Two dimensional flow simulation in intermeshing co-rotating twin screw food extruder die

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Abstract: In this study, two-dimensional flow simulation in food extruder die for intermeshing co-rotating twin-screw extruder were performed by solving Navier-Stokes equation and continuity equation for non-Newtonian fluid using finite element computer package of ANSYS/FLOTRAN. The objective of the study is to determine the nature of flow, heat and pressure distribution in the die and to determine the effect of screw speed on process parameters such as temperature, pressure and flow rate in the die. Four different die geometries were used. The levels of temperature considered were 120°C, 140°C, 160°C and 180°C. The screw speeds (taken as inlet velocity for the die) were 120, 160, 200 and 240 rpm. The results are presented for the flow profile, pressure distribution, temperature distribution and flow rate. For all the velocities considered, temperature has no significant effect on the velocity vector. The concentration of the vectors increase as the cross-sectional area becomes smaller. The vectors are relatively linear and smooth in the transition section of the die and get concentrated towards the die exit. The flow rate increases with increase in inlet velocity. Extruder throughput has a significant effect on the flow rate as reflected in higher flow rate recorded for increased throughput. The pressure at the die exit is lower than the highest pressure obtained for all the experimental runs. As the dough gets to the die exit, the dough experienced pressure drop. A pressure drop of more than 0.8MPa between the entrance and exit of the die was obtained. Experimental results obtained for the die geometries statistically correlate with the simulation results.

Keywords: Flow distribution, food extruder die, finite element, 2-dimensional flow

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1 Introduction

Extrusion process is a very important manufacturing method in many industries especially in food production industries. The process as applied in food industry can be used to produce ready to eat snacks by forcing food dough through the die under high temperature short time (HTST) process. Extrusion process involves flow and heat distribution and efficient control of these flows determines the success or otherwise of any extrusion process. Therefore, it is important that studies be conducted to understand the complex nature of these flows in extrusion process in order to be able to control them for optimum extrusion operation (Adekola, 2015).

In general, twin screw extruder modeling has received increasing attention in recent years probably because of the growing number of applications of this process and the need for better control of their scale up and to widen their development. However, reported works on flow modeling in co-rotating twin screw food extruder die are limited. The basic concept of modeling concerns the definition of mathematical relationships between entrance and target variables.

A through knowledge of the flow behavior inside an extruder provide an insight into the mechanism of mixing and facilitates estimation of residence time distribution (RTD), flow rate, pressure drop and power consumption. The flow pattern may be derived from theoretical velocity profile for food mix in the extruder for Newtonian and non- Newtonian fluids under isothermal and

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non-isothermal conditions for single-screw extruder (Della et al., 1993). The same approach had also been used for twin-screw extruder with intermeshing, counter-rotating screws (Yang and Manas, 1992) to determine material flow pattern.

Few works have been published on the mechanism of material flow and energy transfer in intermeshing co-rotating food extruder mainly due to the complexity of the geometry and the flow behavior. In an attempt to simplify the complex process, Sastrohartono et al., 1991 divided the flow in twin screw extruder barrel into two regions: the translational region and the intermeshing/mixing region. They used finite difference method for the simulation of the translational region, while a finite element method is used for the simulation of the intermeshing region. They concluded that the method can be applied to others screw geometries such as those of self-wiping and fully intermeshing twin screw extruder.

In their work (Adekola et al., 1998) had proposed a method for estimating temperature profile in food extruder die. Three important approaches were used to determine the temperature field in the die, a) by conduction in radial dimension, b) by convection in axial direction and c) by viscous dissipation. Emphasis was placed on food extruder with circular cross-section. This shape represents the majority of the shapes used in food extruders. In order to simplify the equation of flow in dies, the following assumptions were made: 1) The flow is laminar and steady. 2) The dough is incompressible and isotropic with constant thermal properties. 3) Rotational symmetry 4) Kinematically developed velocity profile in entrance section. 5) No slip at wall. 6) Heat transport axially by convection and radially by conduction only.

So far, there is no reported work in literature on the flow and heat analysis in the die of twin screw food extruder for corn.

The first application of flow analysis network (FAN) more generally known as control volume (CV) to describe twin screw flow was reported (Szydlowski and White, 1987, Kim and White, 1989). Their visualization projected the field into a Cartesian (rectangular) co-ordinate system, with the screw held stationary and the barrel moving relative to the flow cavity. The flow pattern within the intermeshing zones of the twin screw extruder, most studies concluded that product temperature (150^oC-200^oC) and pressure (5-19MPa) increase primarily when a flow restriction is present (Ollet *et al*, 1989).

Van der Wal et al., 1996 successfully used finite element package Sepran to perform 3–dimensional flow simulation of kneading elements in an intermeshing corotating twin screw extruder by solving Navier Stokes equations for plastic extrusion. The objective of the calculation is to study the influence of factors such as a shear rate, elongation rate, pressure on mixing and the flow profile in an extruder on various extruder parameters such as fluid viscosity, rotational speed and throughput.

Recently, some research work on 2 or 3-dimensional finite element analysis and modeling for food extrusion processes have been reported (Emin and Schuchmann, 2013; Chen and Friss, 2010). However, works on the application of simulation modeling to flow and heat distribution in twin screw extruder die for corn extrusion is unknown. As a result, it is intended in this present work to carry out some works in that direction. In all the published studies reviewed, flow pattern modeling was restricted to various sections of the extruder screw (compression, melting and metering sections) with virtually no mention of the pattern in extruder die (Adekola, 2014).

Therefore, the objective of this present study is to determine the nature of flow, heat and pressure distribution in the die and to determine the effect of screw speed on process parameters such as temperature, pressure and flow rate in the die.

2 Simulation procedure

Two-dimensional flow simulation in extruder die for intermeshing co-rotating twin screw extruder was performed by solving Navier Stokes equation using the finite element computer package, ANSYS FLOTRAN. The package is a finite element tool for analyzing flow and carrying out heat analysis. The theory of heat and fluid flow fundamentals used in the analysis provided in the program manual (ANSYS, 2009).

