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Research on the micro-extrusion characteristic of mini-screw in the screw extruding spray head

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Abstract Extrusion production capacity is a chief factor of measuring how good the extruding spray head of Fused Deposition Modeling (FDM) is. The main geometrical parameters of screw and barrel (the active length of screw, the diameter of screw, the helix angle, the width of screw arris, the depth of screw channel, the clearance between screw, and barrel, etc.,) and the processing parameters such as screw speed, the pressure of nozzle are closely related to extrusion production capacity. In this article, the spray head is designed to be a special mini-screw extruding spray head and the mini-screw is different from common screw. The characteristics of the mini-screw in the research are that it is small in size, with narrow screw channel and wide screw arris structurally. Based on hydrodynamics and melt conveying theory, the micro-extrusion characteristics of mini-screw used in the screw extruding spray head of FDM were discussed in detail in this article. The relationship between extrusion production capacity and the main geometrical parameters of screw and barrel and the processing parameters is researched. Theoretical analysis was performed to find out the quantitative relationships between production capacity of extrusion and main parameters (the screw speed, main geometrical size of screw, the clearance between screw and barrel, and the pressure of nozzle, etc.,) so that the theoretical guidance on the design of spray head with mini-screw could be provided. The characteristic curves of mini-screw and nozzle are analyzed to find out the jointed work point of spray head. The main factors influencing extrusion capacity of nozzle are discussed in this article. Furthermore, the development of FDM will be promoted and the micro-extrusion theory would be more perfect by the research.

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Introduction

In the processing of Fused Deposition Modeling (FDM), which belongs to the rapid prototyping and manufacturing technology, the configuration design of spray head directly affects the process of FDM and the quality of FDM prototypes [1–3]. Therefore, the spray head is not only the key component of FDM, but also an important part of FDM system.

The spray head of FDM includes two parts [4, 5]: one is the material delivering part, the other is the plasticizing extrusion part. At present, there are two main kinds of spray head that is used for the filar material in FDM, one is ram-extruding spray head, and the other is screw-extruding spray head [5]. The pressure which is needed for extrusion should be high, since the nozzle aperture is usually small in size. In the ram-extruding spray head, the extrusion pressure is always not high enough to extrude continuously, which lead to the process of FDM interrupted. While using the screw-extruding spray head, the plastic melt in the spray head must be under strong pushing effect of screw and extruding, which can be used to solve the problem of less pressure existed in the ram-extruding spray head.

The construction of mini-screw extruding spray head

The spray head is designed into a complex which combines ram with screw, since the raw material belongs to filar type (its diameter is about 1.8 mm), its structural schematic diagram is shown in Fig. 1. It uses the un-melted part of filar material as a ram to push melted part of filar material moving forward, meanwhile makes itself plasticized completely. After the melt material is pushed into the screw channel of mini-screw (its diameter is 10 mm), the screw will implement the uniform

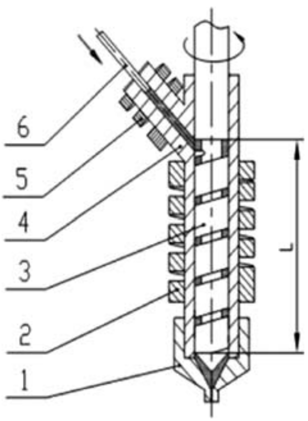
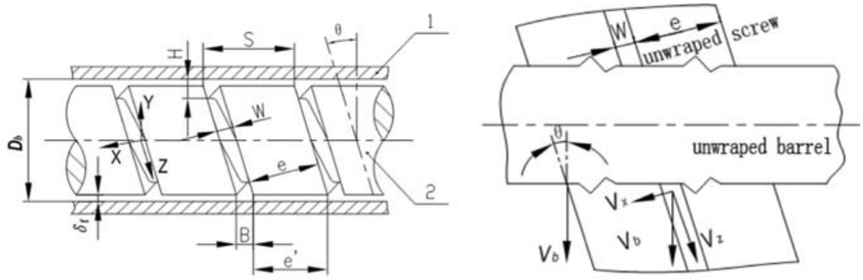


