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Viscosity Models of Polymer Flow in PVC Extrusion Process

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ABSTRACT: An empirical model to decide the viscosities of thermoplastic polymers in the extrusion process. The viscosity is calculated from the screw rotation speed, melt temperature, geometric dimensions of the extruder and material constants, which were experimentally determined. Polyvinyl clorur (PVC) was used in this study to test the effectiveness of the model. Comparing the calculated results, it was found that the viscosities obtained with the present model are in agreement with those obtained by using in line rheometer. The extrusion of PVC polymers with a two layer vented screw has been studied. Experimentally, the pressures and temperatures were measured at the end of each layer, for different processing conditions (screw speed, die geometry etc.). Screw pulling experiments have allowed to observe the partially filling of the different screw sections. The variation of the pressure and the temperature all along the screw, as well as the filling length of the second layer are then obtained. The theoretical results are in good agreement with the experimental measurements.

KEYWORDS: Viscosity model; PVC; Extrusion process.

INTRODUCTION

Compression process in which material is forced to flow through a die orifice to provide long continuous product whose cross sectional shape is determined by the shape of the orifice widely used for thermoplastics and elastomers to mass produce items such as tubing, pipes, hose, structural shapes, sheet and film, continuous filaments, and coated electrical wire carried out as a continuous process; extrudate is then cut into desired lengths. Polymer coating is often applied to wires, strips, tubes or ropes for insulation or protection against corrosion [1, 2].

There are three different methods which are mostly used for this coating process. These methods are coaxial extrusion, dipping and electrostatic deposition process. Gold feed extruders and two layer vented screws are more and more used in the PVC industry. In order to improve the through puts and the operating conditions, screw designs have to be optimized.

Theoretical analysis for different coating processes can be found in the literature. For that purpose trial and error are no more sufficient and it becomes necessary to clearly understand and if possible to compute what happens into the machine during the extrusion process [3, 4].

Design of die and experimental results have also been reported. Zhang *et al.* [5]. Nakazawa and Pittman [6] studied the coating by dipping process by analytically and using finite element method respectively. These were mainly thermal analyses in dip coating process. An experimental study of the electro statically deposition process has been presented in [7]. Here, influence of thermal treatment in an electric field and treatment by a beam of non penetrating electrons have been applied on coating process.

Contrary to thermoplastics, little attention has been paid until now to the PVC extrusion. Recently, different research programs have been developed to remedy this lack [8]. Experimental and theoretical works on single layer extruders have been published and experimentations on single and theoretical approaches of the two layer extrusion process have been developed in the case of thermoplastic materials. In the present study, experimentations have been carried out with EPDM compounds on a two layer vented screw. The results have permitted to define a theoretical approach, leading to a complete description of the flow into the screw [9].

EXPERIMENTAL

Pipes Extrusion Process

Pipe is a tube or hollow cylinder for the conveyance of fluid. The terms “pipe” and “tubing” are almost interchangeable. “Tube” is often made to custom sizes and may have more specific sizes and tolerances than pipe, depending on the application. The term "tubing" can also be applied to tubes of a non-cylindrical nature (*i.e.* square tubing). The term “tubing” is more widely used in the USA and “pipe” elsewhere in the world. Pipe may be specified by standard pipe size designations, such as Nominal Pipe Size (in the US), or by nominal, outside, or inside diameter and wall thickness. Many industrial and government standards exist for the production of pipe and tubing [9].

Most pipes are made through extrusion, in-line with the direction of extrusion, die, sizing or calibrating device or tank, water cooling tank, conveyor, and cutter, if needed, and take off equipment at the end of the line. The line could include a marking device or a testing device. An important requirement is to cool the extrudate rather fast near the die while keeping control of dimensions and properties. Included in the processes are various techniques to control the dimensions/sizes that are either free drawn melts (usually for the small diameter tubes) or sizing features. The total cost of producing the pipe could include material costs of up to 80%. The goal is always to get a tighter tolerance control to reduce material consumption. Dimensional and/or thickness calibrating disks of different designs are used. There are many different ways pipe and tube products used in moving liquids, gases, solids, and so forth. They can be shaped to provide decorations, safety supports, and so on [9].