This package was adapted for use in food extruder die in this study. This will be the first time that a work on simulation and modeling of flow, heat and pressure distribution in food extruder die single or twin screw alike is being reported. The objective of the study is to determine the flow, heat and pressure distribution in the die. It is also to determine the effect of screw speed on process parameters such as temperature, pressure and flow rate in the die using different dies.

Four different geometries of die were used (Figure 1). In this work, screw speeds (which translate into inlet velocity for the die) used for simulation are 120, 160, 200 and 240 rpm. The die temperatures studied are 120°C, 140°C, 160°C and 180°C.

Due to the complex nature of the dough flow in the die, the following assumptions were made for the analysis:

1) The flow is steady and laminar. This is because the dough flow is highly viscous and slow moving.
2) The flow is incompressible i.e. the density is constant. With this assumption, temperature equation for incompressible flow neglects kinetic energy changes and viscous dissipation.
3) The dough is Newtonian.
4) The flow is isothermal.
5) The element/cavity of the die is completely filled.

For FLOTRAN analysis carried out, the steps were divided into two parts: pre processing and post processing. Some processing steps taken in sequence are as follows:

1) Definition of element type. 2D-flow analysis selected.
2) Create areas of the die geometry to be analyzed. Four die geometries were created (Figure 1) and used in the simulation work.

