Numerical Analysis of Non-Newtonian Fluid Flow in Single Screw Extruder and Its Application in Food Industry

Ali Kargar

Abstract— In this research, the behavior of non-Newtonian fluid in the one single screw extruder has been analyzed numerically in order to achieve velocity profile, heat gradient, and pressure distribution and other effective variable. We can describe dynamic behavior of fluid by navier-stokes equations. In extrusion process that is combination of several operation units, consist of mixing, baking, shaping, pulping, cutting and modeling to be formed, raw material with nature of non-Newtonian fluid through one nozzle with mold, has been passed. And produce product with specific form. Extruded are very viscous and consequently fluid flow is laminar. In general, motion equation could be written in exact form by three dimensional relations between elements of tension, rate of cutting and velocity and its derived. By doing this work, rheology of fluid is not being considered. In practical, motion equations specifically by considering rheological model of fluid will be written. And it is necessary that assumption and result due to type of rheology, characterized. Insignificant curvature of screw blades, a negligible effect screw blades on fluid flow, negligible gravity, cylinder temperature is constant and steady of flow are assumptions that considered for solving this problem.

Keywords—: Non-Newtonian fluid-single screw extruder, Rheology of fluid, navier-stokes equations.

I. Introduction

EXTRUSION mainly is a continuous process that including mixing and melting of material with high viscosity such as plastics, polymers and foodstuffs that are mainly divided into three parts of nutrition, transfer and melting and metering area, in part of nutrition, material are entered to the extrusion chamber and by moving forward and due to shear force and reducing space of passing, heated and melted material will be formed as a fluid. In part of metering, heat and pressure of fluid that are steady will be increased. Mechanism of process in any part is different from other parts. And need to be analysed separately. In simulation of extrusion, metering area have important role in quality of producing production. In most of models, this area that form main part of extruder will be considered. Extruder is applicable to machines that pass material through nozzle with a mold, and produce group of product with specific form. Extruder usually divided into three main categories. First category, ones required pressure for applying to material are created by piston. Second category is extruder that required pressure by passing material pulp through two rotary rollers are provided and in third category, pressure by one screw are produced. Ram (extruder with type of piston) is restricted to some special machines like performing with (borwell performer), but screw extruders are widely used in rubber and food industries. Nowadays, using extrusion technology, widely range of production with flavor, colour, texture and various forms will be produced that preparing it with traditional methods is not possible. In the past, analysis of fluid flow and heat transfer in one single screw extruder by number of researchers were examined. In initial (primary) models conditions were considered as Newtonian fluid and isotherm. Progress in researches, in some models, rheology of fluid was considered and thus presented models are closer to the real models. At first, modelling of extrusion for polymeric material was done. And by use of this process in food industry, modelling of nutritious extrusion was propounded that in most of them, due to viscoelastic nutrition property, models were similar the model of polymeric. In some models, special rheology of food has been considered. That most of models has presented for baking extrusion, because, during extrusion process, biochemical reactions has been done. That consequently, rheology of fluid during extrusion, in addition to temperature and applied shear force to fluid due to biochemical interactions are changed. The main studies in this field were concerned to polymeric extrusion material that in many cases can be extended to food extrusion process. The first Non-isothermal model that viscosity was depended to temperature and rate of cutting, in 1959 presented by Colwell & Nicholls [1]. In this model, cross channel flow was over looked. Solving problem by considering cross channel flow for first time was done by Griffith and Zamadits at 1962 and 1969 respectively [2]-[3]. It should be noted that in this model, hydrodynamic and thermal flow supposed fully developed, that assumption of fully developed hydrodynamic floe due to high viscosity of fluid are valid. Thermal developed flow on screw channel at first in 1968 by Yates was studied [4]. Then in 1975 by Fenner and Lindt & Elbirli in 1984 continued [5]-[6]. The first analysis of flow and heat transfer in one screw extruder for channel with limited depth in 1969 by Martin presented [7]. In this study, dimensional ratio considered 1, 5 and were limited to thermal and fully hydrodynamic condition. In this channel, it's enough that calculation performed with flow through plate. For the reason on that, supposed fluids are fully developed hydrodynamic and changes in channel direction of passing fluid are negligible. Thus, this problem will be two dimensional. Although some assumptions (For example, on existence of changes in

