AN EXPERIMENTAL AND THEORITICAL STUDY ON THE PRESSURE DROP OF FLUID AT EXTRUSION PROCESS

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Abstract

This paper investigated the pressure drop during the extrusion processes. The objectives of this investigation were to increase efficiency of plastic extrusion which plastic equipment produced. In the experimental processes, two rectangular dies were used. HD 7255 thermoplastic was used as the fluid material of extrusion. A difference occurred between inlet and outlet. This difference was 2.34 MPa in terms of the pressure drop and was 0.001216 (kg s^{-1}) in terms of the flow rate. The results of power law model is found in good agreement with experimental results for outlet sections of process.

Keywords: Plastic extrusions, Non-Newtonian fluid, Power law model.

Introduction

In this research the pressure drop of fluid was investigated. The extrusion dies are used for the extrusion of thermoplastic raw materials having a broad range of usage area from agricultural irrigation pipes to drainpipes.

The non-Newtonian constitutive equation used is the generalized Newtonian fluid model with the viscosity described by the power law, Bingham, Herschel–Bulkley, Sisko and Robertson–Stiff models (Ferrás, L.L. Nóbrega, J.M. and Pinho, 2012).

A key work by Mitsoulis showed that gravity acting in the direction of flow also reduces exponentially the swelling (Mitsoulis, E. Georgiou, G.C. and Kountouriotis, 2012). When the flow is creeping and gravity is zero, surface tension, slip at the wall, and pressure-dependence of viscosity, all decrease the swelling monotonically, while compressibility increases it after a small initial reduction. The exit correction decreases monotonically with inertia, gravity, and slip, increases monotonically with compressibility and pressure-dependence of the viscosity, and is not affected by surface tension.

Squeeze flow of generalized Newtonian fluids is used with and without wall slip to generate an inverse problem solution methodology for the estimation of the parameters of the shear viscosity and wall slip. Analytical as well as the finite element method (FEM) based numerical solutions of the squeeze flow are used for the analysis and the determination of the parameters (D.M. and Tang, 2007).

Influence of wall friction on mean apparent viscosity reduction of gel propellants in conical radial flow extrusion is investigated analytically and numerically. A parametric study has been conducted to evaluate the effects of injector geometry, rheological constants, wall friction factor and volumetric flow rate on fluid viscosity profile. A lubrication type analysis shows good agreement for values of pressure gradient in the absence of wall slip when walls are perfectly rough (Dubbeldam, J.L.A. and Molenaar, 2003).

In extrusion die design there are two main issues to be solved: how to make the flow distribution more uniform and how to anticipate post-extrusion effects. Trial and error procedures have been the common base to design these tools. The main objective to achieve when designing a new die is to reach the best possible production rate at the highest quality product level with dimensional accuracy, aesthetics and mechanical performance (Carneiro, O. S., Nobrega, J. M., Pinho, 2001; Carneiro, O. S., Nobrega, J. M., 2004;).

Extrusion flows through a slit die are studied for two materials (Rahimia, S., Durbanb, D. and Khosid, 2010): a linear low density polyethylene (LLDPE) which exhibits sharkskin instability for flow rates larger than an onset value and a low density polyethylene (LDPE) which does not show any instability over a broad range of flow rates. By combining laser-Doppler velocimetry (LDV) with rheological measurements in both uniaxial extension and shear, the distributions of tensile and shear stresses in extrusion flows are measured for both materials. The experimentally measured flow fields appear to be qualitatively similar for both the unstable (LLDPE) and stable case (LDPE): around the die exit the flow accelerates near the boundaries and decelerates around the flow axis.

Predicting the required die profile to achieve the desired product dimensions is a very complex task and requires detailed knowledge of material characteristics and flow and heat transfer phenomena, and extensive experience with extrusion processing (Kostic, M. M., Reifschneider, 2006).