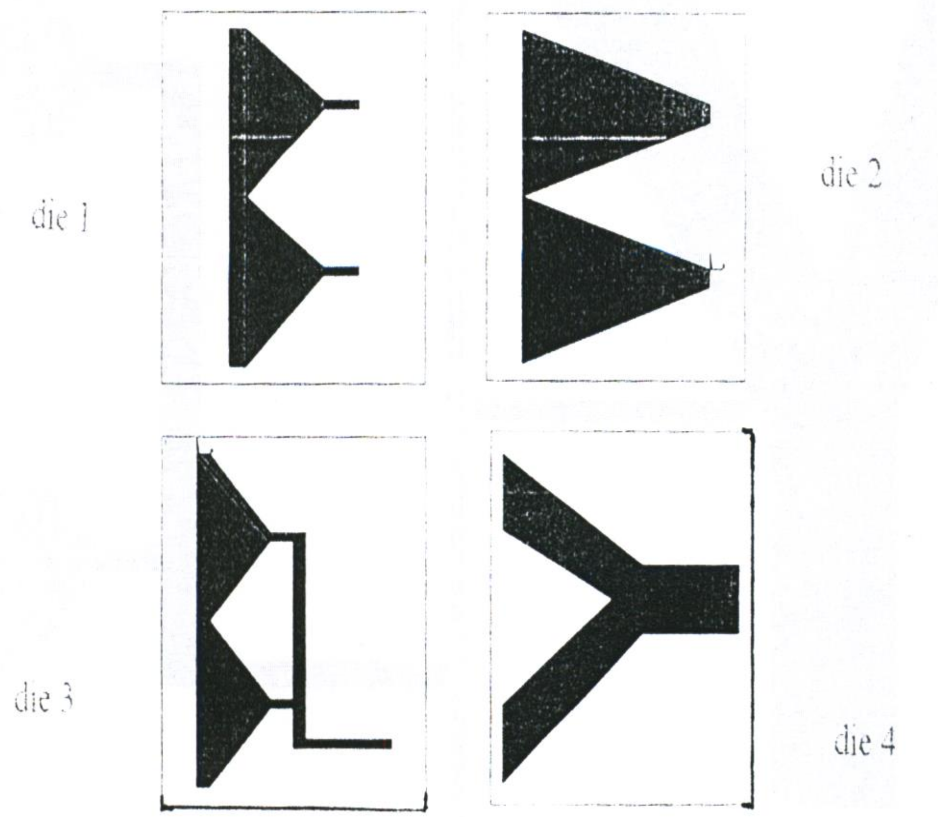


Figure 1 Geometries of dies used for FLOTRAN analysis

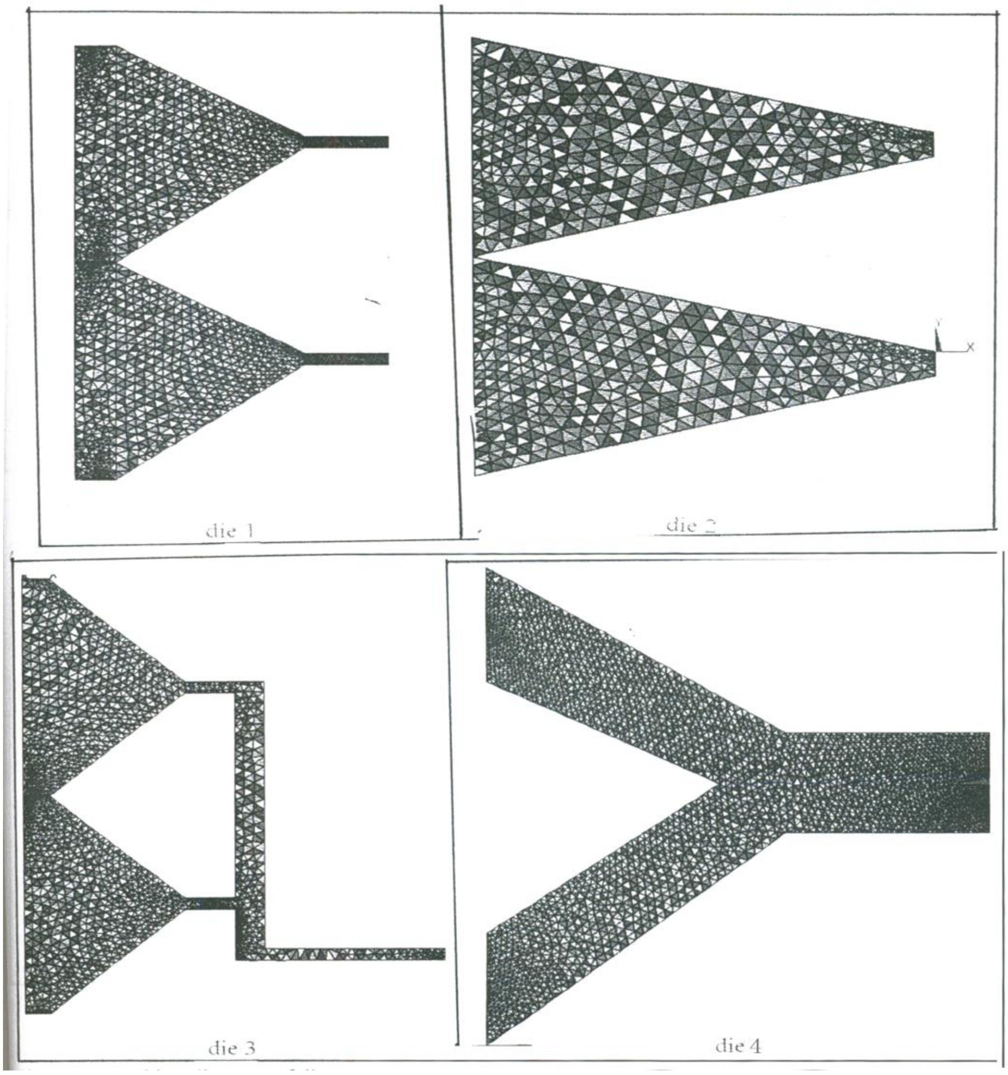


Figure 2 Meshing diagram of dies used in FLOTRAN analysis

3) Define lines, mesh, plot elements and nodes. The mesh shape selected is triangle (Figure 2) for optimum analysis. The finite element mesh (Figure 2) used has been chosen sufficiently fine to ensure satisfactory overall accuracy.

4) Apply velocity boundary conditions. Velocity loads of 160 rpm and 180 rpm were applied in sequence to the nodes at the inlet of the die. These screw speeds represent the inlet velocities of the food dough into the die. Velocity load of 0m/s was applied to the boundary nodes. The rotational speed of the screw (rpm) was changed to linear speed (m/s)

5) Apply thermal boundary condition. Temperature loads of 120°C, 140°C, 160°C and 180°C were applied to the nodes at the inlet of the die. These temperatures represent the temperature of the dough entering the die.

6) Set FLOTRAN solution options and execution controls. Two hundred simulation runs was selected for each of the input process parameter.

7) Set dough properties: Corn dough density was set at 1250 kg/m^3, viscosity set at 12770 Pa.s, specific heat is 2.7 KJ/Kg.K, and thermal conductivity is 0.2 W/m.K as determined in previous study (Adekola, 1999).

8) Set FLOTRAN flow environment parameters

9) Solve the problem

10) Read in result and Plot the temperature solution

11) Plot streamline contours

12) Plot velocity vectors

13) Plot particle traces contoured by temperature ‘temp’

14) Plot particle traces contoured by velocity magnitude ‘Vsum’

3 Results and discussion

Results are presented for the flow profile, pressure, temperature and flow rate for the four dies used in this study. These process parameters are considered the most important for die design (Adekola, 2014), extrusion processes synchronization and modeling of heat and flow distributions in the die. The parameters have also been proved by earlier experiments findings (Adekola, 1999) to have significant effect on the food dough and on the quality of the extrudate produced. The geometries of the dies are given in Figure 1. Different shapes and sizes were used for the simulation to show the effects of studied process parameters on the die. This will help in the optimum selection of die for different purposes intended.

Since it is assumed that the dough is incompressible the effects of density variation were not studied. Temperature of the dough at the die inlet and inlet velocity of the dough into the die were the two variables considered. The values of the inlet velocity studied are 120, 160, 200 and 240 rpm and the value of the temperatures studied are 160°C and 180°C.

3.1 Flow profile

Figures 3 and Figure 4 show the velocity vector plots for the dies at inlet velocity of 160 and 200 rpm respectively. These profiles are similar for other speeds considered. Temperature has no significant effect on the velocity vector. The concentration of the vector increases, as the cross-sectional area becomes smaller. The vectors are relatively linear in the transition section of the die because of the larger area and get concentrated towards the die exit.

Dies 1 and 2 show large concentration of velocity vector towards the die nozzle outlet. This is expected since velocity is proportional to area. However, dies 3 and 4 produced opposite results. Die 4 has too large die exit diameter the same as the inlet therefore the velocity vector are equally distributed within the die. Die 3 has a long die length and as such the flow becomes uniform and stabilized towards the die exit. It could be expected that the extrudate produced by dies 3 and 4 would be smoother and have less expansion ratio than those produced by dies 1 and 2. This is because the pushing force required to force out the extrudate is minimized.

The magnitude of the velocity vector increased with increase in inlet velocity. The general trend is to have higher magnitude at the narrower part of the die. For an inlet speed of 160 rpm, the highest vector magnitude obtained was 278 rpm in die 1, an increase of 118rpm while for inlet speed of 200 rpm, the highest vector magnitude obtained was 316 rpm.