Fig. 1 The structural schematic diagram of mini-screw extruding spray head. *1* Nozzle, *2* Heater, *3* Mini-Screw, *4* Barrel, *5* Heater, *6* Filar material; L-Active length of screw



(a) **(b)**

Fig. 2 **a** The geometrical parameters of screw channel, **b** Ledgement of mini-screw. *1* Barrel, *2* Mini-screw D_b Bore of barrel, δ_f Clearance between screw arris and wall of barrel, *H* Distance from thread's root to internal surface of barrel, *S* Screw-pitch, *W* Width of screw channel, *B* Axial width of screw channel, *e* Normal width of screw arris at top of screw thread, e' Axial width of screw arris at top of screw thread, θ Screw thread angle, V_b Relative motion speed between developed barrel surface and developed screw surface, V_x Velocity distribution of melt in the direction vertical to screw channel, V_z Velocity distribution of melt in the direction of screw channel

plasticization and steadily delivery of melt, raise the melt pressure, and extrude the melt through nozzle with a stable pressure. Meanwhile, the screw's shearing effect on melt is very small.

The extrusion volume of spray head is small, to avoid material decomposition, which is caused by long-time heating, the melt cannot be in screw for a long time. The active length of screw cannot be too long. The active length of screw inside the spray head is *L*, according to its effect to melt material, it is similar to the metering zone of common screw. In addition, the screw channel of mini-screw is also different from common screw, as shown in Fig. 2a. It is a deep and narrow, screw arris is more wide, which makes it achieve the purpose of decreasing the area that melt contacts the barrel. Unlike the mini-screw, the common screw plasticizes the plastic inside the screw channel by shearing and external heater, so the screw channel must be wide and shallow to impact materials to shear and transfer heat. Besides that, to decrease leak flow, the common screw usually uses narrow screw arris. At present, most of the researches on mini-screw extrusion capacity are based on the common screw. Yan et al. [6] reported that extrusion capacity was the key parameter of influencing the precision and efficiency through a mass of experiments. The main conclusions from these studies are that the relationship between screw diameter and extrusion capacity was discussed and rational screw diameter range of the spray head was brought forward, which have provided some guidance for choosing the diameter. Liu et al. [7, 8] did some work about the relationship of screw parameters, extrusion capacity, and temperature, etc. The result showed that the velocity distribution of the melt in screw channel and the formula of extrusion capacity were attained, which did give a great guidance for our design and research of screw-extruding spray head. The researches on particular mini-screw are very few. STRATASYS Inc. invented the screw extruding spray head with a conical screw [9] which had the same function as the particular mini-screw. Owing to the particularity of the mini-screw, it is very necessary to make research on it.

Figure 2 shows the geometrical parameters of screw channel and ledgement of mini-screw. Based on hydrodynamics and melt conveying theory, which was drawn from the characteristics of mini-screw illustrated above, this article makes research on the micro-extrusion characteristics of mini-screw used in screw extruding spray head. Then according to the screw parameters (including the diameter of screw, the depth of screw channel, and the clearance between screw and barrel, etc.,) and the processing parameters (including screw speed, the pressure of nozzle, etc.), the quantitative relationship between production capacity of extrusion and these parameters will be deduced.

The research on relationship between extrusion production capacity and relative parameters

Deduction of basic equation of extrusion production capacity

In order to make research more convenient, the melt is considered as isothermal Newtonian fluid (its viscosity is a constant). The schematic diagram about the geometrical parameters of screw channel and ledgement of mini-screw used in screw extruding spray head are shown in Fig. 2.

In Fig. 2a, the melt is delivered forward along screw channel. According to the continuity equation, the production capacity of extrusion can be obtained by integrating V_z (velocity distribution of melt in the direction of screw channel) with channel width and channel depth, namely

$$Q = P\int_{l0}^{H}\int_{0}^{W} V_z \mathrm{d}y\mathrm{d}x \tag{1}$$

where P is the number of screw thread, in this research case, the screw is a single thread screw, so $P = 1$.