Department of Mechanical Engineering, Quchan Branch, Islamic Azad University, Quchan, Iran (corresponding author to provide, e-mail: ali_kargar_57@yahoo.com).

direction of passing flow) by Martin for simplify the problem, are rarely in agreement with real data. This research has important results about effect of heat convection in cross direct channel for high peclet number.

In 1990, Karwe and Jaluria solve a heat transfer problem in one single screw extruder [8] . Calculation for non-Newtonian fluid with distribution of specific temperature in cylinder and diabetic's screw was carried out. In 1995, Sastrohartono and et all carried out a series of numerical studies during three dimensional flow and heat transfer in one single screw extruder for polymeric material [9]. In this research, three dimensional flow by considering Down channel has modelled. In 1995, fluid flow and heat transfer in one single screw extruder and pressure drop in die solved, by Chiruvella and et all [10]. For simultaneous solving, die model with screw channel by using newton-raphson's method was used. Including non-isothermal and three-dimensional models in which the fluid rheology has been approved, In 1999 was presented by Syrjala [10]. In this model, for solving the flow equations in single screw extruder, the Galerkin's finite element method is used.

II. Physical Expression

In Fig. 1, various part of single screw extruder in general case is shown. Single screw extruder is usually consisting of variety of materials, such as parts of transferring material, melting part or softening materials, gas removal, mixing area, the softened transfer material area, wiredraw or die.

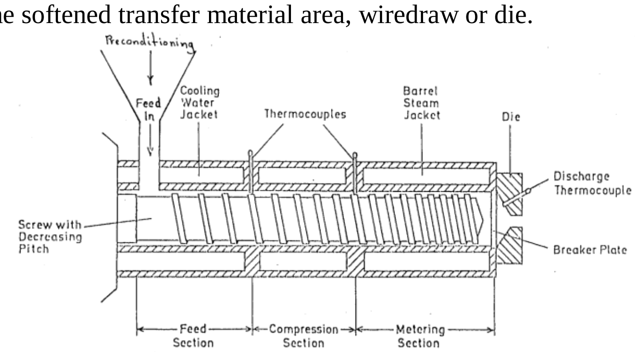

Fig. 1 General schematic of single screw extruder

At first, raw materials imported into the cylindrical chamber and then screws move them during the chamber. Moving forward, reducing the space between the chamber and screw, increase the resistance against moving and thus fill and compress spaces between blades screw and cylinder. By moving material toward the front, screw crushed material and then screw makes material pasty and in the form of semi-solid mass.

If the material heat in temperature more than 100 degree, the process is called baking extrusion. Heat caused by friction and any added heat, causes a rapid increase temperature in the baking region. And then the material passes portion of cylinder that is the minimum volume and are under maximum pressure and shear force. If the ratio of diameter to height of screw blades is large, the channel is considered rectangular and unrolled that is shown in Fig. 2.

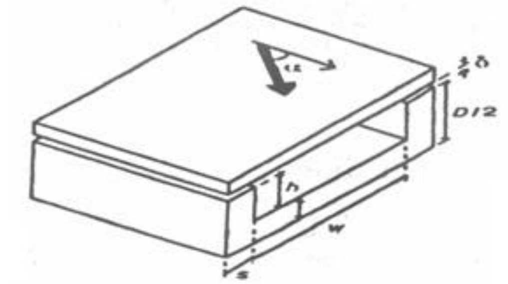

Fig. 2 Geometry of single screw extruder with a negligible curvature of screw blades

Because of this assumption, geometry of flow has been simplified and the equations in cylindrical coordinates can be converted to Cartesian coordinate.