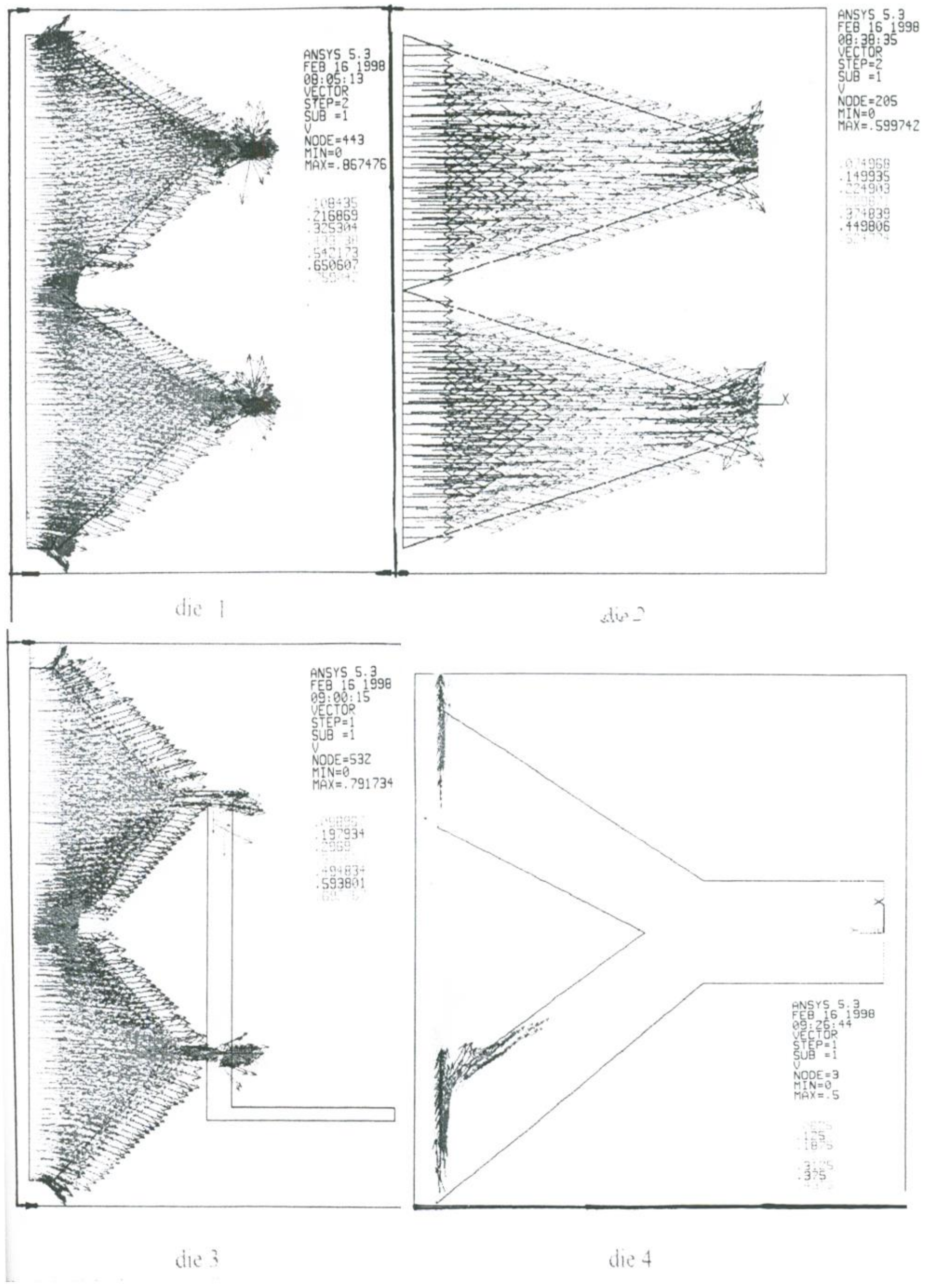


Figure 3 Velocity vector diagram at inlet velocity of 160 rpm

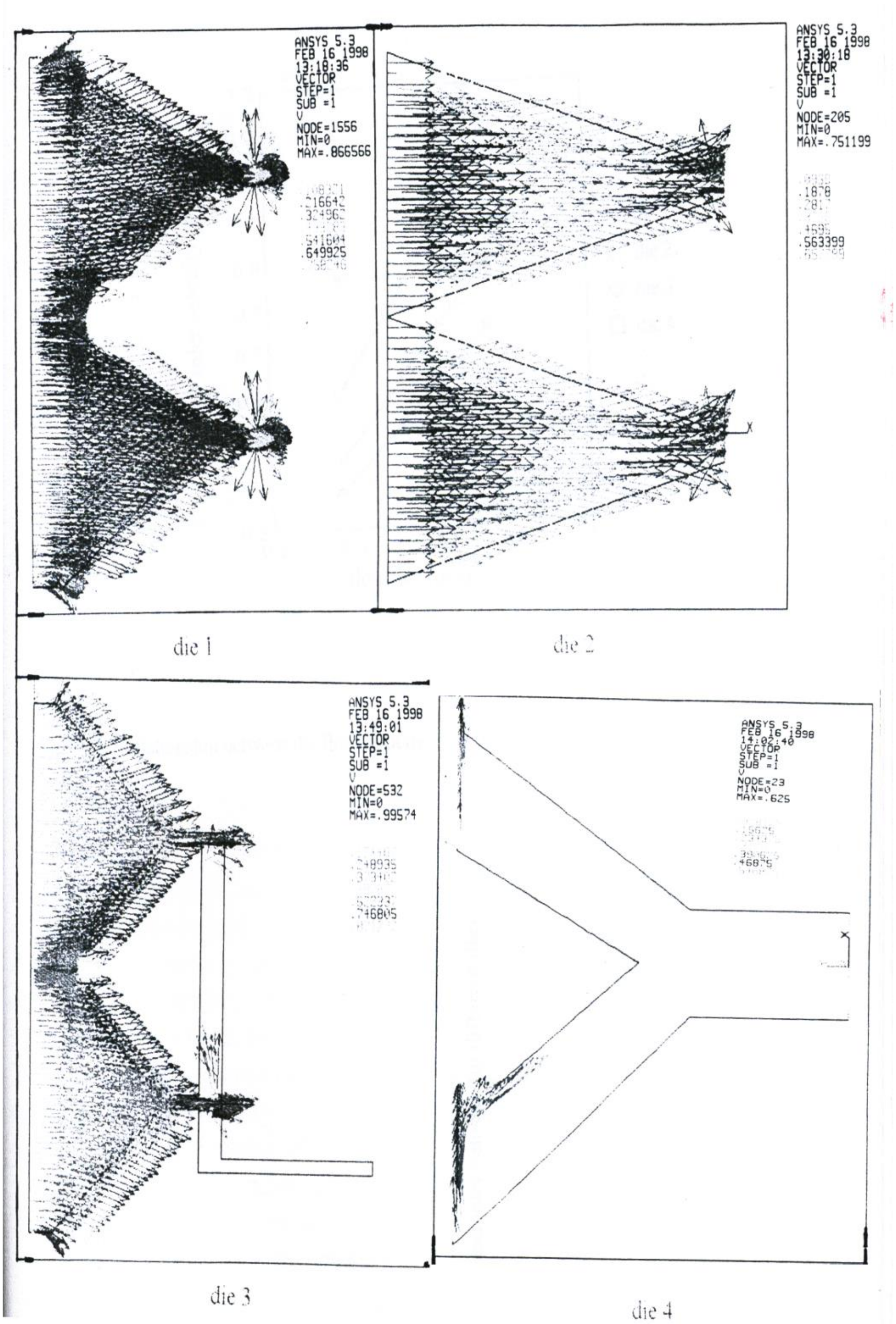


Figure 4 Velocity vector diagram for inlet velocity of 200 rpm

3.2 Flow velocity

The relationship between the flow velocity of dough in the die and the inlet velocity into the die is given in Figure 5. The flow velocity increases with increase in inlet velocity. The highest flow velocity obtained are higher than the inlet velocity for all the dies studied except die 4 which recorded the highest flow velocity as equal to inlet velocity. The reason may be that the dimensions of the die at the die inlet and outlet are the same.

