Fig.11 – Viscosity for different diameters (a) d=1.2cm ; (b) d=2cm ; (c) d=2.8cm avec $Q=10cm^3/s$

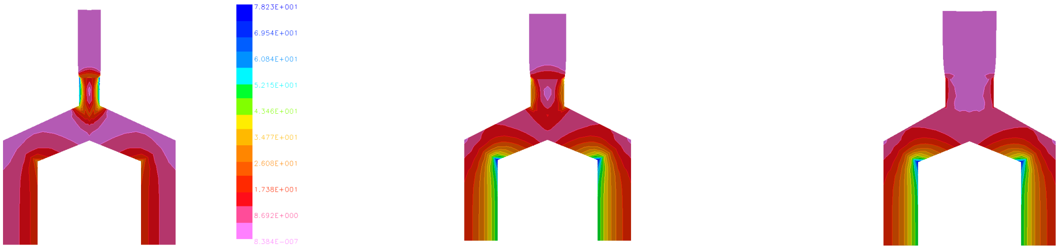

Fig.12 – Shear rates for different diameters : (a) d=1.2cm ; (b) d=2cm ; (c) d=2.8cm avec $Q=10cm^3/s$

Figures 9, 10, 11 and 12 show the influence of the output diameter (d=1.2cm; 2cm; 2.8cm) and for the same flow rate ($Q=10cm^3/s$) as well as the same angular velocity (ω =2 rad/s) on the characteristics of the extruding polymer. According to Fig.9, the greater the diameter of the die the lower the pressure in the area between the end of the screw and the opening of the die. On the other hand, Fig.10 indicates that the flow is completely uniform without the presence of a vortex or counter-current, which is justified by the small number of Reynolds. Fig.11 shows that the increase in the output diameter increases the viscosity of the material in extrusion. On the other hand, the shear rate is inversely proportional to the opening of the matrix as is clear in Fig.12.