III. The Governing Equations

Modeling of extruder by applying continuity momentum and energy rules on very small volume element and then integrating the result over the entire range are done. Equations to determine the distribution of temperature, pressure and speed of extrusion process can be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0 \tag{1}$$

$$\rho \frac{DV}{Dt} = -\nabla P + (\nabla.\tau) + \rho g \tag{2}$$

$$\rho C_v (\frac{\partial T}{\partial t} + V.\nabla T) = \tau : \nabla V + P \nabla.V + \nabla(k \nabla T) \pm \dot{H}_r \tag{3}$$

Where ρ is fluid density, V is fluid velocity vector, $\rho \frac{DV}{Dt}$ is accumulation of mass, ∇P is pressure force, $\nabla.\tau$ is the fluid viscosity force and ρg is gravitational force per unit of fluid.

IV. Numerical Model

With respect to complexity of geometry, solving these equations in cylindrical coordinates and three dimensional is very difficult. So at first, taking some appropriate assumptions solving flow into the extruder on one dimensional conditions that are modeled. These assumptions include: solving in the Metering area, negligible curvature of screw blades, Newtonian fluid, failure to perform chemical reactions, Incompressible fluid, constant temperature of cylinder and negligible effect of gravity, according to above assumptions, momentum and energy equation, governing the extrusion process can be simplified as follows:

$$\frac{\partial p}{\partial x} = \frac{\partial \tau_{yx}}{\partial y} = \mu \frac{\partial^2 v_x}{\partial y^2} \tag{4}$$

$$\frac{\partial p}{\partial z} = \frac{\partial \tau_{yz}}{\partial y} = \mu \frac{\partial^2 v_z}{\partial y^2} \tag{5}$$

$$k \frac{\partial^2 T}{\partial y^2} + \mu \left(\left(\frac{\partial v_x}{\partial y} \right)^2 + \left(\frac{\partial v_z}{\partial y} \right)^2 \right) = 0 \tag{6}$$

The boundary conditions in $y = 0$ is equal to:

$$v_x = 0 \ , \ v_z = 0 \ , \ \frac{\partial T}{\partial y} = 0 \tag{7}$$

And in $y = h$ is as follows:

$$\begin{aligned} & v_x = v_{xb} = \pi \times D_b \times N \times \sin\alpha \\ & v_z = v_{zb} = \pi \times D_b \times N \times \cos\alpha \\ & T = T_b \end{aligned} \tag{8}$$

For discretization of the governing equation and numerical solution finite difference method is used. In Table I values of input data and the geometric characteristics of problem are given.

TABLE I
VALUES OF INPUT DATA AND THE GEOMETRIC CHARACTERISTICS

Symbol	SPECIFICATION	QUANTITY
D_b	Inner diameter of cylinder	$0.102\,m$
L	Axial length of the screw	$0.96\,m$
H	Height of screw channel	$0.005\,m$
W	Depth of screw channel	$0.1\,m$
α	Angle of screw blade with z direction	17.66°
k	Thermal conductivity coefficient	$0.2\ W/m.K$
μ	Viscosity	$100\ pa.s$
N	Engine RPM	$60\,rpm$

V. RESULTS

After numerical solution of the governing equations, curve of temperature change and velocity of V_z and V_x are discussed in Fig. 3 to 8.

In Fig. 3, effect of changing coefficient thermal conductivity of fluid on variable T, V_x , V_z shown.