It was also observed that when the inlet cross-sectional area of the die is smaller, the quantity of dough into the die is smaller which accounts for general low values of flow rate for die 4 when compared with other dies. This shows the flow throughput has a significant effect on the flow velocity. For all the dies considered in this work, the biggest velocity difference recorded between the inlet velocity and flow velocity was 0.2034 m/s (65rpm) for die 3.

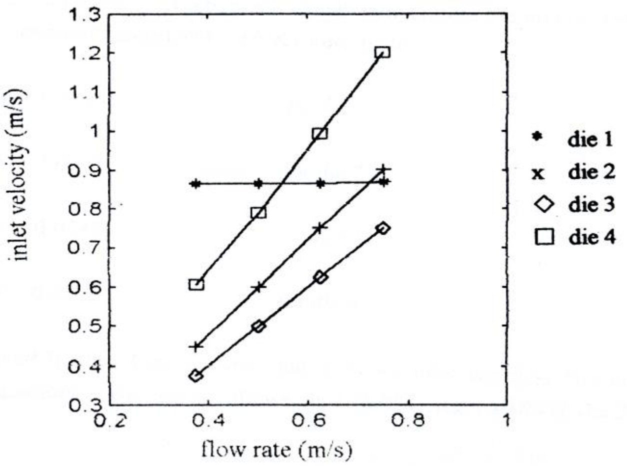


Figure 5 Relationship between the inlet velocity and flow velocity for dies

The simulated highest flow velocity and inlet velocity is related by the following equations below. The flow rate ‘Vsum’ for the dies are shown in Figure 6 for inlet velocity of 0.5m/s (160 rpm) and Figure 7 for inlet velocity of 0.625m/s (200rpm).

$$F = 0.0072V + 0.8629 \qquad \text{for die 1} \qquad (1)$$

$$F = 1.2120V - 0.0063 \qquad \text{for die 2} \qquad (2)$$

$$F = 1.6320V - 0.0243 \qquad \text{for die 3} \qquad (3)$$

$$F = 1.0000V - 0.0000 \qquad \text{for die 4} \qquad (4)$$

Where, F is the simulated highest flow velocity and V is the inlet velocity. The correlation coefficient, r for the equations above are as follows die 1 (0.954), die 2 (0.983), die 3 (0.919), and die 4 (0.966).

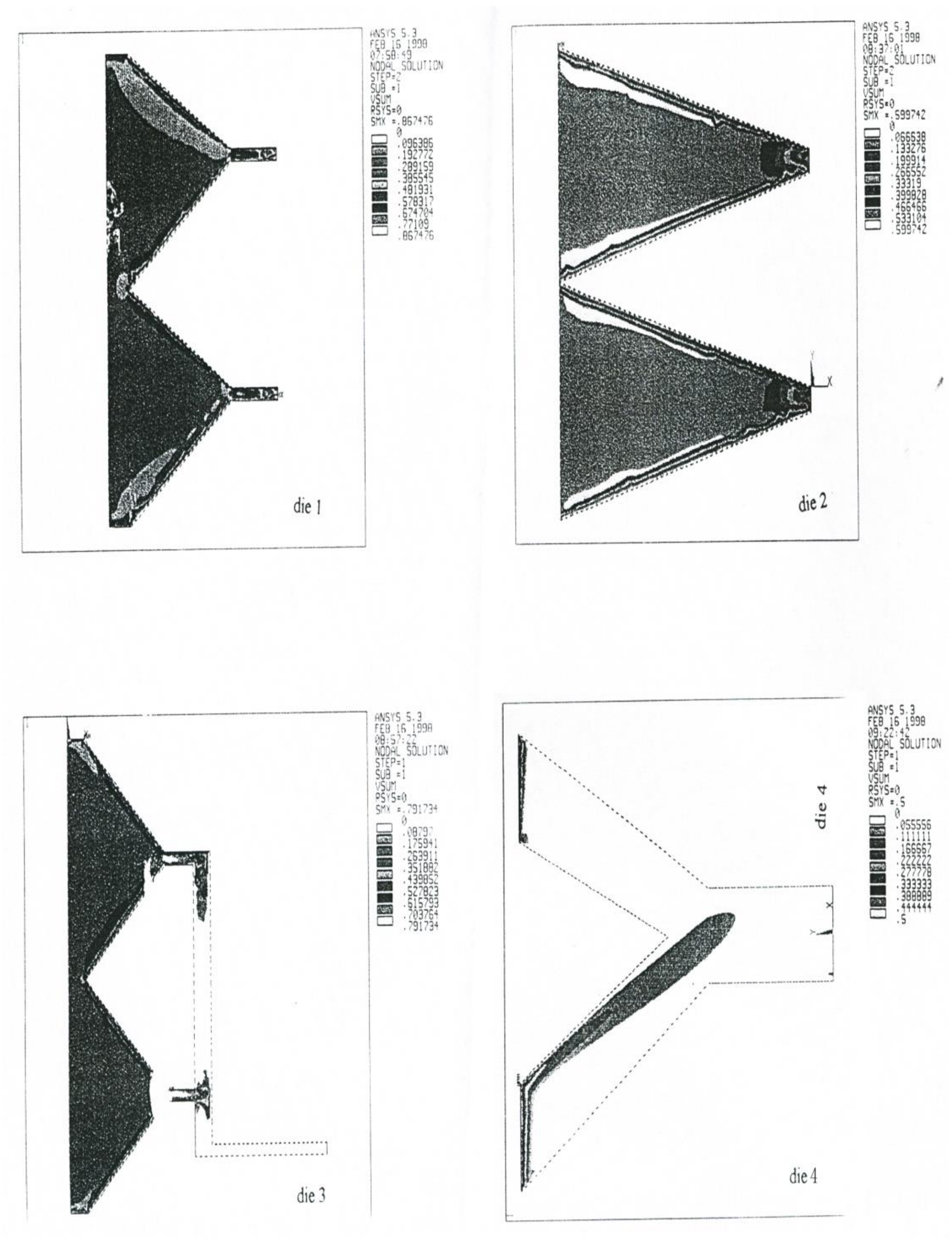


Figure 6 Flow distribution for dies at inlet velocity of 0.5 m/s (160 rpm)