In order to calculate V_z, we could suppose that the barrel is rotating, and calculate V_{bz} [10, 11] (melt component velocity paralleling to the screw channel in the model of drag flow, when the screw is static), and then calculate V_z through the relationship between V_z and V_{bz}, this process is comparatively simple. The relationship between V_z and V_{bz} is shown as follows [6, 7]:

$$\begin{aligned}\frac{V_z}{V_{bz}} = \frac{4}{\pi}\sum_{i=1,3,5}^{\infty}\frac{\sinh(i\pi Y/W)}{i\sinh(i\pi H/W)}\sin\left(\frac{i\pi X}{W}\right) - \left(\frac{1}{2\eta}\frac{\partial p}{\partial Z}\frac{H^2}{V_{bz}}\right)\cdot \\ \left[\left(\frac{Y}{H}\right)^2 - \frac{Y}{H} + \frac{8}{i^3}\sum_{i=1,3,5}^{\infty}\frac{\cosh\left[i\pi\frac{W}{H}\left(\frac{X}{W}-\frac{1}{2}\right)\right]}{i^3\cosh\left(\frac{i\pi W}{2H}\right)}\cdot\sin\left(\frac{i\pi Y}{H}\right)\right]\end{aligned} \tag{2}$$

Substituting Eq. 2 into Eq. 1, and integrating Eq. 1, we get

$$Q = \frac{V_{bz} WH}{2} F_d + \frac{WH^3}{12\eta}\left(-\frac{\partial p}{\partial Z}\right) F_p \quad (3)$$

where the first part is the positive flow, and the second part is inverse flow caused by nozzle pressure. F_d and F_p is the shape factor of drag flow and pressure flow.

When *H/W* is small ($W \geq 10H$), the melt flow in screw channel can be approximately considered as a flow during two infinity boards, which fits dual flat-panel model. When *H/W* is big (e.g., $H/W = 1$), the velocity of each screw channel surface point changes not only along with its vertical position on screw channel height but also with its horizontal position on screw channel width *W*, i.e., it will be influenced by side wall of screw arris. Shape factor F_d and F_p are the influence coefficient of extrusion production capacity during two infinity boards caused by screw arris, the values of both of them could be expressed by the following equations [11].

$$F_d = \frac{16W}{\pi^3 H} \sum_{i=1}^{\infty} \frac{1}{(2i+1)^3} \tanh\left[\frac{(2i+1)\pi H}{2W}\right] \quad (4)$$

$$F_p = 1 - \frac{192H}{\pi^5 W} \sum_{i=1}^{\infty} \frac{1}{(2i+1)^5} \tanh\left[\frac{(2i+1)\pi W}{2H}\right] \quad (5)$$

According to the above equations, we know that F_d and F_p are decided by the value of *H/W* only.

On the right of Eq. 3, the first part represents the drag flow Q_d; and the second part represents the pressure flow Q_p, this part could be positive, negative, or zero, which depends on $(-\partial p/\partial Z)$ [12, 13]. In this equation, the influence of clearance between screw arris and barrel is ignored. If this influence is considered, through proper deduction [11], there will be

$$Q = \frac{WHV_{bz}}{2}\left(1 - \frac{\delta_f}{H}\right) F_d + \frac{WH^3}{12\eta}\left(-\frac{\partial p}{\partial Z}\right)(1 + f_L) F_p \quad (6)$$

where $(1 + f_L)$ is the modifying coefficient, the expression of f_L is shown below [7]:

$$\begin{aligned} f_L &= \left(\frac{\delta_f}{H}\right)^3 \frac{e}{W}\frac{\eta}{\eta_f} + \frac{\left(1 + \frac{e}{W}\right)\left[\frac{6\eta V_{bz}(H-\delta_f)}{H^3(\partial p/\partial Z)} + \frac{1+e/W}{\tan^2\overline{\theta}}\right]}{1 + \frac{\eta_f}{\eta}\left(\frac{H}{\delta_f}\right)^3 \frac{e}{W}} \\ &\cong \left(\frac{\delta_f}{H}\right)^3 \frac{e}{W}\frac{\eta}{\eta_f} + \frac{\left(1 + \frac{e}{W}\right)\left[-\frac{Q_d}{Q_p} + \frac{1+e/W}{\tan^2\overline{\theta}}\right]}{1 + \frac{\eta_f}{\eta}\left(\frac{H}{\delta_f}\right)^3 \frac{e}{W}} \end{aligned} \quad (7)$$