PVC

Polyvinyl chloride is widely used for producing pipes. The most used plastic for application in extrusion is PVC. PVC dry blends allow the processor to take advantages of using their own compounding formulations that should provide costs advantages. In terms of revenue generated, PVC is one of the most valuable products of the chemical industry. Globally, over 50% of PVC manufactured is used in construction. As a building material, PVC is cheap and easy to assemble. In recent years, PVC has been replacing traditional building materials such as wood, concrete and clay in many areas. Despite claims that PVC production negatively affects the natural environment and human health, it is still widely used. The recycling of PVC can be performed in different ways. Some PVC manufacturers have vinyl recycling programs, recycling both manufacturing waste back into their products, as well as post consumer PVC construction materials to reduce the load on landfills. Another alternative to the landfill are incineration, however the incineration of PVC generate air pollutants such as HCl and dioxide. Table 1 shows the most common properties of the rigid PVC [10].

Table 1. Properties of the PVC.

Property	**Value**
Density	1380 kg/m^3
Young’s modulus	2900-3300 MPa
Tensile strength	50-80 MPa
Elongation break	20-40%
Impact strength	2-5 kj/m^2
Glass temperature	87^{o}C
Melting Point	212 ^{o}C
Vic at temperature	85^{o}C
Heat transfer coefficient	0.16 W/m.K
Linear expansion coefficient	8.10^{-5} /K
Specific heat	0.9 kj (kg.K)
Water absorption	0.04-0.4

This study is used experimental system in Figure 1. Figure 1a shows scheme of a two layer vented extruder with a valved bypass and the screw geometry is presented in Figure 1b It is a The presented computer model was used to simulate a 45 mm screw plasticizing extruder with an L/D (length/diameter ratio) of 27/1, equipped with a rod cylindrical die. The first layer length 500 mm, pitch 48 mm includes the feeding section with a single channel which rapidly turns into two parallel channels.

At the end of the first layer is found a strong restriction, which obliges the material to flow in a very thin space (1 mm). After this restriction, the second layer length 480 mm, pitch 45 mm is composed of the venting section, just before the die. The main test device was a capillary rheometer (Rheovis 2100) made by Ceast Co. İn Italy.

The shear rates were obtained between 20 and 500 s^{-1}, as the measured ranges encountered in most polymer extrusion processing. The machine was a laboratory extruder capable of a maximum throughput of about 175 kg/h.

The polymer extrusion experiment was carried out a three screw speeds 25, 50 and 75 r.p.m. for four different melt temperatures 90 °C, 100 °C, 110 °C and 120 °C. The pressure drops for analyzing the in line viscosity data and screw speeds for the viscosity model were written to the hard disk every second. The flow rates at various screw speeds and temperatures were individually investigated in advance for evaluating the in line viscosity data.

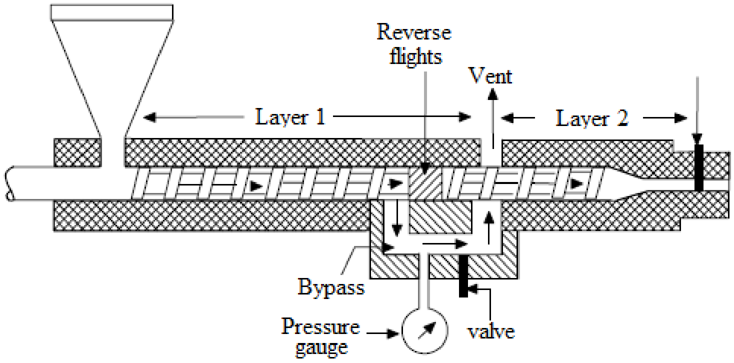

Figure 1a. Scheme of a two layer vented extruder with a valved bypass.

