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Analytical Engineering Designs for Twin Screw Food Extruder Dies

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***Abstract* – In this work, two types of die designs were presented. The designed dies were produced, mounted on food extruder and used for several experiments in our laboratory. The dies differ in shape, length and diameter. Some of the die design considerations and extrusion process optimization parameters employed include: the throughput of the extruder, desired shape, size and uniformity of the extrudate, the relationship between the flow and pressure drop in the die and the relationship between shear rate and viscosity of the food dough. Specific die design considerations also include: die nozzle dimensions such as diameter and length, and number of die hole, ratio of die length to diameter (L/D ratio) and flow, deformation and temperature relationship. This will be the first time that a systematic design work on dies for food extruder is being carried out and reported. The designed dies in this work will be able to handle food dough mostly cereal flours, the die nozzles are circular, nozzles diameters range from 2.5 – 5 mm and nozzle lengths range from 14 – 90 mm. The dies are designed for twin screw extruder screw diameter of 50 –60 mm, extruder output of 30 – 50 kg/h and 100 – 300 rpm screw speeds. The dies were able to withstand temperature of 250 ^{0}C and up to 12 MPa of pressure as frequently experienced in food extrusion processes.**

***Keywords* – Design, Dies, Extruder, Food.**

I. Introduction

The design of food extruder die is very critical to food extrusion operation for it affects the shape of the resulting products and operation of the extruder. The die consists of the land and the interconnecting section. The shape of the die opening determines the shape of the extrudate.

Design criteria for shape control, flow uniformity and pressure distribution are often determined by trial and error, calculations are rarely performed. Designs are based mainly on experience and where calculations are made, they are only to ensure the safe resistance of the die to the desirable external and internal loads (Farrel, 1971; Rauwendaal, 1986). In extrusion process, very complicated flow processes take place in the die and the calculation are extremely complicated and unsystematic (Harmann and Harper, 1974; Adekola, 1999). Rheological and thermodynamic dimensioning has to be carried out for the design of die because it relates the mechanical aspect of the design to biochemical aspect of food (Adekola, et al, 1998).

Most die cross sections used in food extruder are circle, slits and annuli. The operating characteristics of food extruder are determined by combining the extruder flow with that of the die at the die end. Assuming that the flow through the die is laminar, Newtonian and using Hagen Poiseulle equation, the rate of flow, Q through orifices of various shapes, neglecting entrance and exit losses can be calculated (Adekola et al, 1998; Tadmon and Klein, 1969).

$$Q = K\frac{\Delta P}{\mu_d} \tag{1}$$

Where, K is the geometric constant depending on type of die opening, ΔP is the pressure drop across die, and μ_d is the viscosity of the dough at die. For some cross-sections, K is given as:

$$\text{Circle:} \quad K = \frac{\pi R^4}{8L_d} \tag{2}$$

where R is the radius and L_d is the length of die

It is common to assume no pressure drop effect at the die end for most analysis of food extruder die. This is contrary to the theory of fluid dynamics, which stipulates that significant pressure drops occur at the constriction at the entrance of the die and the expansion at the exit. Both radial and longitudinal expansions are required to fully characterize the expansion process (Tadmor and Klein, 1970).

Extrusion puffing is caused by the formation and release of water vapor at, or near the die exit. The size and rate at which vapor bubbles form and travel to the surface is a function of moisture content, die pressure, die temperature, residence time in the die, swelling pressure and rheological properties (Yacu, 1990). Reported works on correlation between dough rheology, die geometry and operating conditions to die swell and cellular structure of the final extrudate are very few (White, 1990)

Most food extruder dies usually have small L/D ratios, thereby making it difficult to measure accurately the pressure gradient over their length. Increasing L/D on food extruder die will alter the process history giving incorrect rheological information (Sohkey et al, 1997).

Detailed theoretical considerations and calculations used for this food extruder dies design have been documented (Adekola, 1999).

II. Design Considerations

The important design consideration for twin screw food extruder had been suggested (Adekola and Ma, 1999). The following considerations are important in the design and operation of food extruder die.