where $\overline{\theta}$ is the average screw thread angle; η_f is the average viscosity of melt in the clearance between screw arris and barrel; η is the viscosity of melt inside screw channel.

$\lim_{\delta_f \to 0} f_L = 0$. If $\delta_f = 0$, the Eq. 6 will be transformed into Eq. 3. If the pressure gradient is replaced with axial pressure drop, i.e.,

$$-\frac{\partial p}{\partial Z} = -\frac{p_2 - p_1}{L}\sin\overline{\theta} \tag{8}$$

with

$$W = \pi D_b \tan\theta_b \cos\overline{\theta} - e \tag{9a}$$

$$W = B\cos\overline{\theta} \tag{9b}$$

where θ_b is the screw thread angle at top of screw arris.

Thus, substituting $V_{bz} = V_b \cos\theta_b = \pi D_b n \sin\theta_b$ [11] and Eq. 8, 9a into Eq. 6, we get

$$Q = \alpha n F_d \left(1 - \frac{\delta_f}{H}\right) + \frac{\beta}{\eta} F_p \left(\frac{p_1 - p_2}{L_3}\right)(1 + f_L) \tag{10}$$

where p_1 is the melt pressure at top of screw; p_2 is the melt pressure of screw thread starting. α and β are the constants of positive flow and inverse flow, respectively, and the expressions of the two are shown below:

$$\alpha = \frac{\pi}{2} D_b^2 H \left(\frac{\cos\overline{\theta}}{\cos\theta_b} - \frac{ep}{\pi D_b \sin\theta_b}\right)\sin\theta_b \cos\theta_b \tag{11}$$

$$\beta = \frac{\pi}{12} D_b H^3 \left(\frac{\cos\overline{\theta}}{\cos\theta_b} - \frac{ep}{\pi D_b \sin\theta_b}\right)\sin\theta_b \sin\overline{\theta} \tag{12}$$

If the screw channel is shallow, angle θ could be assumed as a constant, the two equations above could be simplified.

In Eq. 9a and 9b, if the influence of extrusion production capacity caused by clearance is considered as another item of this equation, we could get the rough formula to calculate the production capacity of extrusion as follows:

$$Q = \alpha n F_d \left(1 - \frac{\delta_f}{H}\right) - \frac{\beta}{\eta} F_p \left(\frac{p_2 - p_1}{L}\right)(1 + f_L) - \frac{\pi^2 D_b^2 \delta^3 \tan\theta}{10W}\left(\frac{p_2 - p_1}{\eta_f L}\right) \tag{13}$$

If let

$$\gamma = \pi^2 D_b^2 \delta^3 \tan\theta / 10W \tag{14}$$

Equation 13 could be written to

$$Q = \alpha n F_d \left(1 - \frac{\delta_f}{H}\right) - \left[\frac{\beta}{\eta} F_p (1 + f_L) + \frac{\gamma}{\eta_f}\right]\left(\frac{p_2 - p_1}{L}\right) \tag{15}$$

where γ is the constant of leak flow.

Let Eq. 15 be written as

$$Q = Q_d - Q_p - Q_L$$

In this equation, each item of the right side represents the positive flow, the pressure flow, and the leak flow, respectively. In this article, every relative parameter is known, so the relationship between extrusion production capacity and relative parameters could be obtained by selecting different parameters.

Relationship between extrusion production capacity and relative parameters

If the clearance between screw and barrel is ignored, that is $\delta_f = 0$ mm, the bore of barrel D_b will be equal to external diameter of screw D_s, i.e., $D_b = D_s = 10$ mm $= 10^{-2}$ m; the active length of screw is $L = 41$ mm $= 0.041$ m. The approximate depth of screw channel which from screw thread root to barrel internal surface is $H = 1.8$ mm $= 1.8 \times 10^{-3}$m.