3.3 Dough temperature

The highest temperature obtained is almost the same as the input inlet temperature within the range of ±2°C. The temperature reduces as the dough flow through the die. The low temperatures obtained are at the exit of the die nozzle for all the dies. The lowest temperature calculated by the program at the die nozzle exit is 20°C for all the input temperatures. Figure 8 shows the temperature distribution in the dies for inlet temperature of 160°C set for this study. The trend is similar for other inputted die inlet temperatures. The simulated results for die exit temperatures compare favorably with the results obtained during experiments for dies 1 and 2.

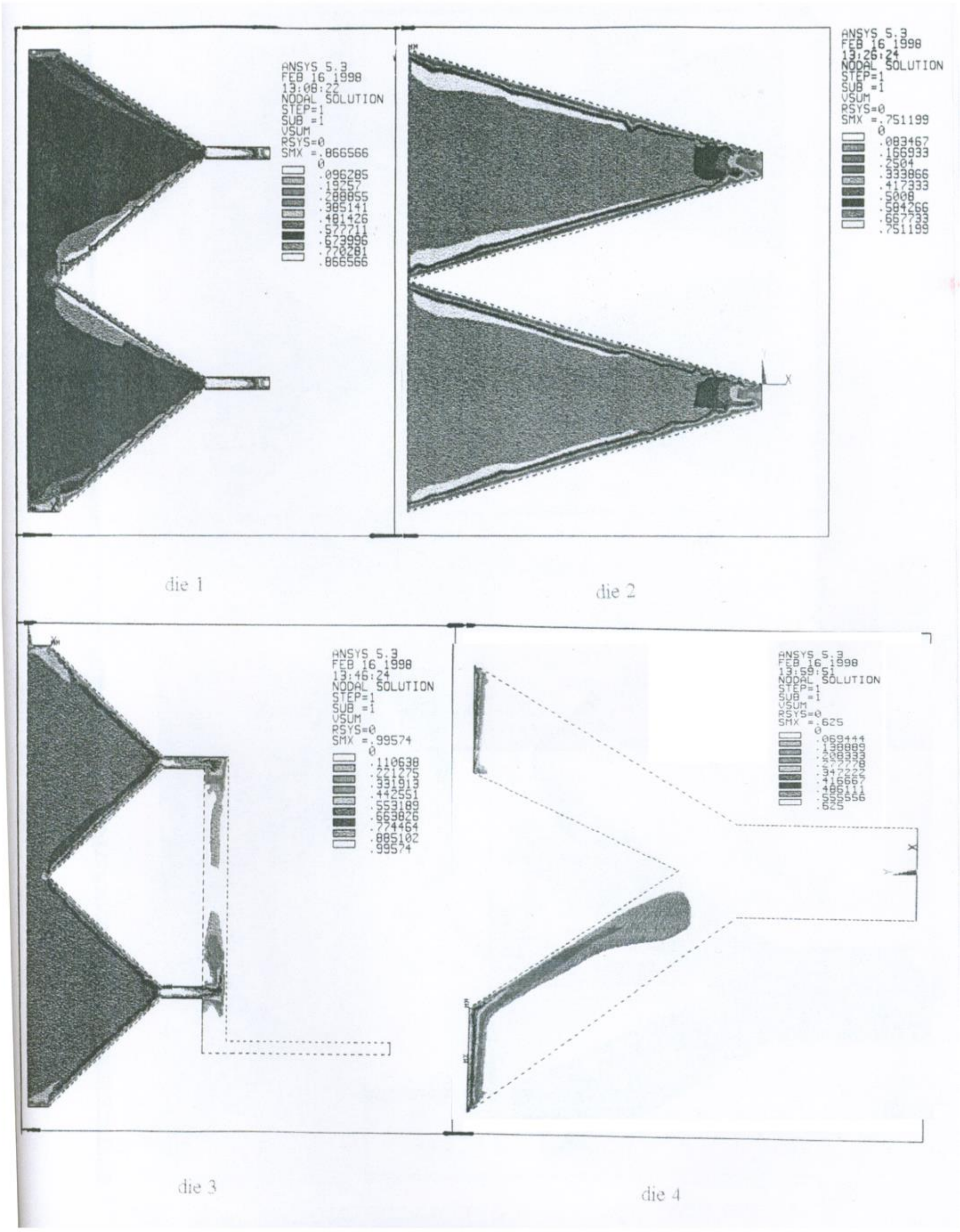


Figure 7 Flow distribution for dies at inlet velocity of 0.625 m/s (200 rpm)