1. The throughput of the extruder. There has to be correlation between the capacity of the extruder and the ability of the die to satisfy the production requirements. Otherwise, there may be clogging at the die end. The

effect is excessive pressure at the die end, which might results in extruder improper operation.

2. The desired shape and uniformity of the extrudate has to be ensured. Appropriate land length will ensure uniform resistance at various die cross-sections.
3. The relationship between flow and pressure drop and the relationship between shear rate and viscosity are essential in the design of extruder die. The pressure drop at the die entrance for viscoelastic fluid is far greater than the pressure drop at the entrance for Newtonian fluid of nearly the same viscosity.
4. Another important consideration in the design of the die is the effect of die nozzle L/D (die nozzle length to diameter ratio). Expansion volume depends largely on die dimensions.
5. Design of food extruder also involves selecting the length and number of die hole. This is important to meet production capacity and quality. In this case, the operating pressure for the extruder and maximum shear stress in the die must be known in addition to the knowledge of physical properties of the raw material and extruded product.
6. The flow, deformation, and temperature relationship is also important for consideration in extruder die design.

Based on the above design considerations, two die geometries were designed and tested. The sketches of the die geometries are shown in Fig. 1 and Fig. 2.

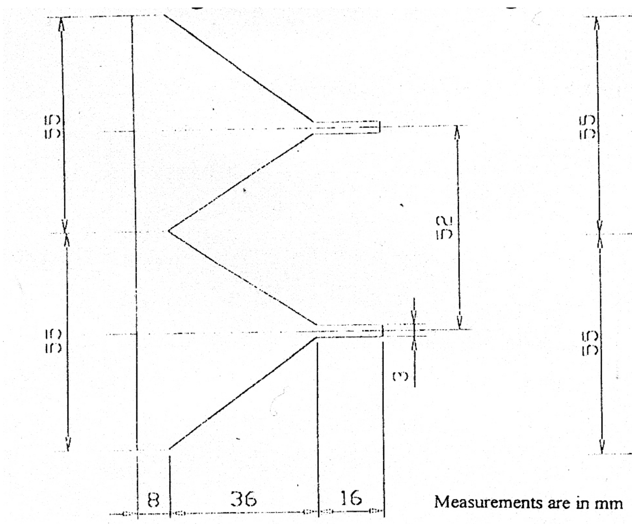

Fig.1. Extruder die (Geometry 1)

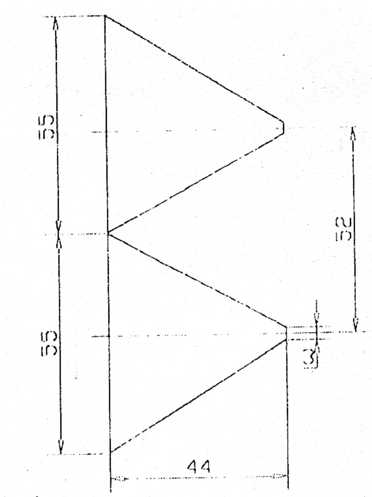

Fig.2. Extruder die (Geometry 2)

The characteristics of the designed dies are as follow:

1. The dies were designed to handle food dough from cereal flour.
2. The die shape is cylindrical and the die hole is circular since most of the products to be extruded are circular in nature.
3. The die nozzle diameter ranges from 2.5-14mm and the die length ranges from 44-69 mm.
4. The dies are designed for twin screw extruder for a single screw diameter of between 50 and 60 mm.
5. The extruder throughput ranges from 30 to 50 kg/hr for screw speeds between 100 to 300 rpm.
6. The dies are designed to withstand temperature of up to 250 ^{0}C and a pressure of up to 12 MPa.

III. Design Calculations and Analysis

The calculation procedures is similar for the two geometries, therefore further computation will be limited to geometry 1. The calculations are divided into three namely i) optimization of the land length ii) calculation of the pressure drop iii) determination of number and length of dies.