The diameter of screw root:

$$D_s' = D_b - 2H = 10 - 2 \times 1.8 = 6.4 \text{ mm} = 6.4 \times 10^{-3}\text{m}.$$

The average diameter of screw:

$$\overline{D} = D_b - H = 10 - 1.8 = 8.2 \text{ mm} = 8.2 \times 10^{-3}\text{m}.$$

The screw lead:

$$l = D_b = 10^{-2} \text{ m}.$$

The screw thread angle at top of screw arris:

$$\theta_b = \arctan\frac{l}{\pi D_b} = \arctan\frac{D_b}{\pi D_b} = 17^\circ 40'.$$

The screw thread angle at the root of screw:

$$\theta_s = \arctan\frac{l}{\pi D_s'} = \arctan\frac{10}{\pi \times 6.4} = 26^\circ 26'.$$

The average screw thread angle of screw:

$$\overline{\theta} = \arctan\frac{l}{\pi \overline{\overline{D}}} = \arctan\frac{10}{\pi \times 8.2} = 21^\circ 13'.$$

The screw pitch:

$$s = l = 10 \text{ mm} = 10^{-2} \text{ m}.$$

The axial width of screw channel:

$$B = 1.8 \text{ mm} = 1.8 \times 10^{-3} \text{ m}.$$

The width of screw channel:

$$W = B\cos\theta = 1.8 \times 0.9528 = 1.72 \text{ mm} = 1.72 \times 10^{-3}\text{m}.$$

The normal width of screw arris at the top of screw thread:

$$e = l\cos\overline{\theta} - W = 10 \times 0.9322 - 1.68 = 7.64 \text{ mm} = 7.64 \times 10^{-3} \text{ m},$$

and H/W = 1.8/1.72 = 1.04.

Substituting $H/W = 1.04$ into Eqs. 4 and 5, respectively, we get $F_d = 0.47$, $F_p = 0.38$. The angle θ cannot be assumed as a constant for this screw is single thread one, and the screw channel is not shallow. Equations 11 and 12 could be selected to calculate, got

$$\alpha = 0.46 \times 10^{-7} \text{ m}^3; \quad \beta = 0.03 \times 10^{-11} \text{ m}^3.$$

As $\delta_f = 0$ mm, $e = 7.64 \times 10^{-3} m$, so $f_L = 0$, $(1 - \delta_1/H) \approx 1$, $\gamma = 0$.

Substitute above parameters into Eq. 15, it would be

$$\begin{aligned} Q &= \alpha n F_d - \frac{\beta}{\eta} F_p \left(\frac{p_2 - p_1}{L} \right) \\ &= 0.22 \times 10^{-7} n - \frac{0.01 \times 10^{-11}}{\eta} \left(\frac{p_2 - p_1}{0.041} \right) \end{aligned}$$

The jointed work point of spray head

The characteristic curve of mini-screw

According to Eqs. 11, 12, and 14, we know that α, β, and γ are only related to the screw size. Assuming melt viscosity in clearance or screw channel is the same, the Eq. 13 can be written as

$$Q = \alpha n - (\beta + \gamma) \Delta p / \eta L \tag{16}$$

Apparently, the Eq. 16 is a linear equation. By mapping on a Cartesian coordinate system coordinating with Q and Δp, we will get a series of Q–Δp lines with different rotate speed n. The slopes of these lines are $(\beta + \gamma)/\eta L$.These series of lines express the geometrical characteristic of mini-screw, so it is called the characteristic curve of mini-screw.