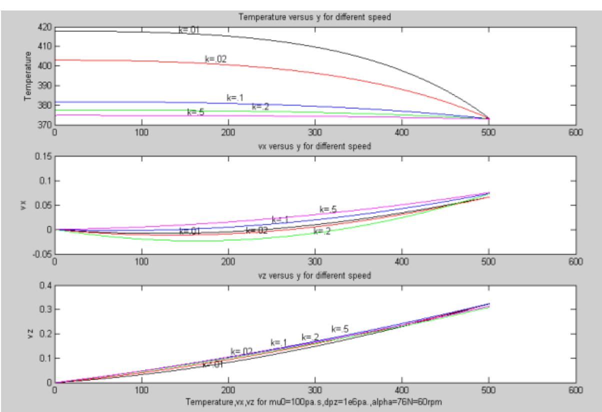

Fig. 3 Effect of changing coefficient thermal conductivity of fluid on T, V_x , V_z

As can be seen, with increasing of thermal conductivity from 0.1-0.2 $W/m.K$, Heat transfer rate in the y direction increases and speed of between the cylinder and the screw decreases. In Fig. 4, effect of changing fluid viscosity on variable T, V_x , V_z shown.

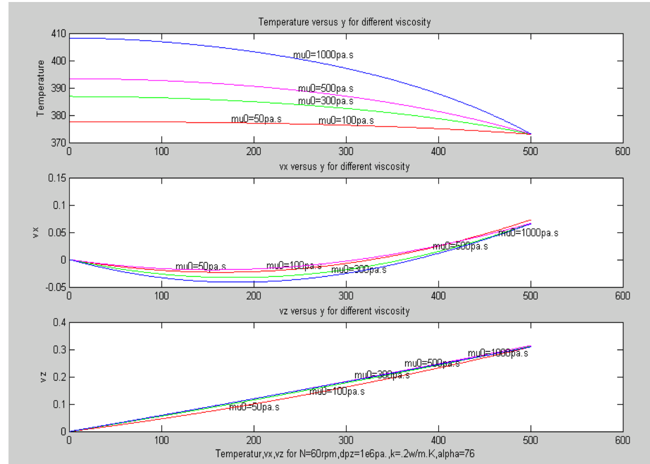

Fig.4 Effect of changing fluid viscosity on T, V_x , V_z

As expected, with increasing in viscosity due to shear stress and thus increasing speed difference, temperature difference between cylinder and screw are increased. In Fig. 5, effect of changing rotation speed of cylinder from 30-300 rpm shown.

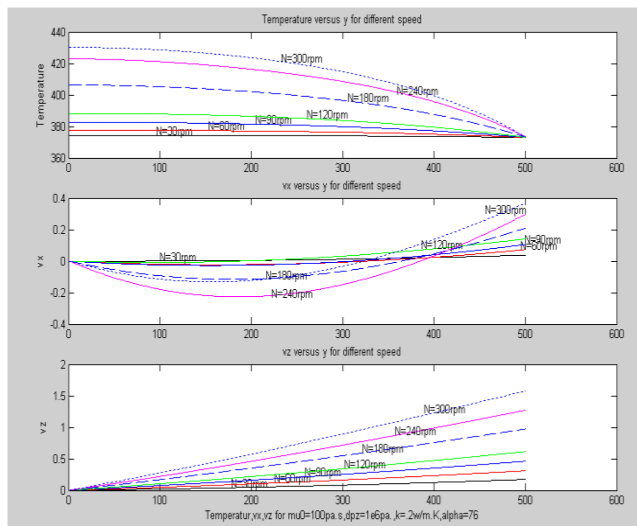

Fig. 5 Effect of changing rotation speed of cylinder on T, V_x , V_z

By increasing N, speed in cylinder wall is increased and slope of changes between cylinder and screw will increase. By increasing speed, viscosity dissipation is increased and thus temperature difference between cylinder wall and screw will increase. In Fig. 6, effect of changing angle of screw blades in range of 15 to 76 degree are shown.