In the work of Baldi, the effects of extrusion parameters (temperature and imposed flow rate) on the oscillating flow exhibited by a HDPE melt were analyzed by capillary rheometry. All the tests were performed using a fixed die geometry (Baldi, F., Franceschini, A., Briatico-Vangosa, F., Locati, D. and Riccò, 2010). The results put in evidence that the imposed flow rate (piston speed) has an influence on the kinetics of the processes that govern the oscillating flow but not on the extrusion pressure levels characteristic of the instabilities, which are strongly dependent, in a complex way, only on the temperature.

The linear scaling relation between the period of the spurt oscillations and the length of the die and the barrel height was demonstrated to be independent of shear thinning or the precise form of the slip relation (Burghelea, T.I., Griess, H.J. and Münstedt, 2010).

In many of the researches on extrusion dies, the effects of flow characteristics and surface qualities on the flow of the material were analyzed by using finite element analysis method. In this study, experimental and finite element methods were used and the results were compared.

Materials and Methods

The experimental processes were conducted by an experimental setup connected to a plastic extruder machine which had the capacity of 70 kg h-1 and had the power of 22 kW. There is a dehydrator with temperature control on the extruder machine in order to dehumidify humid raw material. The outlet hole caliber of the extruder machine is 60 mm. The experimental setup used in the study consists of three parts: the link adapter, the flow regulator head and experimental die. The general assembly drawing of the experimental setup connected to the extruder machine is presented in Fig. 1.

Fig.1. The experimental setup assembly

A flow regulator head was used between the link adapter and the die in order to put the flow of the material used in experimental setups. The Polyflow analysis programme was used in the design of the flow regulator head used for the purpose of keeping at the equal speed rate in each point of atmosphere outlet of the die and generating homogeneous flow of extruded raw material. When the experimental die was connected to the extruder machine directly without the flow regulator head, the speed rate of the fluid was high in the center point axis of the die and the fluid moved at a lower speed rate in the side sections. This case caused errors in the pressure measurements. Also, production geometry becomes deformed because of irregular flow. The thermoplastic material penetrating into the flow regulator head was directed to the side sections of the die because of the head geometry of the flow regulator. Thus the flow of the material in the die was at the same speed rate in the whole die profile (Fig. 2).

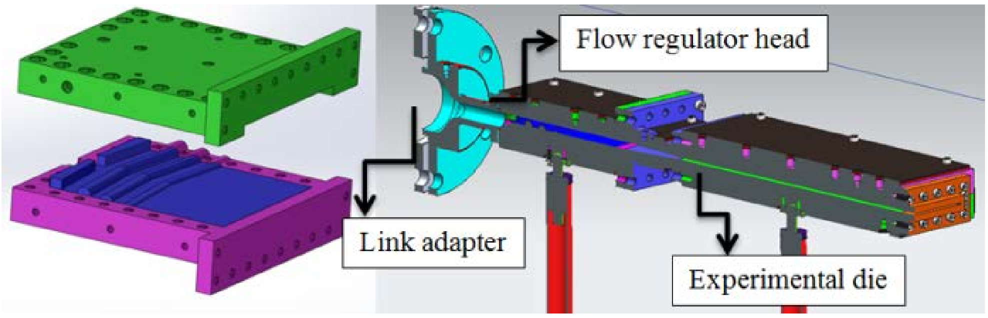

Fig.2. Central cross-section of the experimental set up

In the experimental processes, two extrusion dies were used.The experiment results were obtained by operating the dies under the same experiment conditions by being connected to the extruder machine one by one.

The experiment dies were designed as rectangular shapes in order to measure more accurately the pressure differences. While die dimensions were being determined, the dies were produced in 3 x 200 x 500 (mm) channel sections taking account of the extruder machine's capacity.