When the filar material is ABS, with its temperature in 250° and its rate of shear ς in 3,000 s^{-1}, it can get $\eta = 900P = 90 Pa \cdot s$ [10]. According to calculating and mapping with the design data, there will be

$$\begin{aligned} Q =& 0.46 \times 10^{-7} n - \frac{0.03 \times 10^{-11} \Delta p}{90 \times 41 \times 10^{-3}} \\ =& 0.46 \times 10^{-7} n - 8.1 \times 10^{-14} \Delta p \end{aligned}$$

Let $n_1 = 60$ r/min $= 1$ r/s; $n_2 = 50$ r/min $= 0.83$ r/s; $n_3 = 40$ r/min $= 0.67$ r/s, respectively, we will get the characteristic curves of mini-screw shown as Fig. 3.

The melt delivered by the screw must be extruded through nozzle. Therefore, both the extrusion production capacity of mini-screw and the extrusion production capacity of the nozzle should be discussed.

The characteristic curve of nozzle

In the structure of FDM spray head, the approximate shape of nozzle is the same as the one shown in Fig. 4.

Based on the capacity equation of laminar flow in hydrodynamics, the capacity of melt, which is extruded from nozzle, can be calculated [11, 14]. The equation can be simplified as below:

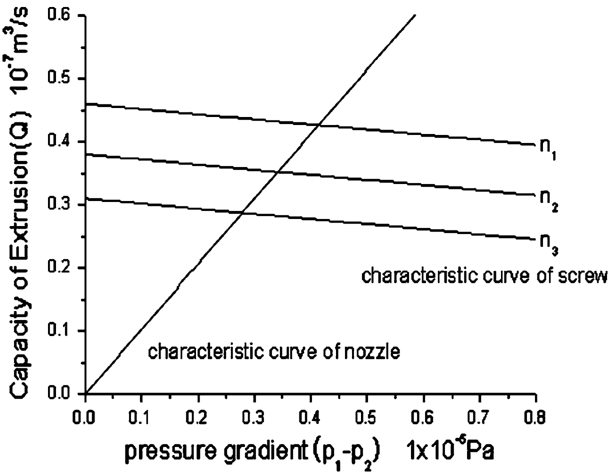


Fig. 3 The jointed work point of spray head

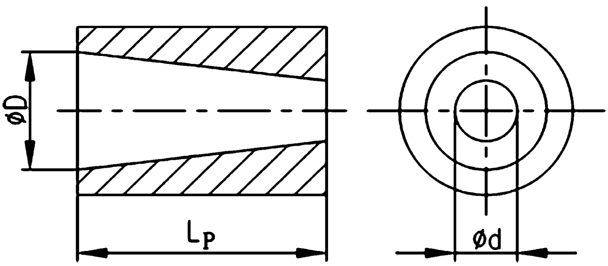


Fig. 4 The approximate shape of nozzle.ϕD Bore of nozzle connecting with barrel, ϕd Bore of nozzle exit, L_p Length of nozzle

$$Q = K\Delta p_{\mathrm{p}}/\eta \tag{17}$$

where Δp_{p} is the pressure gradient in nozzle; K is the constant of resistance in nozzle, it is only concerned with geometrical parameters of nozzle. According to the structure of nozzle shown in Fig. 4, the equation for calculating parameter K is founded as below [14]:

$$K = \frac{3\pi D^3 d^3}{128 L_{\mathrm{p}}(D^2 + Dd + d^2)} \tag{18}$$

If $D = 16$ mm, $d = 0.3$ mm, and $\mathrm{L_p} = 11$ mm, we get:

$$K = 2.87 \times 10^{-12} m^3$$

$$K/\eta = 2.87 \times 10^{-12} \div 90 = 3 \times 10^{-14} (Pa \cdot s)^{-1}$$

The Eq. 17 is also a linear equation, of which the slope is K/η. The line is called the characteristic curve of nozzle because it presents the characteristic of nozzle, which is shown in Fig. 3. From Eq. 17, it can be found when $\Delta p_{\mathrm{p}} = 0$, $Q = 0$. The characteristic curve of nozzle is a line through origin.