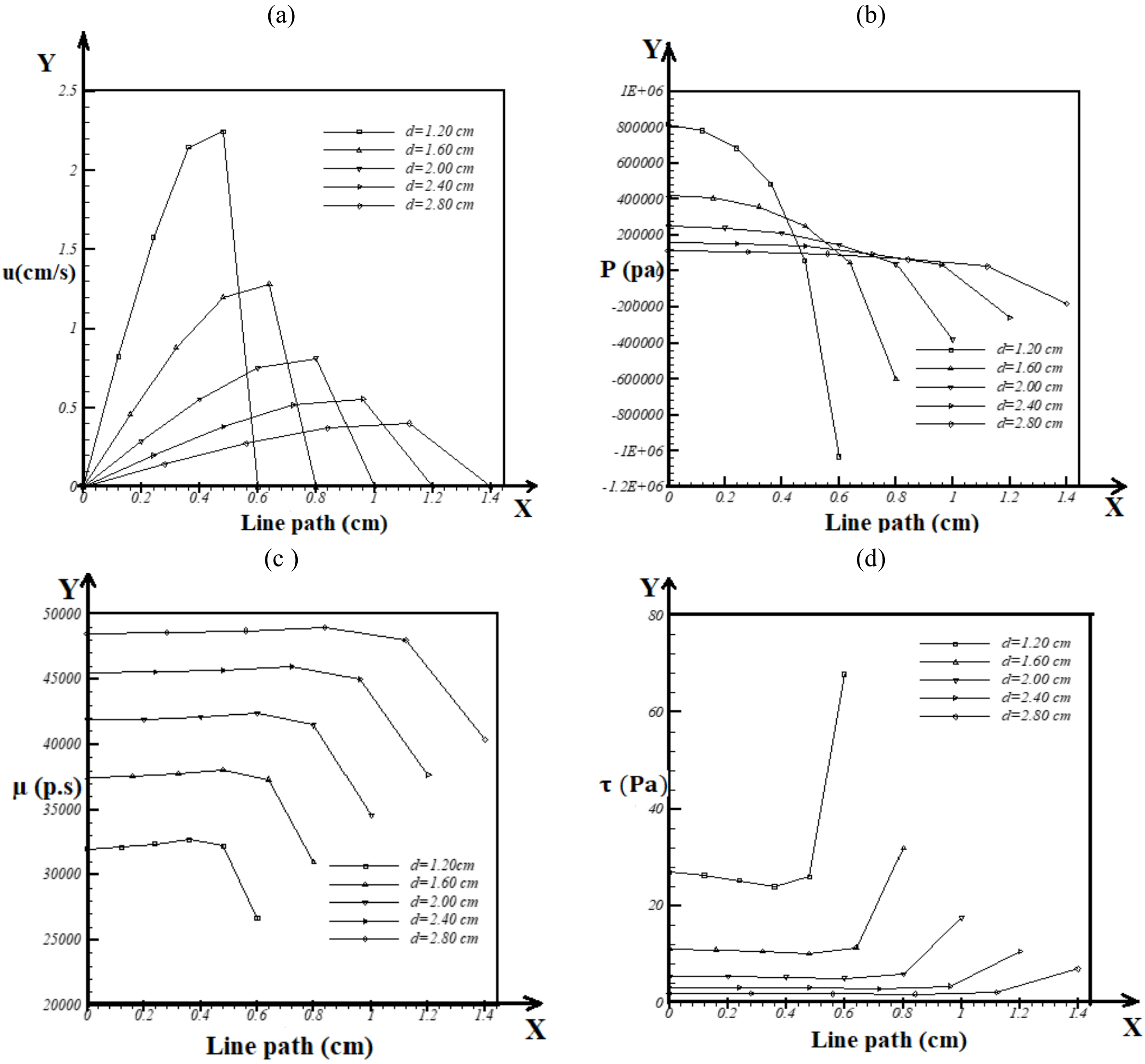

Fig.13 – Effect of the output diameter on the distribution of the exudate characteristics at the outlet of the matrix following line path: (a) longitudinal velocity ; (b) pressure; (c) viscosity et (d) shear ratefor (Q=10cm^3/s, ω=2π rad/s)

The comparative study of the extrusion output parameters in the output section is clearly shown in Fig.13. It appears that the greater the aperture of the matrix, the more uniform these characteristics become. On the other hand, for small diameters the extrusion leaves the matrix faster under high pressure and with low viscosity and higher shear rate in comparison with that of the large opening.

Conclusion:

In order to improve the extruder the influence of several parameters on the velocity, viscosity, pressure and shear rate have been studied. Mentioned parameters are as follows: 1-the diameter of the extruder screw, 2-the output diameter of the matrix, 3-the angular rotation velocity of the screw and 4-the shear rate of the polymer stream through the extruder

It is appearing that the variation of the screw diameter has no significant influence on the pressure, velocity, viscosity and shear rates of the polymer. However, increasing the size of the machine can only increase its size.

For the study of the influence of the matrix output diameter on these parameters, it is clear that the greater the aperture of the matrix, the more uniform these characteristics become. On the other hand, for small diameters the extrusion leaves the matrix faster under high pressure and with low viscosity and higher shear rates in comparison with that of the large opening.

It is showed in the first case, that there is no significant qualitative influence of the screw diameter on the pressure, the current line, the viscosity and the shear rates. In the second case it is appearing that that more the aperture of the matrix is large the more these characteristics become more uniform. Moreover, it has been showed in the third case that the change of the angular velocity does not change any physical magnitude of the previously mentioned parameters. The last case shows that to have the smooth extruded hard and low viscosity it is necessary to diminish the flow. On the other hand, if reverse characteristics are needed, low flow should be used.

REFERENCES

[1] R. Guy, Extrusion cooking Technologies and applications, Published by Woodhead Publishing Limited, Cambridge CB1 6AH, England, 2001.

[2] Vergnes B. and Puissant S., Single screw extrusion (part 2), Techniques of the Engineer.AM 3 651,1-10, 2002b.

[3] Vergnes B. and Puissant S., Single screw extrusion (part 1), Techniques of the Engineer.AM 3 650, 1-16, 2002a.

[4] Michaeli W., (1992) Extrusion Dies for plastic and Rubber: design and engineering computations' 2nd Edition by Hanser Publisher.

[5] Ulysse P., Optimal extrusion die design to achieve flow balance, Inter. J. of Machine Tools & Manufacture 39 (1999) pp.1047–1064.

[6] S.E. Carreras, Extrusion stability of molten polymers effects of pressure and structure of aba-type copolymerestriblocs. Doctoral thesis at the University Joseph Fourier-Grenoble, France, 2005.

[7] J. L. Den Otter, Mechanisms of melt fracture. Plast. & Polym. 38(1970) pp.155-168.

[8] Prasad A. (1999), Polyethylene low-density, Polymer Data Handbook, Published by Oxford University Press, pp. 518

[9] Ulysse P., Johnson R.E., A die design model for thin section extrusions, Int. J. Mech. Sci. 41 (1999) pp.1067-1088.

[10] Ansys polyflow, 15.1 User`s Guide 2013.

NOMENCLATURE

Re	Reynolds number	/
Q	Flow rate	cm^3/s
P	Pressure	Pa
u	Velocity	cm/s
μ	Viscosity	Pa.s
ρ	Volumic mass	kg/m^3
τ	Shear rate	Pa
ω	Angular velocity	rad/s
D	Screw diameter	cm
d	Outlet diameter matrix	cm