SIMULATION OF FLOUR FLOW IN EXTRUSION PROCESS BY USING COMPUTATIONAL FLUID DYNAMICS COMMERCIAL SOFTWARE

Weerasak Lertsiriyothin and Methee Kumtib

School of Mechanical Engineering, Suranaree University of Technology, Thailand

ABTRACT: In an extrusion process, food-shape formation is dependent on the complex physical and chemical transformation of biomaterials which occur under the influences of thermal and mechanical energy. On the other hand, the flow of raw material during process governs the final shape of the product. In order to obtain a stable product shape, there is traditionally a need of experimenting for an optimization of the process control parameters. Such a process is notable for time and budget consuming. The attempt of this study is to increase the efficiency of process optimization by applying the transport phenomena data obtained via computational fluid dynamics commercial software. The CFD simulation of flour flow in the extruder, presented here, is covered the prediction of the feed rate, screw rotating speed on the velocity and pressure profiles in the single screw extruder.

KEYWORDS: Single screw extruder, Numerical simulation, Extrusion process optimization, Pseudoplastic

1. INTRODUCTION

Extrusion is simply the operation of shaping plastics or dough-like materials by forcing it through a restriction or die. Examples extruding foods include pasta, noodles, and expanded snack, a dog, cat foods and pie crust doughs [6].

A food extruder is a device that expedites the shaping and restructuring process for food ingredients. Extrusion is a highly versatile unit operation that can be applied to variety of food processes. Extruders can be used to cook, form, mix, and shape food products under conditions that favor quality retention, high productivity and low cost.

In order to create the optimization chart for controlling extrusion process, there is a need of fully understanding the effect of process control parameters on the flour flow characteristic and product shape formation. The objective of this research is therefore to gain this important fundamental knowledge via numerical simulation results. Since the screw of extruder is usually a complex geometry, finding the critical condition for process parameters requires a use of 3-D numerical simulation for tracking a change of rheological property of the flour during the flow process. Some of the simulation results are present in the following section.

2. MATERIALS AND METHODS

2.1 Rheology properties of wheat dough

Wheat dough is selected as a flour type in this simulation. The wheat dough is non-newtonian fluid that has power-law like material as shown in Eq. (1) [3].

$$\eta = k\dot{\gamma}^{n-1}e^{T_0/T} \qquad (1)$$

where $\dot{\gamma}$ is shear rate, T is actual temperature and k, n, T_0 are constant input parameters, consistency index = 4450 $N \cdot s/m^2$; n is a measure of the deviation of the fluid from Newtonian power-law index), the value of n=0.35 determines the class of the fluid as shear-thinning (pse plastics); T_0 is the reference temperature at 306 K. Other physical properties of wheat doug density $(\rho = 1450\ kg/\mathrm{m}^3)$ and specific heat $(C_p = 1976\ \mathrm{J}/kg \cdot K)$.

2.2 Screw configurations

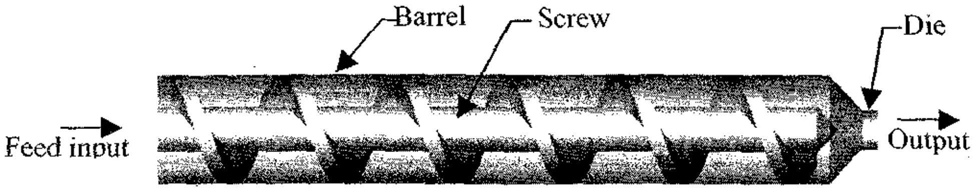


Fig. 1 Single screw extruder

The extruder has one uniform size and is fitted with two different dies. The geometries screw consists of diameter, D = 3.52 cm; channel depth, H = 1.1 cm; helix angle, φ= 17.66 clearance, ε = 0.04 cm; L/D = 6. Two die sizes are diameter of 13 and 3 mm with a same length o mm [2].

2.3 Governing Equations

The governing equations for simulation of flour flow model are derived from the bas conservation principles of mass, momentum and energy. For a viscoelastic fluid, these equations m be written as follows [2].

Mass continuity equation $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad (2)$$

Momentum equation $$\rho \frac{d\mathbf{v}}{dt} = \rho g - \nabla P + \nabla \cdot \tau \qquad (3)$$

Stress tensor $$\tau = \eta \cdot (\nabla \mathbf{v} + \nabla \mathbf{v}^T) \qquad (4)$$

Energy equation $$\rho C_p (\mathbf{v}.\nabla T) + \tau : \nabla \mathbf{v} + \nabla \cdot q = 0 \qquad (5)$$

where $\mathbf{v}$ is velocity vector, T is temperature and P is pressure

2.4 Numerical simulation

The flour flow is non-isothermal condition. Numerical solutions, which require simultaneo solving of above equations, were done by using Fluent® software. **SIMPLE** algorithm with the order upwind discretisation schemes is used for computing the numerical solutions. The finite volum mesh was created by using automatic mesh adjustment based on screw shapes. Total mesh element is about 60,000 nodes.