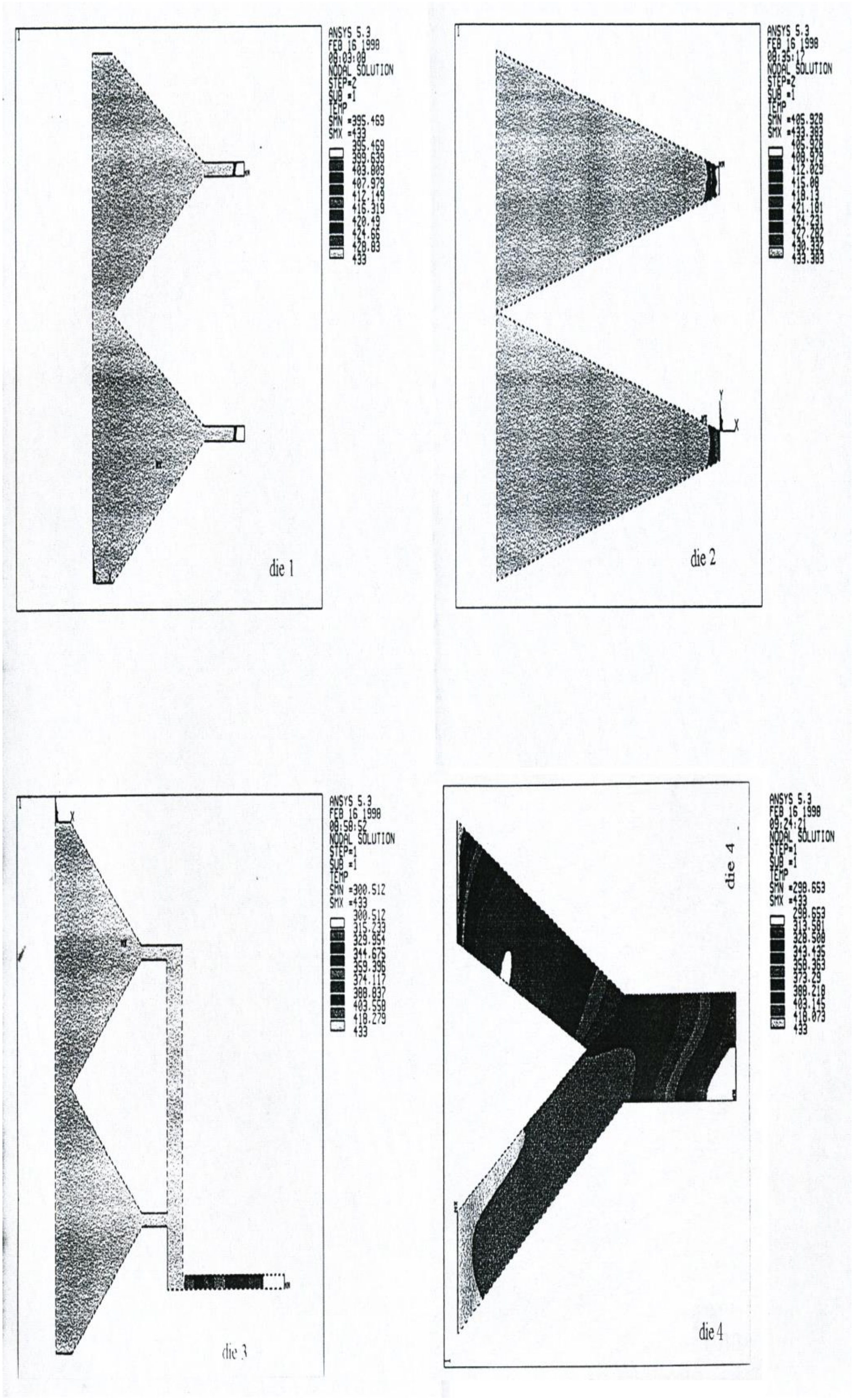


Figure 8 Temperature distribution for inlet temperature of 433K (160^{o}C)

At higher screw speed, the minimum temperature in the die decreased (Figure 9). The temperature differences between the maximum and minimum values obtained for the dies are 37.53K, 27.07K, 132.49K and 134.35K for dies 1, 2, 3 and 4 respectively. High temperature difference such as those obtained above caused variation in the quality of extrudate produced and could be responsible for the burning often experienced during extrusion cooking. Although, the dough residence time in the die is short, it is not unlikely that a wide temperature variation within a short time and length will not affect the chemical food constituent of the dough in the die.

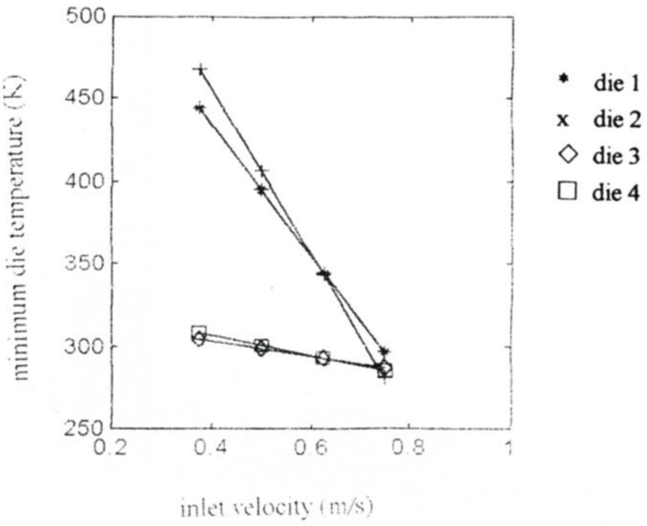


Figure 9 Relationship between minimum die temperature and inlet velocity

3.4 Die pressure

It is important to calculate the build up pressure before the extrudates are out and to estimate the pressure distribution in the die. Figure 10 shows the effects of inlet velocity on pressure. The pressures were measured during experimentation with the pressure gauge sensor mounted on the food extruder at the entrance of the dough into the die.

Figure 11 shows the pressure distribution for the dies studied at inlet velocity of 0.5 m/s (160 rpm) and inlet temperature of 433 K (160^{o}C). The pressure increases with screw speed. The pressure at the die exit is lower than the highest pressure recorded for all the simulation runs. In fact, as the dough gets to the dough exit, there is pressure drop. A pressure drop of more than 0.8MPa between the entrance and exit of the die was obtained.