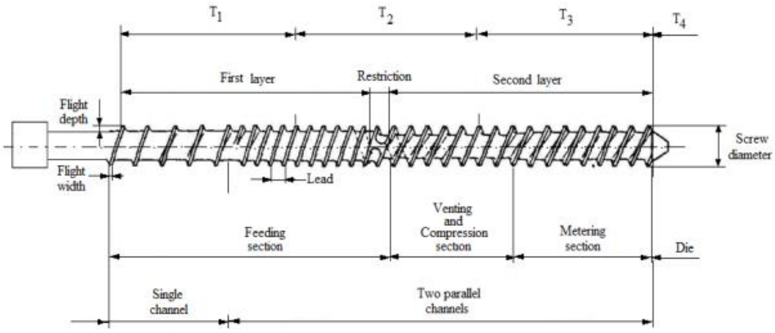

Figure 1b. Screw layers ($T_1 = 90$°C, $T_2 = 100$°C, $T_3 = 110$°C, $T_4 = 120$°C).

Pressure and temperature transducers have been implanted at the end of each layer experiments were carried out at three different values of the rotation speed 25, 50 and 75 rpm using die geometries that it has a final diameter of 5 mm.

Experimental results are given in Table 2 and in Figure 2. The flow rate various linearly with the screw speed. Final pressures and temperatures of each layer increase with the screw speed and in the same operating conditions, screw pulling experiments were carried out and in a steady state, the screw rotation is suddenly stopped and the barrel rapidly cooled. Extracting the screw from the barrel permits then to observe the situation of the material into the screw. The measurements of temperature, pressure and flow rate were done in a continuous way.

A typical result is the first layer is totally filled by the PVC, at least from the beginning of the double flight. On the other hand, the second layer is only very partially filled, the flow is discontinuous on the major portion of the layer, showing the point where the channel is again completely filled. When varying the screw speed, the filling conditions do not vary greatly. In particular, the filling conditions do not vary greatly.

Table 2. Q, P, T values of first layer and second layer for three different N values.

Screw speed (Rpm)	First layer			Second layer		
	Q Kg/h	P Bar	T ºC	Q Kg/h	P Bar	T ºC
25	19.6	115	89	20.3	47.5	97
50	34.9	132	91	40.5	52.5	101
75	60.0	139	93	41.8	56	104

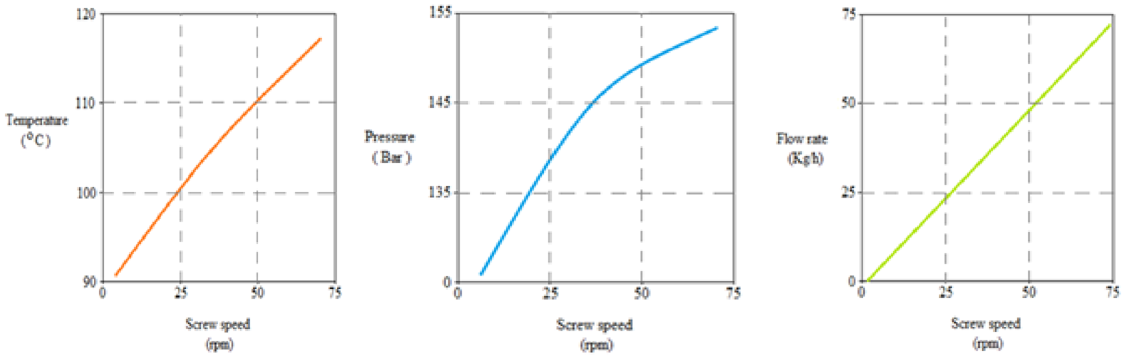

Figure 2. a) The temperature various linearly with the screw speed; b) The pressure various linearly with the screw speed; c) The flow rate various linearly with the screw speed.

In particular, the filling length of the second layer remains quite constant the operating conditions of the two layers appear to be very different: the first layer, totally filled, will impose the flow rate at a given screw speed. Depending on the second layer will be continuous on a more or less important distance.

