THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF THE EFFECT OF THE RADIAL CLEARANCE BETWEEN BARREL AND SCREW ON THE EXTRUDER FLOW RATE

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ABSTRACT

The influence of the radial screw clearance between barrel and screw on the extruder flow rate has been studied on the single screw, industrial, 90 mm extruder used in everyday practice as the extruder for the outer sami-conductive layer in the production of power cables insulated by XLPE. It was shown on the bases of the experimental results and the theoretical approach being accepted, that the leakage flow parts can not be neglected and that the radial screw clearance is an important parameter that should be permanently controlled in order to prevent and to stop production line rate drop.

INTRODUCTION

The aim of this paper is to present an experimental and theoretical investigations of the effect of the radial screw clearance as a part of the trybomechanical system barrel - screw - polymer on the extruder flow rate. The rise of the functional radial clearance which takes place thanks to the wearing process during the exploitation of an extruder, can greatly reduce the extruder flow rate, which, in turn, reduce the production rate of an extrusion line. It is obvious that the radial screw clearance of an extruder should be permanently controlled and known as well as its effect on the extruder flow rate.
In order to accomplish that, the experimental work was carried out on the industrial, 90 mm extruder which is being used as the extruder for the outer sami-conductive layer in the production of power cables in everyday practice of FKS, but, in this case, the polymer being extruded was chosen to be LDPE.
The experimental dates obtained in this way are the extruder Net flow rate, Drag flow rate as well as the values of the pressure and temperatures of the melt in the extruder head. In this case, the pressure of the polymer in the extruder head is assumed to be the pressure drop of the polymer in the metering section of the extruder (2, 5, 6, 7). Having these dates, the leakage part of Drag flow and the leakage part of Pressure flow, actually caused by the existence of the functional radial clearance, were determined mostly on the bases of the experimental results but, when it was necessary, the accepted theoretical approach was applied.
The theoretical approach that was accepted in this work is the “Metering section theory” based on the flat plate model of an extruder (1, 2, 3, 4).

THEORETICAL

The theoretical approach applied in this paper refers to the metering section of the plasticating extruder with shallow rectangular channels, Newtonian behavior and isothermal flow of polymer melt (1, 2, 3, 4).
Solving the partial differential equation for the velocity distribution in the down channel direction:

$$\frac{\partial P}{\partial z} = \mu \cdot \left(\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} \right) \qquad (1)$$

and the integral:

$$Q = \int_0^H \int_0^W v_z \cdot dydx \qquad (2)$$

the expression for the flow rate which includes the effect of radial flight clearance is given as follows:

$$Q_N = \alpha_{EX} \cdot N \cdot \left(1 - \frac{\delta_f}{H}\right) \cdot F_d - \frac{\beta_{EX}}{\mu} \cdot \left(\frac{\Delta P}{L}\right)\left(1 + f_L\right) \cdot F_p \qquad (3)$$

where:

$$\alpha_{EX} = \frac{\pi^2 D_b^2 H}{2} \cdot \left(1 - \frac{ep}{\pi D_b \sin\theta}\right) \cdot \sin\theta \cos\theta \qquad (4)$$

$$\beta_{EX} = \frac{\pi D_b H^3}{12} \cdot \left(1 - \frac{ep}{\pi D_b \sin\theta}\right) \cdot \sin^2\theta \qquad (5)$$

The equation (3) is the basic equation which is going to be used throughout this work. This equation suggests a linear dependence between the extruder flow rate and pressure drop in the metering section of the screw as well as the linear dependence between the extruder Drag flow rate (the first term in eq.3) and the screw speed, N.
The expression for the leakage part of Drag flow is as follows:

$$Q_{DL} = p \cdot \frac{WHV_{bz}\delta_f}{2H} \cdot F_d \qquad (6)$$

and the expression for the leakage part of Pressure flow is as follows:

$$Q_{PL} = p \cdot \frac{WH^3}{12\mu} \cdot \left(-\frac{\partial P}{\partial z} \right) \cdot f_L \cdot F_p \tag{7}$$

where f_L is the expression defined in reference 3.