3. RESULTS AND DISCUSSIONS

The numerical simulations for flour flow in the single screw extruder are summarized in the following sections.

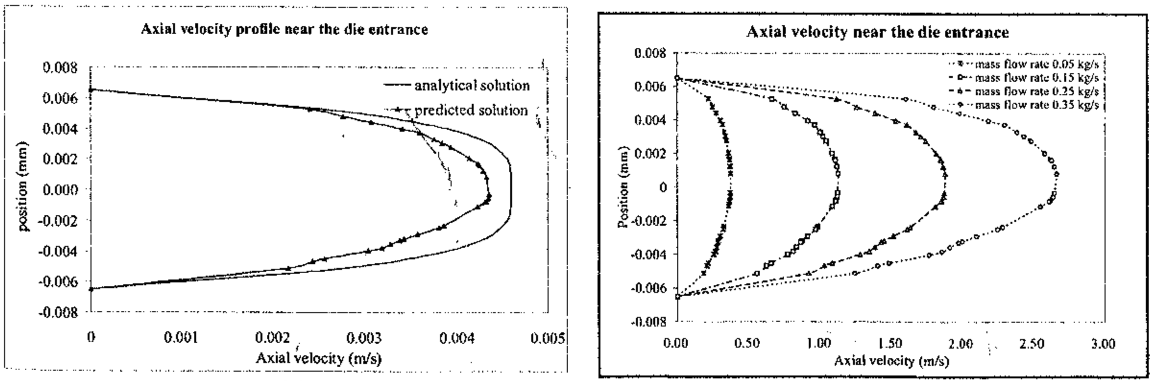
3.1 Validation of numerical solution

There is no known analytical solution solved for the complex flour flow in the extruder therefore, it is commonly practiced to check the predicted pressure at the die with the experimental measured pressure. However, the problem statement for this research is focused on the simulation of flour flow in the single screw extruder that is equipped with circular die shape. So, the validation of numerical solution is conveniently done by comparing the predicted pressure and velocity profiles at the die to those values obtained from known analytical solution that is derived for a non-Newtonian fluid flow through the circular die. For the Pseudoplastic fluid, a distribution of axial velocity in the radius direction over a cross-section of a flow channel for a circular die is given by Eq. (6) [5].

$$v_z(r)=\phi\left(\frac{\Delta p}{2L}\right)^m\left[\frac{R^{m+1}-r^{m+1}}{m+1}\right] \tag{6}$$

where $\phi=\frac{1}{k^m}$; Δp is difference pressure at the die exit; L is length; R is radius of the die; r is variable radius ; m is flow exponent and $m=\frac{1}{n}$.

Figure 2(a) shows the change of predicted axial velocities near the die is similar to the ones calculated by Eq. (6). The maximum axial velocity occurs at the die center. All of the axial velocities computed via the analytical solution are greater than the predicted ones. The error of average velocity is to be 15% and a corresponding pressure error is about 8% (data not shown here). A source of error for analytical solution is due to the use of the average values of ϕ and Δp in the calculation. Nevertheless, a closed proximity of the comparison result can be interpreted that the accuracy of numerical simulation for pressure and velocity profiles along the screw flight is right.



(a) (b)

