ON THE DESIGN OF LONG-SLIT UNIFORM-RESISTANCE EXTRUSION HEADS

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In the manufacture of sheeting from thermoplastics by extrusion the polymer melt is fed into the forming slit by a long-slit extrusion head of the collector type (the melt is fed to the slit channel through a pipe pointing in a direction normal to the flow of the material through the slit); "fish tail" pipes are also used in which the polymer melt leaving the cylinder is distributed over the diverging slit channel.

The most labor-consuming task in designing such heads is to ensure a uniform extrusion velocity over the entire width of the head. The nonuniform flow of the material over the width of the head is due to the fact that the polymer melt has to cover parts of varying lengths. For example, Fig. 1 shows schematically a long-slit head which consists of a distributing channel (collector) and the mouthpiece. The figure shows that in this head the difference of the resistances (lengths of paths) for the elementary streamlines of the material issued through the center and through the sides of the head are not equal.

The total resistance to the flow of material through the edges of the head can be divided into the resistance to the flow of material on its path along the distributing channel and to the resistance experienced between the lips of the head. The melt leaving the head in the center (in the case being considered at the inlet) has to overcome only the resistance offered by the lips. Consequently, during an isothermal extrusion through a head with a constant slit height and constant lip dimensions (over the entire width of the head) a low resistance to the flow of material can be expected in the center of the head with correspondingly higher work of extrusion.

In order to achieve a uniform extrusion over the entire width of the head it is necessary to minimize the pressure gradient over the length of the collector. In practice this is achieved by the use of various moving (heads with throttling dampers and slides) or stationary ("fish tail" or "island" type heads) resistors which weaken the flow of the melt being extruded in the center and intensify it at the sides. These resistances are selected by adjustment during the testing of long-slit heads which makes their operation more complicated and increases the cost of their manufacture.

In papers [1-3] the crosshead-slit dies are designed by the so-called method of the uniformity index (some investigators call it the coefficient of the constancy of extrusion); the uniformity index is defined as the ratio of the discharge from the increment of length adjacent to the far end of the slit to the discharge from the increment of length adjacent to the feed port. However, a head designed by this method shows a nonuniform discharge over the width which is indicated by different indices of uniformity. It is obvious that the design of the crosshead-slit dies with a uniform resistance can only be done analytically.

Let us now consider the flow of the polymer melt through a collector crosshead-slit die (Fig. 1).

The discharge of the melt through the long slit can be expressed by the equation [4, 5]:

\[ Q_1 = \frac{cLh^{n+2}}{2^{n+1}} \left( \frac{\rho}{t} \right)^n, \]

where \( c \) and \( n \) are the rheological constants of the polymer in the power law \( dv/dn = c \tau^n \); \( t \) is the depth of the slit measured in the direction of the flow through the forming slit, cm; \( L \) is the width of the slit measured in the direction of the flow through the collector, cm; \( h \) is the height of the slit, cm; and \( \rho \) is the pressure needed to discharge the material through the head, kgf/cm².

* Deceased.
From Eq. (1) we obtain

\[ t = \left[ \frac{c b h^{\frac{n+2}{n+1}}}{2^{n+1} (n-2) Q_{sl}} \right] \left( \frac{L}{R} \right)^{\frac{n}{n-1}} \left( \frac{z}{L} \right)^{\frac{n+1}{n}}. \]  

Equation (2) shows that if the depth of the slit (lips) is proportional to the pressure of the melt at all points over the width of the head then it is possible to achieve identical extrusion rates. This means that the output per increment width of the head is constant:

\[ Q_{sl}/L = \text{const}. \]

We must find an equation which relates the depth \( t \) of lips to the coordinate \( z \) directed along the axis of the head collector. From this equation we could obtain a table of \( t = f(z) \) values needed for the manufacture of a crosshead-slit die with a uniform resistance to the flow (heads ensuring uniform extrusion over the width). It is obvious that the flow through the slit channel is equal to the flow rate in the collector. Combined consideration of the discharge through the collector and through the crosshead-slit and the assumption that the extrusion rate over the width of the head is uniform produce a differential equation which, after solving, gives the law governing the variation of the slit depth over the head width:

\[ t = t_i - \left[ \frac{(n+3) L^{n+1} h^{n+2}}{2 z R^{n+3} (n-2)} \right] \left( \frac{L}{R} \right)^{\frac{n}{n-1}} \left[ 1 - \left( \frac{z}{L} \right)^{\frac{n+1}{n}} \right]. \]

where \( t \) is the depth of the slit in any point \( z \), cm; \( z \) is the coordinate axis directed along the collector axis opposite to the direction of the flow of the melt (increases from 0 in the far end of the collector to \( L \) near the feed port); \( t_i \) is the depth of the slit in the feed-port end, cm; and \( R \) is the radius of the collector, cm. The depth of the slit \( t_i \) in the feed end can be found from Eq. (2) by substituting in it, for \( p \), the pressure at the head inlet \( p_0 \). For approximate calculations the value of \( t_i \) can be chosen arbitrarily.

In designing crosshead-slit extrusion dies with a uniform resistance by the variation of the depth of the slit the following calculation procedure can be recommended. If the values of \( h \), \( p_0 \), and \( Q_{sl} \) are known, we assumed the length of head collector using the width of the sheet being extruded. Thereupon we determine the rheological constants \( c \) and \( n \) of the polymer at the processing temperature. Then, by substituting the values of \( p_0 \), \( Q_{sl} \), \( h \), \( n \), \( c \), and \( L \) into Eq. (2) we find the depth of the slit at the feed port end \( t_i \). As the next step we determine from the equation of the polymer melt flow through a circular channel [1, 2], the radius of the head collector (arbitrary values can be used) and, after substituting the values of \( R \), \( h \), \( n \), \( L \), and the increasing values of \( z/L \) into Eq. (3), we obtain the following values of the slit depth \( t \) in any point of \( z \). This calculation produces the values \( t = f(z) \) needed for the manufacture of the die.

Equation (3) shows that with all other dimensions of the head remaining the same the variation of the slit depth depends on the value of the rheological exponent \( n \). In order to determine the law for the variation of \( t \) over the head width as a function of \( z \) the authors of the present paper designed a uniform-resistance crosshead-slit die. For comparing the equalizing ability of the crosshead-slit die at a constant slit depth in the feed zone we calculated \( t \) with increasing values of the rheological exponent \( n \). The results of the calculation are given in Fig. 2.

This figure shows that with all other conditions remaining equal an increase of the exponent \( n \) causes a deterioration of the equalizing ability of the head (the values \( t/t_i \) over the width of the head decrease). Thus, by varying the depth of the slit it is possible to equalize the resistance to the discharge of the polymer melt. It is obvious that exactly the same effect can be obtained by varying the height of the slit.