EXPERIMENTAL WORK

Through this experimental work the experimental dates which will be used for determination of the leakage flow parts of the extruder were obtained and in that sense the experimental work was organized.
The measurements of the extruder Net flow rates and Drag flow rates were taken for the screw speeds of 5 (min^{-1}), 10 (min^{-1}) and 20 (min^{-1}) except the Drag flow rate which was measured for 15 (min^{-1}) too, but each experimental point was determined by measuring 3 samples of the extruder output per one minute with time gap of two minute between each measurement. The stabilization times between each two screw speeds were 15 minutes. The average value of the three measurements was taken to be the representative one. At the same time, the pressure and temperature of the polymer being extruded, both at the same location were measured and recorded.
The variation of the pressure in the extruder head was accomplished through the replacement of the dies (nozzles) in that way that the screw is stopped for a while, the nozzle (die) is changed with new one and, finally, the screw speed is set to the minimum chosen value. When the measurements are performed for each screw speed, the same procedure is repeated until every given nozzle is used. Nozzles (dies) which were used in this experimental work have inside diameters of 5,1 mm, 8,1 mm and 11,2 mm but the length of each nozzle is 195, 2 mm.

DISCUSSION

From the equation (3) after multiplication by ρ it can be seen the mass Drag flow rate is given by the following expression:

$$G_D = \alpha_{EX} \cdot N \cdot \left(1 - \frac{\delta_f}{H} \right) \cdot F_d \cdot \rho \tag{8}$$

and the mass Pressure flow by the expression:

$$G_P = \frac{\beta_{EX}}{\mu} \cdot \left(\frac{\Delta P}{L} \right) \cdot (1 + f_L) \cdot F_p \cdot \rho \tag{9}$$

The leakage part of the Drag flow can be obtained from the eq. (8):

$$G_{DL} = \alpha_{EX} \cdot N \cdot F_d \cdot \rho - G_D \qquad (10)$$

where G_D represents here the measured value of Drag flow while the expression :

$$G_{DT} = \alpha_{EX} \cdot N \cdot F_d \cdot \rho \qquad (11)$$

represents the value calculated from the accepted theoretical approach for the case of $\delta_f = 0$. In the same way the leakage part of Pressure flow can be obtained from the eq. (9):

$$G_{PL} = G_P - \frac{\beta_{EX}}{\mu} \cdot \left(\frac{\Delta P}{L}\right) \cdot F_p \cdot \rho \qquad (12)$$

where G_P represents here the value calculated from the equation (3) using the measured values of the extruder Drag flow rate and the extruder Net flow rate: $G_P = G_D - G_N$.

The second expression on the right hand side of the equation (12) represents the value of the Pressure flow, G_{PT}, calculated by the accepted theoretical approach for the case of $\delta_f = 0$.

On the bases of the experimental results, the screw characteristics for each screw speed were formed and they were presented on the figure 1.