If Eq. 17 is written to $\Delta p_{\mathrm{p}}/\eta = Q/K$, and substituting it into Eq. 16 while the pressure difference in Eq. 16 is replaced by the pressure gradient of nozzle Δp_p (it would cause a little error), we have:

$$Q = \alpha n[1 + (\beta + \gamma)/(KL)] \tag{19}$$

Let Eq. 17 be equal to Eq. 16, we get:

$$\Delta p_p = \frac{\alpha n \eta}{K + (\beta + \gamma)/L} \tag{20}$$

An important relationship can be found from Eqs. 9a, 9b and 20. That is, Q is proportional to n, and Δp_p is also proportional to $n\eta$. Therefore, characteristic curves of screw and nozzle in Fig. 3 can be drawn based on this relationship. The curves which show the important relationship on n–K–Δp_p–Q are important for practical prototyping of FDM technology.

Based on the characteristic curve of nozzle in Fig. 3, it is easily found that higher the pressure of nozzle is, more the melt (Q) is extruded from nozzle. Based on characteristic curve of screw, Q decreases when Δp increases. When the pressure of nozzle increases both drag flow and leak flow would be increased, but Q reversely decreases. Therefore, extrusion production capacity is affected by both characteristic curve of screw and characteristic curve of nozzle.

Actually, most polymer melt are non-Newtonian and the spray head is not working under the isothermal condition, so the viscosity is not constant. Therefore, the curve of Δp–Q should be a curve but not a line. If the viscosity (η) in equation above is substituted by average value of effective viscosity (η_{a}), the new equations and the jointed work points, which are more close to practical process, can be found.

Main factors influencing extrusion capacity of nozzle

Relationship between geometrical parameters and extrusion capacity

Based on equations about capacity of extrusion, geometrical parameters of screw have the effect on the capacity.

(1) Relationship between diameter of screw (D) and capacity: based on Eqs. 11 and 13, Q is nearly proportional to the square of D, namely, when D increases, Q would be increased obviously. Its effect is much more than the effect of n on Q.
(2) Relationship between depth of screw channel (H) and capacity: this relationship is complex. Positive flow (Q_{d}) is proportional to H, while pressure flow is proportional to the cube of H. Obviously, an over deep depth of screw channel is not good for capacity, and it is also proved that there should be an optimal depth of screw channel. Moreover, before the depth is chosen, the parameters (e.g., resistance in nozzle) should be considered.
(3) Relationship between the active length of screw (L) and capacity: based on Eq. 13, pressure flow and leak flow have an inverse ratio with L. When L increases, pressure flow and leak flow are decreased, but the total capacity is increased.

Relationship between rotate speed of screw and extrusion capacity

According to Eq. 19, the rotate speed of screw (n) is proportional to extrusion capacity (Q). Namely, Q is decided by both the rotate speed and geometrical parameters of nozzle and screw. It was proved in practical process that in some range rotate speed, the extrusion capacity is proportional to rotate speed of screw. This relationship is worthwhile in practice. It is one of the most important methods to increase capacity of extrusion.

Relationship between clearance (δ_f) and extrusion capacity

According to Eq. 14, capacity of leak flow is proportional to cube of clearance (δ_f), namely, if δ_f increased, Q would decrease obviously.

Relationship between pressure of nozzle and extrusion capacity

According to Eq. 13, positive flow is independent of pressure difference ($p_2 - p_1$), but both pressure flow and leak flow are proportional to ($p_2 - p_1$). Therefore, it would decrease extrusion capacity when Δp is increased.

Conclusions

Based on hydrodynamics and melt conveying theory, the micro-extrusion characteristics of mini-screw used in screw extruding spray head was researched in detail in this article. It was found that the extrusion production capacity was affected by both characteristic curve of screw and characteristic curve of nozzle. Based on characteristic curve of screw, Q decreases when Δp increases. There are some factors that affect characteristic curve of screw, such as rotate speed of screw (n), depth of screw channel (H), active length of screw (L), the pressure difference between top of screw, and screw thread start (Δp), etc. These factors should be considered during practical design and application. In addition, during the calculation in this article, the temperature of barrel and nozzle is supposed to be constant. However, the shape of characteristic curves and jointed work point would also be changed when the temperature changed. This process should be a direction for further studies in the future.

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