THEORETICAL

First of all, we have to define the rheological behavior of the PVC polymers used in the experimentations, the viscosity of a polymer melt in the polymer processing, the first thing is to investigate the relationship between viscosity, temperature and screw rotation speed for the material.

The shear rate is a function of screw speed and temperature, hence the relationship between viscosity, temperature and shear rate of the material has to be investigated. In the literature, many efforts have been made to establish the relationship between viscosity, temperature and shear rate; e.g. the Andrade's Equation [10]. In these papers, it was assumed that the relationship between viscosity and shear rate is described by the power-law Equation [10] as

$$\eta = m\dot{\gamma}^{\,n-1} \quad (1)$$

Where η is viscosity, $\dot{\gamma}$ is shear rate, m is consistency index and n is power law index .Taking the natural log of both sides of the power law equation and let $p = n-1$ and $q = \ln m$, then

$$\ln \eta = p \ln \dot{\gamma} + q \quad (2)$$

If ln (η) is plotted against ln ($\dot{\gamma}$), Equation (2) is a straight line for a constant temperature, where p and q are the tangent and intercept of the plotted straight line, respectively. For several different temperatures, the flow curves of the viscosity plotted against the shear rate in logarithmic scales are traditionally assumed to be paralleled straight lines. In these papers, the flow in the melt layer is considered to be a linear flow of a power law fluid, the coefficients of the power law result from local analysis of the Klein function (3). The molten polymer is considered to be a shear thinning fluid, obeying the following expression,

$$\ln \eta = A_o + A_1 \ln \dot{\gamma} + A_{11} \ln^2 \dot{\gamma} + A_{12} T \ln \dot{\gamma} + A_2 T + A_{22} T^2 \quad (3)$$

where η is the viscosity, T the temperature, $\dot{\gamma}$ the shear rate, and A_0 - A_{22} are coefficients of the polynomial. To compute the flow of the PVC in each layer of the screw, this study used a computation model developed in Mardin Pipe Co. laboratory in the case of the extrusion of thermoplastic materials. The rheological parameters of polymer were computed from data obtained in Instron Rheovis 2100 capillary rheometer by curve fitting Equation (3) to the viscosity data using nonlinear regression. Other physical properties were taken from handbooks. The simulations were confirmed with experimental runs. For each run, the melt pressure at four locations was measured using strain gauges three inserted in the barrel and one in the die and the melt temperature was measured in the die using three thermocouples immersed in the melt.

This model is derived from the well-known work of Tadmor and Klein [11]. It is main assumptions are as follow, the screw channel is unrolled and the barrel considered as a moving plane, the behavior of the rubber is described by a power law, there is no slip at the walls. This assumption, much debated by different authors [12, 13] has been chosen in a first step, but could be modified if necessary, heat transfer from the barrel and screw walls are taken into account by means of heat transfer coefficients, defined following the values of Graetz and Brinkman numbers [14], flow equations are solved using a slab method: in each slab, mechanical and thermal balance equations are simultaneously computer, in order to provide the evolution of the pressure, mean temperature, velocity feel etc. Figure 3 shows that tangents of the plotted lines are not constants. Instead, they vary with the temperature.

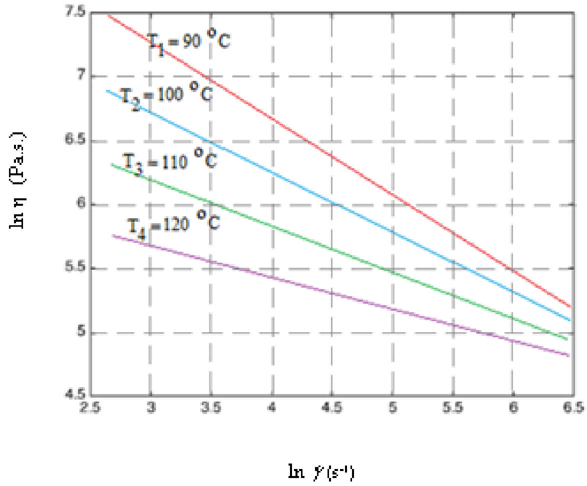

Figure 3. Values of ln η against ln for PVC at the four temperatures.