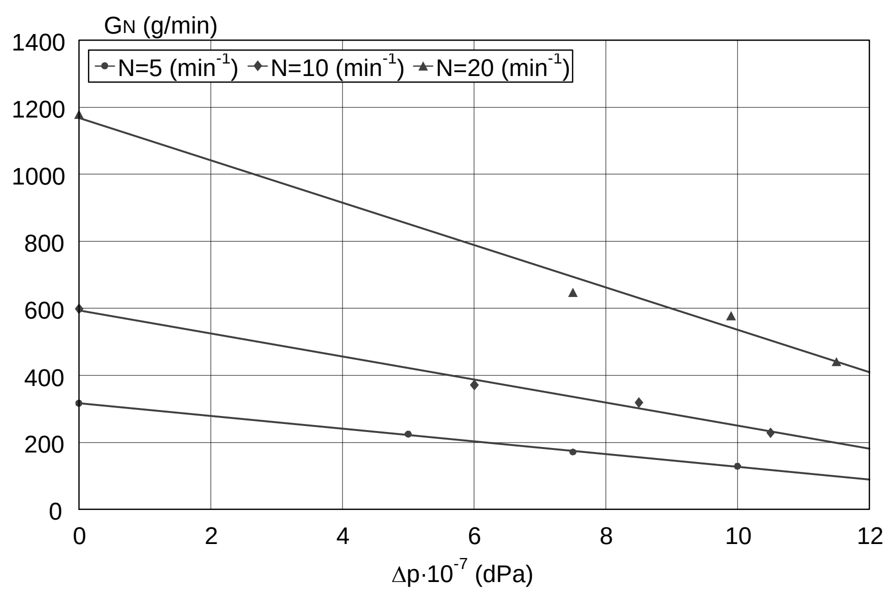

Figure 1. Screw characteristics for the experimental screw

It can be seen (Fig. 1) the screw characteristics show linear dependence between the extruder Net flow rate and the pressure drop which is in accordance with the accepted theoretical approach and it is especially pronounced at the lower screw speeds.

Experimental results show linear dependence between Drag flow rates and screw speeds which is also in agreement with the accepted theoretical approach and this dependence was presented on figure 2. On the same figure, the calculated Drag flow rates (eq. 8) as well as the leakage part of Drag flow, G_{DL}, were presented.

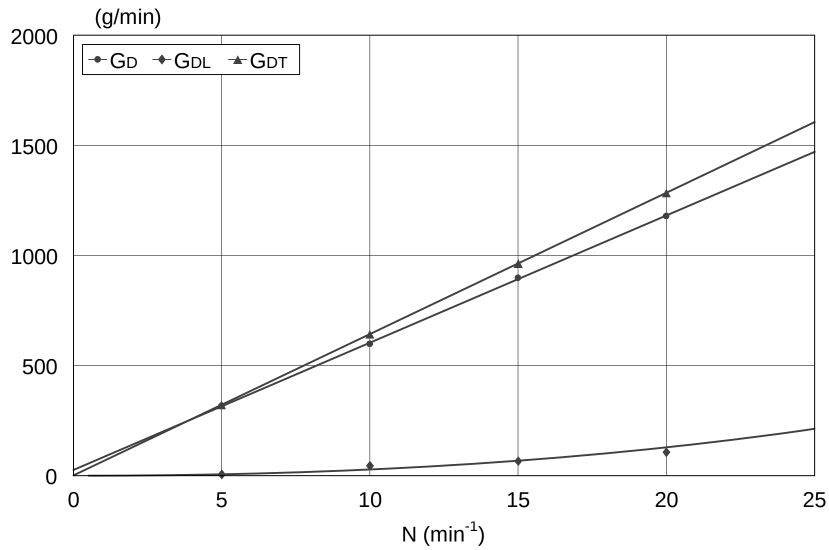

Figure 2. Linear dependence between Drag flow rates and screw speeds

Pressure flow rates, calculated on the bases of the experimental dates ($G_P = G_D - G_N$), and leakage parts of Pressure flow obtained by eq. (12), as the functions of pressure drop, were shown on figure 3 for each screw speed. It can be seen from Fig. 3 there is linear dependence between the Pressure flow rate and pressure drop which is more pronounced at the lower screw speeds but this is not the case when the leakage part of Pressure flow is concerned. It can be rather noticed the leakage parts of Pressure flow are almost constant for each screw speed (almost does not depend on the pressure drop).