Three pressure sensors were used on the experiment die. Pressure sensors had the capacity of 70 MPa. The pressure sensors were placed on the die at intervals of 200 mm with screwed joint. In order to make an accurate measurement, the detector edge of the sensor was assembled on the same plane with inner surface of the die so as to contact with the fluid. These sensors were also used for temperature measurement. The temperature and pressure data obtained from pressure sensors was transferred to indicator with a special data cable. The pressure measurement sensitivity of the indicators was ±0.1 MPa and the temperature measurement sensitivity of the indicators was ±3°C. The extrusion die and assembled pressure sensors (PT), resistance plates (R), thermocouples (T) used in tests are shown in Fig. 3. PT1, PT2, PT3 were the pressure sensors from the extruder machine to outlet of die respectively. Pressure sensors were put in equal intervals in order to interpret the change of pressure difference more easily.

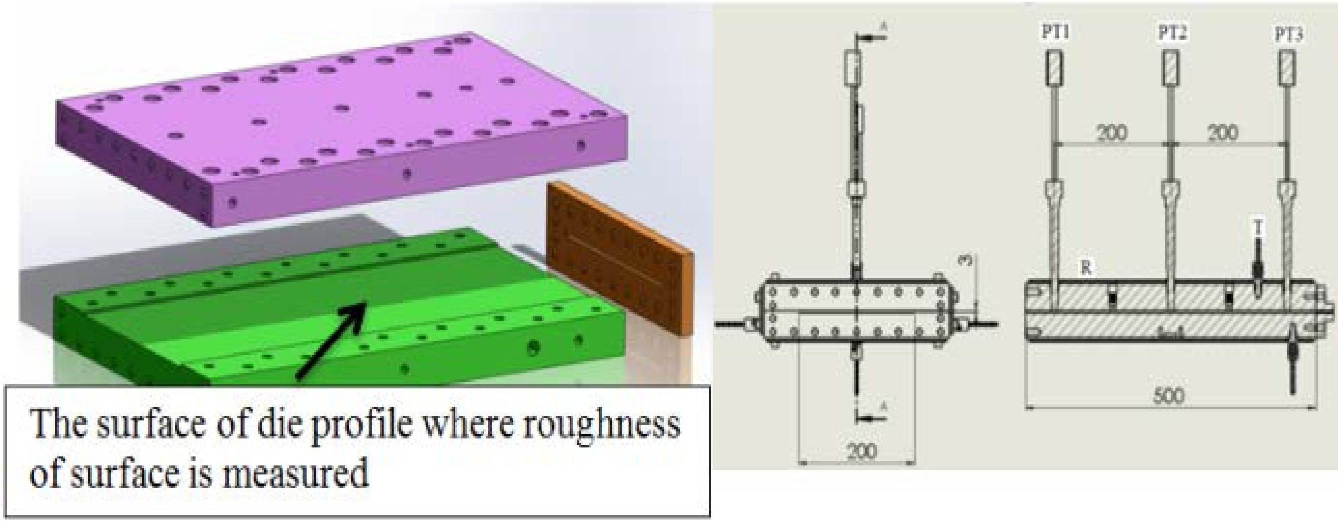

Fig.3. Experimental die and its dimensions

Before the trial of each dies the extruder machine and the dies were enabled to reach steady state by keeping in heat for 90 minutes. In the experiments, a dehumidifier was used to prevent moisture of content of raw materials. The dehumidifier temperature was set to 70°C. The revolution of the extruder machine used in tests was chosen as 100 rpm. The experiment duration got much longer as flow rate was too low at lower speeds and experiment die leaked raw material at higher speeds because of high pressure.

60 minutes of three repetitive extrusion processes were carried out for each experiment die. The amount of raw material obtained at the end of each extrusion period was measured with precision scales. As the die profile and amount of the raw material was defined, the calculation of flow rate was done by using mass flow rate formula.

$$\dot{m} = \rho v A , \qquad (1)$$

where $m^{\cdot}$ is mass flow rate (kg h^{-1}), ρ is density (kg m^{-3}), v is velocity (m h^{-1}), and A is flow area (m^2).

Heating operation was carried out on extruder machine and on eight sections of the experiment set for a regular flow and a steady viscosity. T1, T2, T3, T4 were respectively heating sections on extruder machine and T5, T6, T7, T8 were heating sections on experimental setup (Fig. 4). The dies and other parts of experiment set were heated by plaque shaped resistances. The temperature of the resistances used for heating extruder machine and experiment set were controlled by the help of thermocouples. Process temperature values can be entered via control panel of the machine. In Table 1, set values of the heating sections are presented.