RESULTS AND DISCUSSION

The pressure increased with the rotational speed of the screw, and consequently, with the output. The measured of the model were in acceptable agreement with the experimental runs. Some results are shown in Figure 4.

This model is only used in the screw sections which are totally filled by the material. For the first layer, we assume following the experimental results, that the filling length corresponds to the double flight section. Characteristic curves plotted in Figure 5 giving the variation of the flow rate with the pressure for different screw speeds may be calculated. These characteristic curves are limited at low pressure by the maximum value of the flow rate arising from the first layer.

Table 3 shows the measured viscosities of PVC in the laboratory at various temperatures and shear rates in the selected ranges.

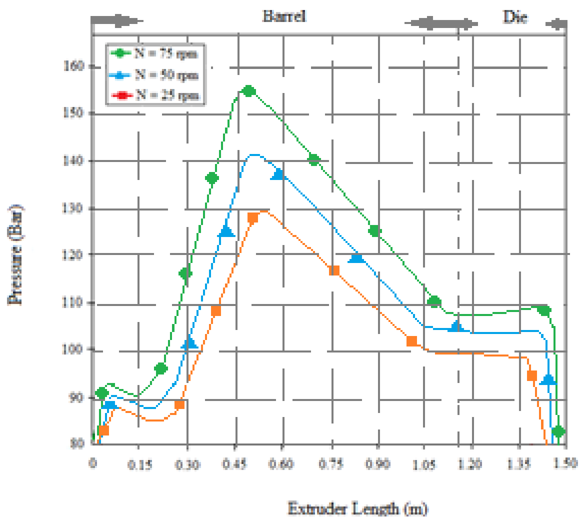

Figure 4. Variation of the pressure for three screw speeds in barrel and die.

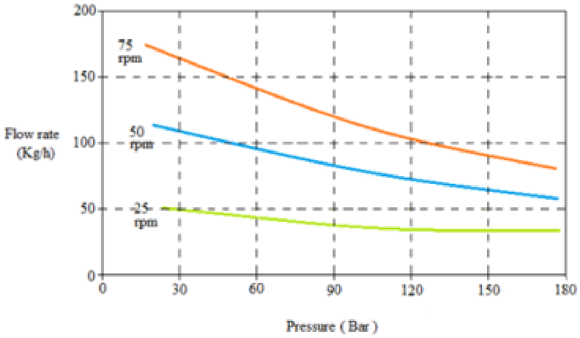

Figure 5. Variation of the flow rate with the three pressures for different screw speeds.

$\dot{\gamma}$ (s^{-1})	T_1 = 90 °C	T_2 = 100 °C	T_3 = 110 °C	T_4 = 120 °C
20	1345.671	1167.890	873.284	736.099
40	906.650	876.312	679.059	541.400
100	563.211	459.413	401.045	365.790
200	345.314	306.591	271.568	321.180
400	289.037	195.234	198.540	125.932
500	237.443	181.504	155.867	101.412

η (Pa.s.)

Table 3. Viscosities of PVC at various temperatures and shear rates.

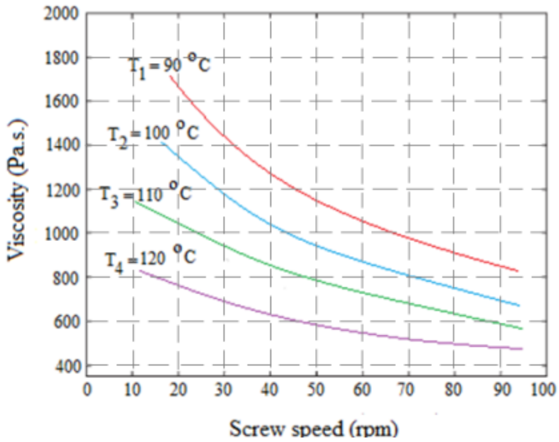

Figure 6. Viscosities against screw speed at various temperatures.