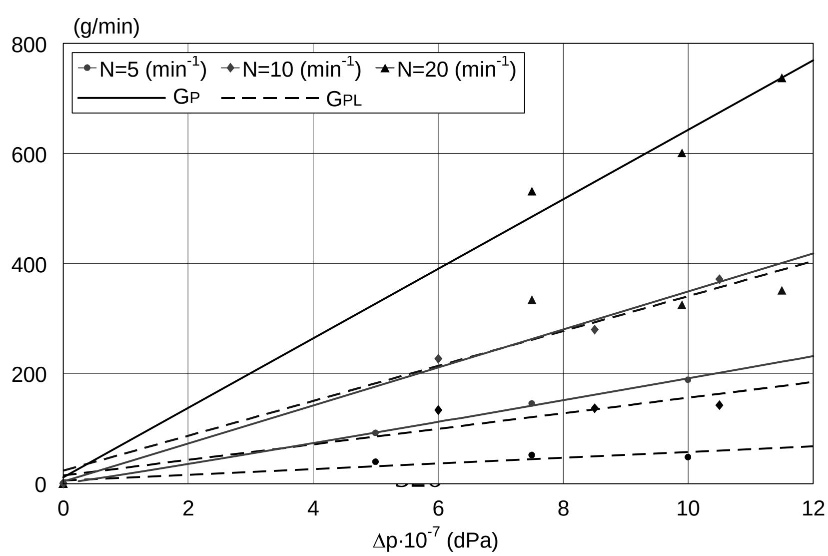

Figure 3. Pressure flow rates and leakage parts of Pressure versus pressure drop

The average Pressure flow rates, calculated for each screw speed, as well as the average leakage parts of Pressure flow together with the leakage parts of Drag flow were shown on figure 4 as a functions of screw speeds. This way of presentation seems to be reasonable especially when the leakage parts of Pressure flow are being considered for they almost do not depend on the pressure drop. It is seen the average Pressure flow rate and the leakage part of Drag flow show almost linear dependence on the screw speed but this is not the case with the leakage part of Pressure flow.

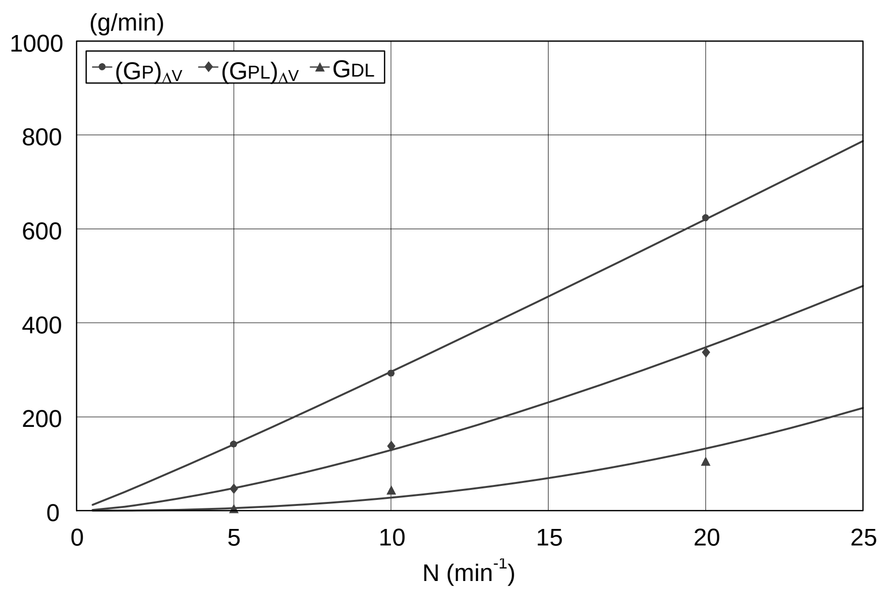

Figure 4. Dependence of the average Pressure flow rates, the average leakage parts of pressure flow and the leakage parts of Drag flow on screw speed

The fractions of the leakage flow parts with respect to the measured Net flow rate, taking the screw speed as a parameter, were shown on figure 5 as a functions of the measured pressure drop.