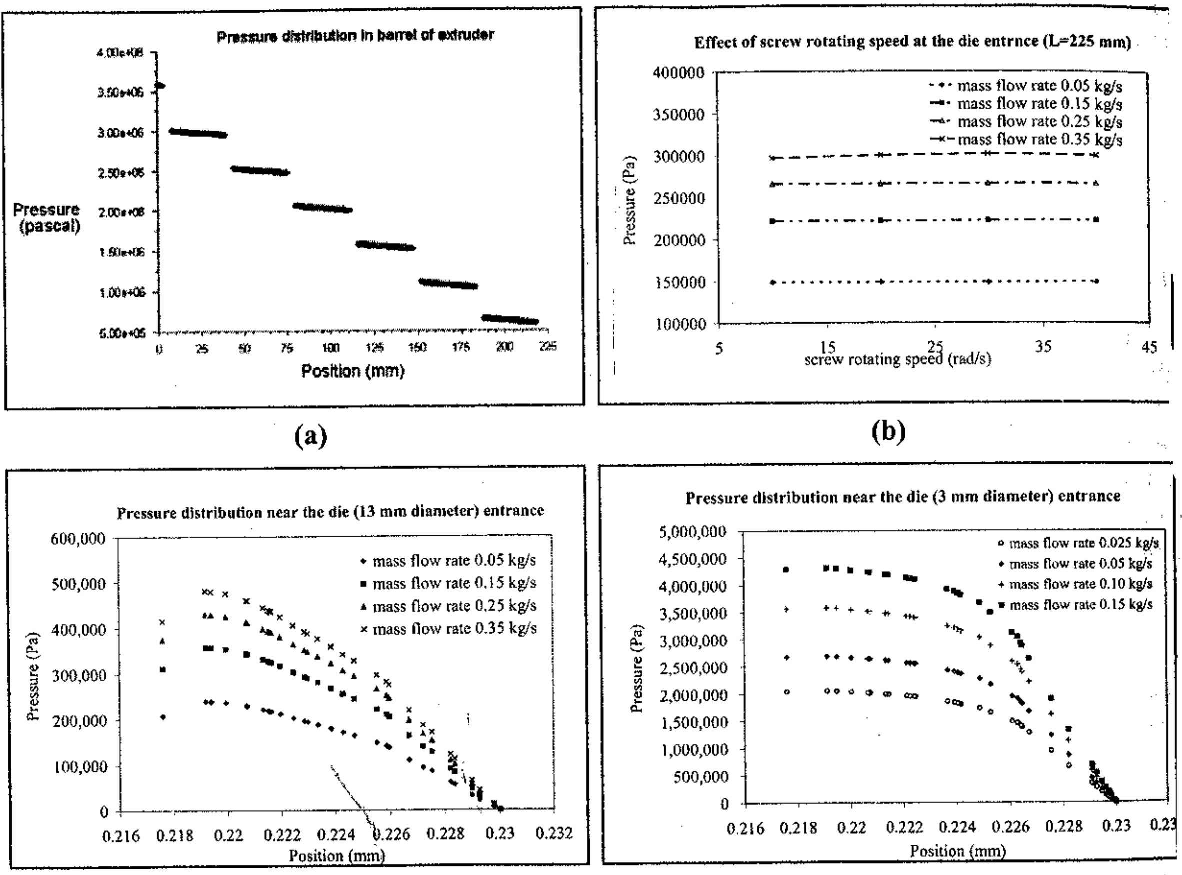
Fig. 2 (a) Comparison of predicted axial velocity with analytical axial velocity over a cross-section of die for the test conditions of 13 mm diameter, mass flow rate 2.1 kg/h and 2.1 rad/s
(b) Comparison of axial velocity for various mass flow rate at screw rotating speed of 10 rad/s

3.2 Effect of feed rate on velocity development

The distribution of axial velocity profiles over a cross-sectional plane of the die for various mass flow rate are shown in Fig. 2(b). For the same rotating speed, the maximum values of axial velocity increase as the incremental of mass flow rate.

3.3 Effect of feed rate, screw rotating speed, and die geometry on pressure development

Figure 3(a) presents pressure values along the axial direction of the screw at a constant radi position of 15 mm. The pressure distribution pattern for all of the simulation cases is decreased from a high pressure at the feed entrance to atmospheric pressure at the die exit. This result is similar to the data published by Das [1]. Pressure discontinuity points are the effect of absent points due to the screw flight geometry. Since the mass flow rate is considered high for all testing cases, the flow through the die channel is under the influence of drag force only. So the screw rotating speed has merely effect on the die pressure as shown in Fig. 3(b). In fact the screw rotating speed affects only the residence time distribution of material in the extruder. The pressure simulation results also display that the higher the mass flow rate is, the higher pressure distribution occurs near the die entrance (data shown in both Fig. 3(c) and (d)). As being expected, the smaller die geometry requires higher pressure to extrude the same mass flow rate of wheat dough.



(a) (b)

(c) (d)

Fig. 3 (a) pressure distribution for ω= 10 rad/s, $\dot{m}$ = 2 kg/h, T-barrel = 313 K, T-screw = 303 K, exit P = 5 bar; (b) effect of ω ; (c) & (d) pressure distribution near the die entrance for constant ω=10 rad/s, T-barrel = 363 K, T-screw = 303 K, exit P = 0 Pa, die diameter 13, 3 mm, respectively.

4. CONCLUSION

Numerical simulation of flour flow in a single screw extruder provides an elucidation for an influence of some processing parameters on the flow characteristic of Pseudoplastic type of flour. For a uniform screw geometry, the main parameters affecting the pressure and velocity distribution in the extruder are mass flow rate, die geometry, but not the screw rotating speed. The mathematical validation of numerical results proofs a satisfaction for the pressure predicted near the die entrance. In order to produce a process design chart, there is a need of further investigation on other process control parameters such as moisture content, temperature, and screw geometry.

5. REFERENCES

[1] Das M. K., Ghoshdastidar P. S., (2001). Experimental validation of a quasi three-dimensional conjugate heat transfer model for the metering section of a single-screw plasticating extruder. *Material Processing Technology*. (120): 397-411.

[2] Dhanasakharan K.M. and Kokini J.L., (2003). Design and scaling of wheat dough extrusion by numerical simulation of flow and heat transfer, *Journal of Food Process Engineering,* article in press: 1-10.

[3] Harper J.M. (1981). Extruder of food. United State of America.

[4] Rauwendaal C. (2001). Polymer Extrusion (4^{th} ed.). New York: Hanser.

[5] Water M., (1991). Extrusion Dies for plastics and Rubber: design and Engineering Computations. New York: Barcelona.

[6] White J.L. (1991). Twin screw extrusion: Technology and principle. New York: Carl Hanser Verlag.