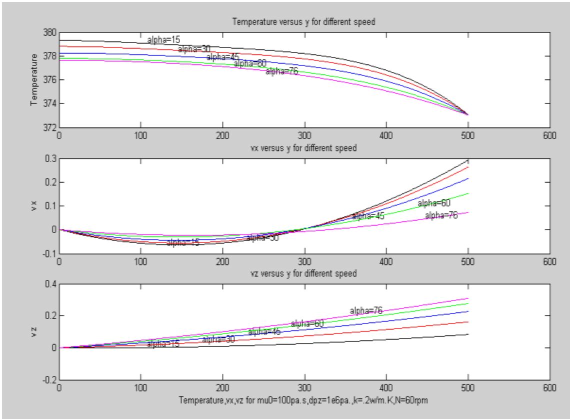

Fig. 6 Effect of changing angle of screw blades on T, V_x, V_z

By increasing angle of screw blades from 15 to 76 degree, temperature difference between cylinder and screw is decreased. As well as, slope of diagram V_x is decreased. And effect of changes depth of channel on parameters is shown in Fig. 7.

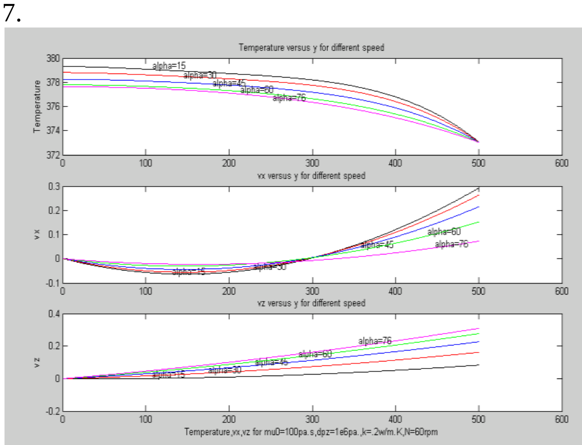

Fig. 7 Effect of changing in depth of channel on T, V_x, V_z

By changing the depth of the channel, these parameters due to the lack of mathematical relationship between channel and temperature and speed parameters width do not change significantly.

VI. Conclusion

In the present work, flow on single screw extruder was analyzed. After solving equations, influence of different parameters including thermal coefficient of conductivity of fluid, viscosity, rotation speed of cylinder, angle of screw blades and changing of depth of channel on viscosity and temperature of fluid were discussed.

References

[1] R.E.Colwell and K.R.Nicholls, The screw extruder, Ind..Eng.chem. Vol.51,pp.841-843,1959
[2] R.M.Griffith, Fully developed flow in screw extruders, Ind.Eng.Chem.Fundam, Vol.1, pp.181-187, 1962.
[3] H.J.Zamadits and J.R.A.Pearson, Flow of polymer melts in extruders, Part I ,The effect of transverse flow of a superposal steady temperature profile, Trans.Soc, Rheol., Vol.13, PP.357-358, 1969.
[4] B.Yates, Temperature development in single screw extruders,Ph.D. thesis ,university of Cambridge ,1968.
[5] .T.Fenner, the design of large hot melt extruders, polymer, Vol.16, PP.298-304, 1975.
[6] B-Elbirli and J.T.Lindt, A note on the numerical treatment of the thermally developing flow in screw extruders, polymer Eng.Sci, Vol.24, PP.482-487, 1984.
[7] B.Martin, Numerical studies of steady state extrusion processes, Ph.D.Thesis, university of Cambridge, 1969.
[8] Karwe, M.V.and Jaluria,Y. Numerical simulation of fluid flow and heat transfer in a single-screw extruder for Non-Newtonian fluids, Numerical heat transfer, Part A17(1990), 167-190.
[9] Sastrohartono, T.Jaluria, Y.Esseghir, M.Sernas, Numerical experimental study of three dimensional transport in the channel of an extruder for polymeric materials, Int.J.Heat mass transfer Vol.38 (1995), 1957-1973.
[10] Chiruvella.R.V., Jaluria.Y, and Abib.A.H, Numerical simulation of fluid flow and heat transfer in a single-screw extruder with different dies, polymer Eng.Sci.35(1995), 261-273.
[11] Seppo Syrjala, On the analysis of fluid flow and heat transfer in the melt conveying section of a single-screw extruder, Numerical heat transfer, Part. A, 35(1999), 25-47.