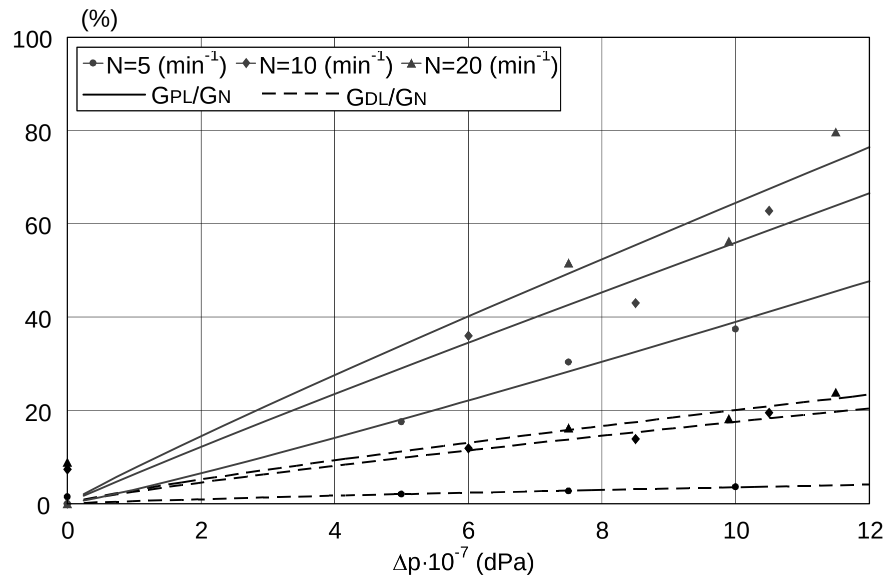

Figure 5. Fractions of the leakage parts with respect to the Net flow rate as a functions of the pressure drop

The fractions of the leakage parts of Drag flow represent the linear functions with respect to the pressure drop but this is not the case with the fractions of the leakage parts of Pressure flow except for the lowest chosen screw speed. The fractions of the leakage parts of Pressure flow are higher when the pressure drops are higher which suggests the operation with minimum possible pressure drop (the operation with the die which gives the minimum pressure drop, but, the demand for good extrudate quality, at the same time, should be satisfied).

CONCLUSION

Calculations and graphical presentations of the performed experimental and theoretical investigations show that the leakage flow parts, actually caused by the existence of the functional radial screw clearance in the system barrel - screw, can not be neglected especially when the leakage part of Pressure flow is concerned. This suggests the operation with minimum possible pressure drop, that means the die which gives the minimum pressure drop should be chosen, satisfying, at the same time, the demand for good extrudate quality.

It can be expected this effect will be more pronounced as the radial screw clearance is increasing thanks to the wearing process that takes place during the extruder operation.

The radial screw clearance is an important parameter which should be permanently and systematically controlled during the exploitation period of an single screw extruder in order to prevent and to avoid the production rate drop of an extrusion line.

NOMENCLATURE

P = pressure, ($gcm^{-1}s^{-2}$).
x = rectangular coordinate (cross channel direction), (cm).
y = rectangular coordinate (channel depth direction), (cm).
z = rectangular coordinate (down channel direction), (cm).
v_z = velocity component in the z direction, (cms^{-1}).
Q = volumetric flow rate of the extrudate, (cm^3s^{-1}).
Q_{DL}= leakage part of Drag flow, (cm^3s^{-1}).
Q_{PL}= leakage part of Pressure flow, (cm^3s^{-1}).
G_D = mass Drag flow rate, (gs^{-1}).
G_N = mass Net flow rate, (gs^{-1}).
G_P = the mass Pressure flow rate, (gs^{-1}).
H = channel depth, (cm).
W = width of the screw channel perpendicular to the flights, (cm).
N = screw speed, (s^{-1}).
F_d = shape correction factor for Drag flow, (1).
F_p = shape correction factor for Pressure flow, (1).
ΔP= pressure drop, ($gcm^{-1}s^{-2}$).
L = lenght of the metering section of the screw, (cm).
f_L = factor for leakage Pressure flow, (1).
D_b = inside barrel diameter, (cm).
e = width of the screw flights, perpendicular to the flights, (cm).
p = number of flights in parallel, (1).
α_{EX} = constant, (cm^3).
β_{EX} = constant, (cm^4).
δ_f = radial screw clearance, (cm).
μ = viscosity, ($gcm^{-1}s^{-1}$).
θ = helix angle, radians.
ρ = density, (gcm^{-3}).

REFERENCES

1. Bernhardt, E. C., "Processing of thermoplastic materials", New York, Reinhold publishing Co., 1962.
2. Fisher, E. G., "Extrusion of plastics", London, Iliffe books Ltd., 1964.
3. Z. Tadmor, I. Klein, "Engineering principles of plasticating extrusion", R. E. Krieser publishing Co., 1970.
4. Maddock, B. H., "An improved mixing-screw design", SPE Journal, July 1967.
5. Maddock, B. H., "How to predict extruder performance with polyethylene", Plastic Technol., 3, 1957.
6. Gaspar, E., "Problems and trends in europen extruder design", SPE Journal, October 1959.
7. Sackett, D. R., "Viscosity data for extruder", SPE Journal, October 1956.