A. Optimization of the Land Length

The importance of optimizing the die land length is to ensure uniformity of extrudate and to reduce the resistance of the die to the flow of dough. The designed die can then be modified to fit the optimum value. Mathematically, the relationship between pressure drop and length of land section is linear. The mathematical procedure is as follows:

a) Calculate the quantity of melt flowing through the trapezoidal part of the circular die, Q_{tr} and the cylindrical part, Q_{cy} :

$$Q_i = \frac{Q}{\sum F} F_i \qquad (3)$$

where Q_i is the flow rate through the i-th part, mm^3/s, F_i is the area of i-th part, mm^2, and Q is the total quantity of melt flowing through, mm^3/s.

b) Calculate the values of

$$m_{tr} = m_{cy} = \frac{1}{B_{3T} + 2C_{3T}\log\left(\frac{4Q}{\pi R^3}\right)} \qquad (4)$$

c) Calculate the values of:

$$\log R_{tr} = A_{3T} + B_{3T}\log\frac{8(m_{tr}+3)Q_i}{\pi D_i^3} + C_{3T}\log^2\frac{8(m_{tr}+3)Q_i}{\pi D_i^3} \qquad (5)$$

or

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$$\log R_{cy} = A_{3T} + B_{3T} \log \frac{8(m_{cy}+3)Q_i}{\pi D_i^3} + C_{3T} \log^2 \frac{8(m_{cy}+3)Q_i}{\pi D_i^3} \quad (6)$$

d) Calculate the value of L_i, if ΔP is 1MPa, which is given by:

$$L_{tr} = \frac{D}{4}\frac{1}{R_{tr}} \quad (7)$$

or

$$L_{cy} = \frac{D}{4}\frac{1}{R_{cy}} \quad (8)$$

e) Calculate the ratio of the obtained land and the land length :

$$\frac{L_{tr}}{L_{cy}} = x \quad (9)$$

The land L_{tr} will be:

$$L_{tr} = xL_{min} \quad (10)$$

The design parameters are: the mass of extrudate produced is 50 kg/h, temperature at the die, T is 160 ^{0}C, minimum land section L_{min} is 2 mm. The diameter of the trapezoidal section is 55 mm at the top and 3 mm at the bottom. The diameter of the cylindrical section is 3 mm. The dough density (corn flour) is assumed to be 1.5 g/cm^3 and the coefficient of the flow curve equation determined experimentally are as follows [12]:

A_{3T1} = -1.0153637; B_{3T1} = 0.4266734; C_{3T1} = 0.005667364; T_1= 180

A_{3T2} = -0.84651444; B_{3T2}=0.42305885; C_{3T2}=- 0.00693047; T_2 = 120

From the flow curve equation (Sors and Balazs, 1989), the equation of flow curve obtained from the equation of two boundary curves by interpolation is:

$$\log S_t = \log S_1 + \left(\frac{T-T_1}{T_2-T_1}\right)(\log S_2 - \log S_1) \quad (11)$$

and if

$$q = \left(\frac{T-T_1}{T_2-T_1}\right) \quad (12)$$

then

$$A_{3T} = A_{3T1} + q(A_{3T2} - A_{3T1})$$
$$B_{3T} = B_{3T1} + q(B_{3T2} - B_{3T1}) \quad (13)$$
$$C_{3T} = C_{3T1} + q(C_{3T2} - C_{3T1})$$

where :

T_1 is the lower limit of processing temperature, ^{0}C; T_2 is the upper limit of processing temperature, ^{0}C; T is the actual processing temperature, ^{0}C

$$q = \frac{160-180}{120-180} = 0.33$$

From the flow equations given above,

A_{3T} = -0.959643444;

B_{3T} = 0.425480598;

C_{3T} = -0.00608418898

Since the extruder throughput is 50 kg/h, then

$$Q = \frac{50\times10^6}{3600\times1.5} = 9259.26mm^3/s$$

For the trapezoidal section of the extruder, it is first assumed to have a cylindrical shape with different outer diameters since the length is yet to be calculated. Therefore, the mean diameter is: (55+3)/2 = 29mm.