Figure 6 shows the averaged viscosity values collected by the in line rheometer for each temperature at various screw speeds. Comparing viscosity values calculated by those evaluated by the in line rheometer. The in line viscosities are very much less than those calculated by the measured model. A reasonable explanation for the differences is that the orifice diameter of the in line viscometer is around 5-10 times of that of a laboratory rheometer.

The pressure drop in the in line rheometer is therefore much lower than that of the laboratory rheometer. According to Equation (1), the obtained in line viscosities will be lower. The in line rheometer has a 2 cm inside diameter and two pressure transducers installed at a distance of 8 cm, similar to the capillary rheometer. This in line rheometer was equipped to measure the viscosity of the polymer melt based on the pressure drop and flow rate.

The unique operating point corresponding to the case studied may be now determined, owing to the fact that the flow rate is imposed by the first layer on an horizontal line, corresponding to the value of the flow rate computed in the first layer, this point, which is unique, will give for the second layer the values of the final pressure, final temperature and length of filling [15].

It is important to compare these theoretical results with the experimental values previously measured. The agreement is very good concerning the flow rate and the pressure in the second layer. The values of the temperatures at the end of each layer are well described by the model, even if in the second layer the theoretical values are slightly higher than the experimental ones.

The filling length of the second layer is well approximated by the computation, as well as its independency in function of the screw speed. The main disparity concerns the value of the pressure at the end of the first layer. The theoretical values are too important and the difference between the two results may attain a factor two. At the present state of this study, we do not exactly know what the reason of this disagreement is.

However, it can be thought than the strong variation of the local geometry at the restriction entry may be at the origin of the phenomenon in this region, the lubrication assumption used in the computation of the pressure is no more valid. Moreover, strong elongation or viscous elastic effects may occur which can modify the local flow conditions. Finally, the boundary condition of no slip at the barrel wall may perhaps be questioned [16-17].

Despite the problem of the pressure in the first layer, the model may be used to describe the evolutions of the PVC polymers all along the screw in different conditions. For example are presented the variations of the temperature and pressure for three different values of the rotation speed and a die of final diameter equal to 5 mm. We can see that the screw seed, though it permits to greatly modify the flow rate, has a low influence on these parameters. In particular, the operating conditions of the second layer remain quite constant.

On the other hand, if we modify the die geometry, the first layer is not affected, but the operating conditions of the second layer may be very different. In particular, the length of filling is very dependent on the back pressure created by the flow through the die, if this back pressure is too high, serious problems may occur at the venting orifice of the screw [18].

CONCLUSION

The viscosity models that can be used in extrusion have been proved to be generally in good agreement with the modified data analyzed by the in line rheometer. The models were built based on the empirical material model investigated in advance in the laboratory. Experimentations on a two layer vented screw, in particular screw pulling experiments, have permit to observe the flow conditions in the different screw sections.

The computation method which has been developed leads to the description of the pressure and temperature evolutions in each layer of the screw and to the filling rate of the second layer. Except for the pressure at the end of the first layer, the theoretical results are in good agreement with the experimental ones. This type of computation permits to better understand the two layer extrusion process. It may be used in order to optimize the screw geometry study is going on by testing different PVC polymers and other screw geometries.

FUTURE WORK

The polymer extrusion process, in addition to the variable the extruded or coated wire quality of extruder systems can be controlled in a structure can be converted to variables. In this way, input increasing the number of output, the control problem becomes a bit more complicated. Example, the viscosity, flow rate, material rates variables and density rates variables in polymer melt, screw geometry and features, screw speed and screw type with the participation of the system against the performance of predictive control algorithm is the effect of dead time can be tested.

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