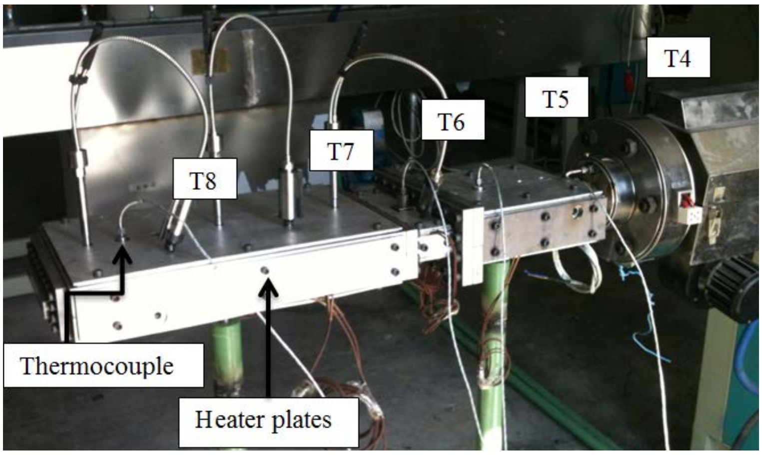

Fig.4. Heating sections of the experimental set up

Table 1. Temperature set values which were applied to the system

Sections	T1	T2	T3	T4	T5	T6	T7	T8
Temperature Values (°C)	180	180	170	170	170	170	170	170

A digital active counter with 3 phases were used in the system in order to determine the effect of two different dies used in experiment set on energy consumption.

An electronic scale with ±1g sensitivity and the capacity of 30 kg was used in order to scale the amount of extruded raw material in each experiment process.

All the equipment and the die used in the experimental study were modeled with Siemens Unigraphics NX8 CAD programme and production drawings were generated with the same programme. Mesh operations were done in the programme of Gambit and flow analysis was done in the programme of Polyflow.

HD - 14, HC HD 7255 Polietilen (HDPE) was used as thermoplastic raw material in experiments.

All experiments were executed in the ambient temperature of 20 °C.

Mathematical Model

This power law model is based on the following approaches and assumptions:

1- The model is one dimensional.
2- Gravitational and inertial forces are neglected.
3- Steady-state conditions.
4- The flow is fully developed.
5- Power Law Non-Newtonian flow model was used.

$$\mu = m(\dot{\gamma})^{(n-1)}$$

Where μ is the dynamic viscosity (Pa s), m is the constant, $\dot{\gamma}$ is the shear strain rate (s^{-1}), and n is power law Index.

6- "Zero Wall Speed" was accepted as boundary condition for all sides in the die flow geometry except for inlet and outlet sides. Inlet and outlet mass flow rate of the pattern is 4.379 kg h^{-1} and the raw material is NPC 14, HC HD 7255 Polietilen (HDPE).

7- it was assumed that temperature distribution of polymer is uniform and equal 170 ^{o}C (isothermal) and for this temperature related parameters for Power Law model parameters:
m= 3000 s, *n*= 0.6.

8- The polymer melt flow is assumed to be incompressible.
$\nabla \cdot V = 0$

9- Gravitational and inertial forces are neglected.
$V.\nabla.V = 0$

10- Pressure is function only z-direction

Governing Equations:

Momentum Equation:

$$\frac{\partial P}{\partial z} = \frac{\partial \tau}{\partial y} \tag{1}$$

$$\tau = \mu \frac{\partial u}{\partial y} \tag{2}$$

$$\mu = m(\dot{\gamma})^{(n-1)} \tag{3}$$

$$\dot{\gamma} = (\frac{\partial u}{\partial y})^{n} \tag{4}$$

Boundary Conditions:

at z= 0 : p(z)=2.84 Mpa

Results and Discussion

Model Results

The fluid moves at different speed rates at the inlet of flow regulator head. The speed of the fluid was the same on the each point of outlet of regulator head because of internal geometry. The fluid reached homogeneous flow rate after flow regulator head was extruded from experimental die with same speed.
A pressure decrease from inlet to outlet of the die is observed. The pressure, which is 2.84 MPa at the inlet of the experiment set, decreased to 0.41 MPa at the outlet of the die.