Area of trapezoidal section is:

$$F_{tr} = \frac{29^2\pi}{4} = 660.52mm^2$$

Area of cylindrical section is :

$$F_{cy} = \frac{3^2\pi}{4} = 7.07mm^2$$

Total area = 660.52 + 7.07 = 667.59mm^2

The quantity of melt flowing through the trapezoidal section is :

$$Q_{tr} = \frac{9259.26\times660.52}{667.59} = 9161.20mm^3/s$$

Likewise, for the cylindrical section:

$$Q_{cy} = \frac{9259.26\times7.07}{667.59} = 98.06mm^3/s$$

hence

$$\frac{4Q_{tr}}{\pi R} = \frac{4\times9161.20}{\pi(14.5)^3} = 3.83$$

$$\log\frac{4Q_{tr}}{\pi R} = 0.58$$

$$\frac{4Q_{cy}}{\pi R} = \frac{4\times98.06}{\pi(1.5)^3} = 37.0$$

$$\log\frac{4Q_{cy}}{\pi R} = 1.57$$

$$m_{tr} = \frac{1}{0.425480598 + 2(-0.00608418898)0.58} = 0.42$$

$$m_{cy} = \frac{1}{0.425480598 + 2(-0.00608418898)1.57} = 0.41$$

$$\log R_{tr} = -0.959643444 + 0.425480598 \log\frac{8(0.42+3)9161.20}{\pi(29)^3} 0.00608418898 \log^2\frac{8(0.42+3)9161.2}{\pi(29)^3}$$

$$\log R_{tr} = -0.74225007$$

$$R_{tr} = 0.18$$

Likewise:

$$\log R_{cy} = -0.959643444 + 0.425480598 \log\frac{8(0.41+3)98.06}{\pi(3)^3} - 0.00608418898 \log^2\frac{8(0.41+3)98.06}{\pi(3)^3}$$

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$$\log R_{cy} = -0.32292797$$

$$R_{cy} = 0.48$$

Therefore,

$$L_{tr} = \frac{29}{4}\frac{1}{0.18} = 40.28$$

$$L_{cy} = \frac{3}{4}\frac{1}{0.48} = 1.56$$

Thus the ratio :

$$x = L_{tr} : L_{cy} = 40.48 : 1.56 = 25.95$$

and if $L_{min} = 2$, then

$L_{cy} = 51.9$mm

B. Determination of Number of Die Holes

It is often necessary to determine the number and length of die in the design of die. This is important in order to ensure that the production capacity matches the capacity the die can handle. The number of die holes is the total flow divided by the flow through each hole. For proper die design, die operating pressure and maximum shear stress in the die have to be determined. Literatures on food extrusion often take the maximum shear stress in the die to be less than 0.7MPa. This maximum pressure will give smooth surface in the extruded product and prevent surface roughness in food product.

In the determination of the number of die holes required, it is necessary to assume some design parameters. For this design, corn dough of 20% moisture is extruded at extruder temperature of 160 ^{0}C. Dough density is assumed to be 1500kg/m^3 and the viscosity, $\eta = 8700\left(\dot{\gamma}\right)^{-0.49}$, Ns/m^2. The shear stress at the wall of the die should be kept at a value less than 0.3 MPa. The extruder throughput is 50 kg/hr to produce round-shaped expanded extrudate of 10 mm in diameter. The radius of the die is 1.5 mm. It is assumed that the die end effects are negligible. The solution procedure for the number of die holes required is as follow:

a) Compute the volumetric flow, Q

$$Q = \frac{\dot{m}}{\rho} \tag{14}$$

b) Compute the flow through each die hole, Q_{di} such that τ_w maximum is not exceeded.

c) Compute the number of die holes

$$N_d = \frac{Q}{Q_{di}} \tag{15}$$

$$Q = \frac{50}{1500 \times 3600} = 9.26 \times 10^{-06} m^3/s = 9.26 cm^3/s$$

$$\eta = 8700\left(\dot{\gamma}\right)^{-0.49}$$

then

$$\tau = 8700\left(\dot{\gamma}\right)^{0.51}, N/m^2$$

equating $\dot{\gamma}$ with τ_w

$$3.0 \times 10^5 = 8700\left(\dot{\gamma}_w\right)^{0.51}$$

$$\dot{\gamma}_w = 1035 s^{-1}$$

since

$$\dot{\gamma}_w = \frac{3n+1}{4n}\left(\frac{4Q_{di}}{\pi R^3}\right) \tag{16}$$

$$Q_{di} = 1035\left[\frac{4(0.51)}{3(0.51)+1}\right]\frac{\pi(0.15)^3}{4} = 2.21 cm^3/s$$

The number of die holes:

$$N_d = \frac{9.26}{2.21} = 4.2$$

So use 4 dies holes.

Alternatively, the length of die hole can be calculated since the pressure drop across the die is known. From the calculations of the pressure drop done in earlier work, the highest pressure drop is 4.832 MPa (Adekola, 1999).

Using the formula:

$$\tau_w = \frac{\Delta PR}{2L} \tag{17}$$

Therefore,

$$L = \frac{\Delta PR}{2\tau_w} = \frac{4.832 \times 10^6 \times 0.15}{2\left(3.5 \times 10^5\right)} = 1.04 cm = 10.4 mm$$

It should be noted that the number of die could be reduced by increasing die hole length by a simple proportion and vice versa. For this design, the number of die can be reduced from 4 to 2 by increasing the length from 10.4mm to 20.8mm (Fig.3).

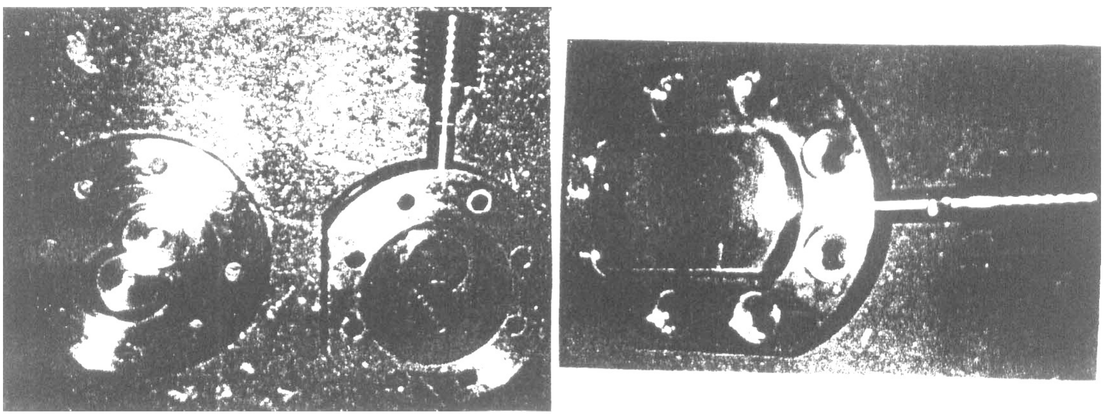

Fig.3. Designed die mounted on Twin Screw Food Extruder for Experiments

The above procedure can serve as a guide in the design of food extruder die. The nature of the food to be extruded, the flow curve characteristics of the food dough, the throughput of the extruder and the variable design parameters are very important considerations in the design work. Works on the food dough flow curve has to be further improved in order to minimize the variation between the design and practical dies. The experience with the plastic extrusion would be of great help.

IV. Conclusion

Design considerations proposed in this work are ideal for most food extruder die. The desired shape, size and uniformity of the extrudate, extruder throughput and die dimensions such as nozzle diameter and length are very important considerations in food extruder design. In addition to these considerations, design optimization for the die must also incorporate determination of pressure drop, land length optimization and number of die to match extruder throughput.

Future work is needed into studies of computer aided design for food extruder die. The design should incorporate thermo-mechanical properties of die material and dough. In addition, biological and rheological properties of food dough should equally be incorporated.

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