Experimental processes results

The results of the experimental processes of the dies which were produced grinding operations are given in Table 1.

Table 1. The results of the experimental processes of the dies

Results of the experimental processes	Mean
The rate of flow (m h^{-1})	7.668
The amount of raw material (Kg h^{-1})	4.39
Pressure value 1 (MPa)	1.9
Pressure value 2 (MPa)	0.9
Pressure value 3 (MPa)	0.5
The exit temperature of the raw material (°C)	160

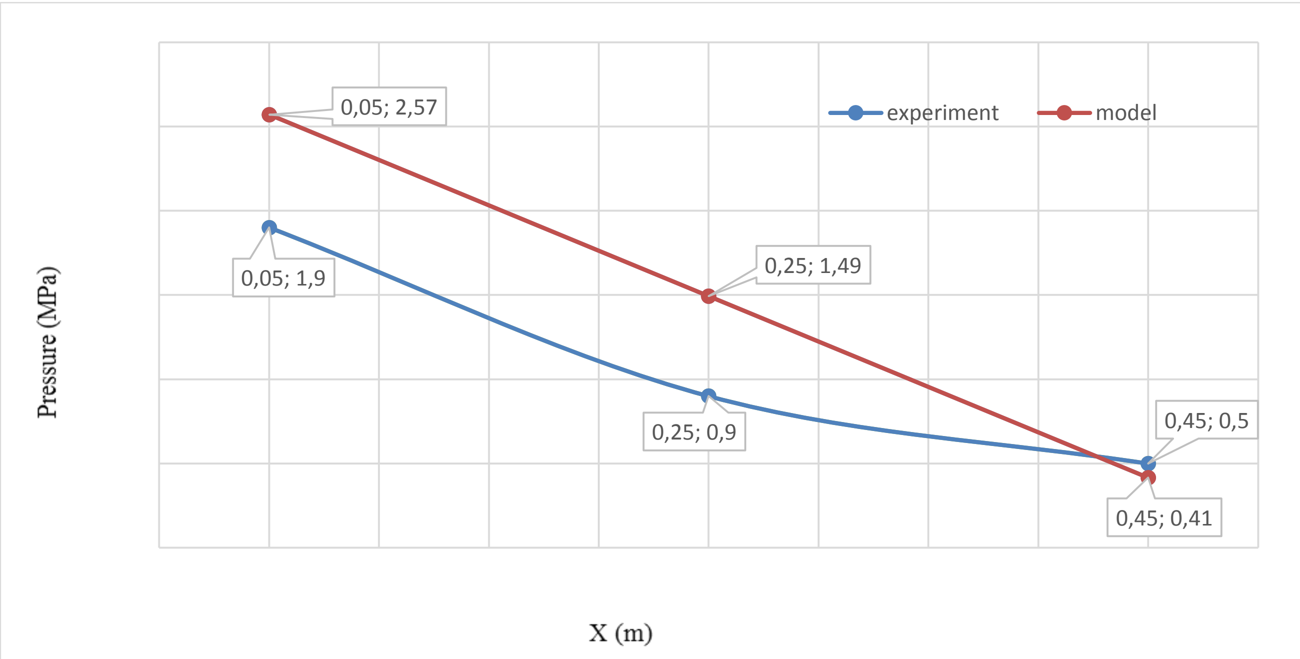

Fig.8. Comparison of pressure values in terms of the result of model and experiment

Conclusions

As a consequence of this study we understand that the model which we used is appropriate for this process. There is a small difference between model and experiment results for outlet section of process. In the future works other non-newtonian models may be studied for better approximations to experimental results.

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