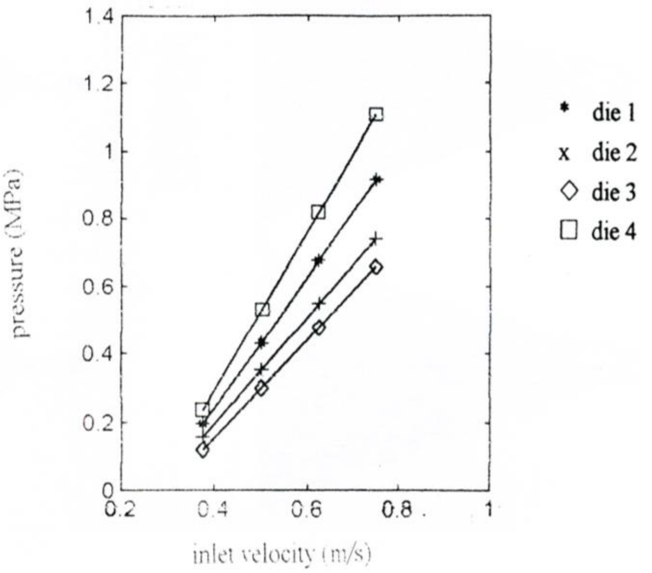


Figure 10 Relationship between pressure and inlet velocity at 0.5 m/s (160 rpm) and 433K (160^{o}C)

The pressure at the die exit is lower than the highest pressure recorded for all the simulation runs. In fact, as the dough gets to the dough exit, there is pressure drop. A pressure drop of more than 0.8MPa between the entrance and exit of the die was obtained.

The highest value of 0.434MPa obtained for die 1 compares favorably with the experimental result. The following equations relate the simulated pressure obtained and the inlet velocity for the dies.

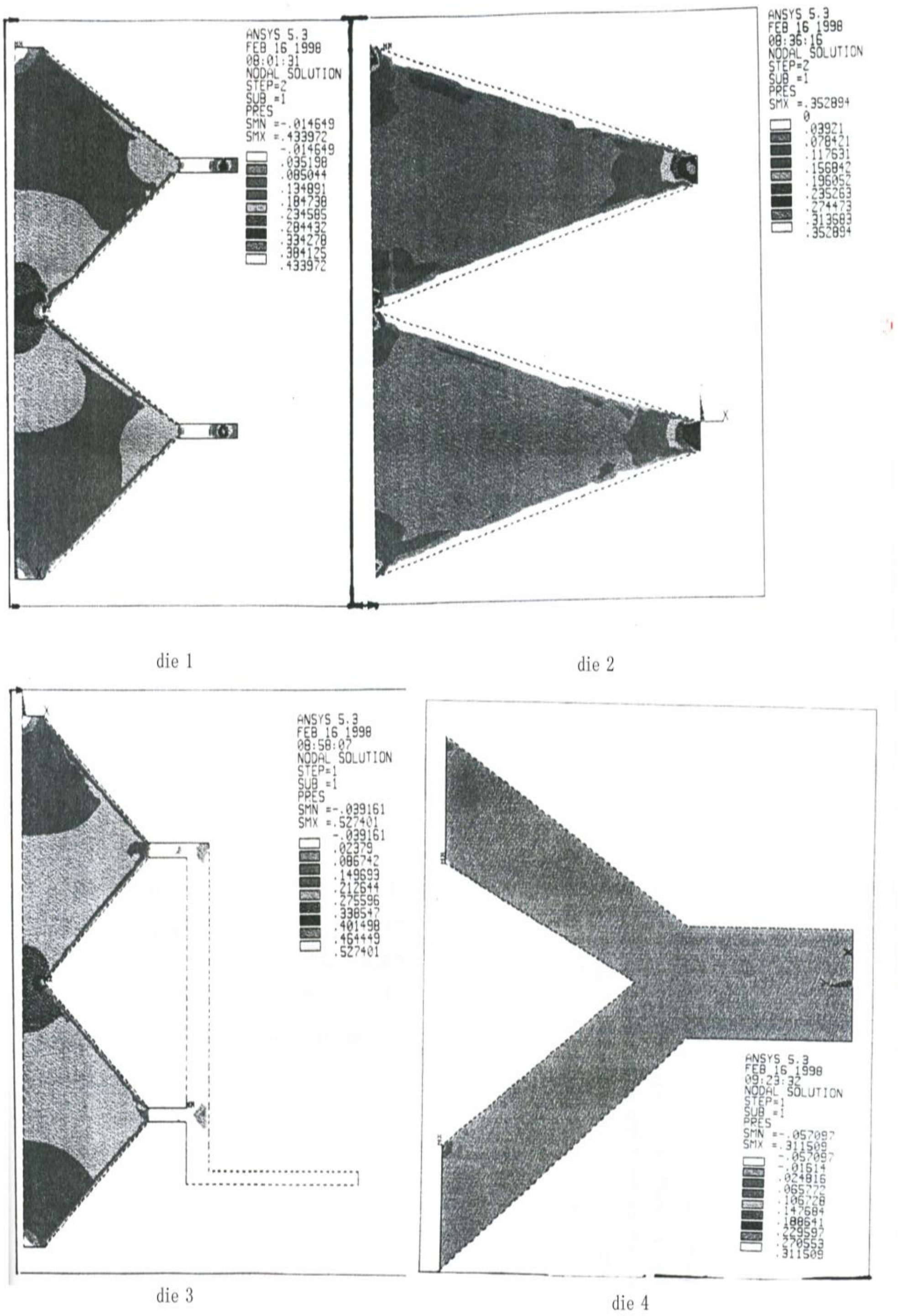
$P = 1.928V - 0.530$ for die 1 (5)

$P = 1.559V - 0.427$ for die 2 (6)

$P = 2.327V - 0.636$ for die 3 (7)

$P = 1.433V - 0.416$ for die 4 (8)

Where, P is the simulated pressure and V is the inlet velocity. The correlation coefficient, r for the equations above are die 1 (0.955), die 2 (0.976), die 3 (0.994), and die 4 (0.981) respectively.



die 1 die 2

die 3 die 4

Figure 11 Pressure distribution for dies at inlet temperature of 433K (160^{o}C) and inlet velocity of 0.5m/s (160 rpm)

4 Conclusions

With the simulation carried out in this work, it is possible to estimate the value of pressure, temperature, flow velocity e.t.a. at any point within the die. This can not be done experimentally even with present sophisticated technique and instrumentation. The simulation also made it possible to know the range values of pressure, temperature and flow rate.

These process parameters are important in die design and modeling. It is evident from the simulation results that the effect of die length, diameter and throughput are also significant. This can help to understand why expansion characteristics differ with dies even with the same corn dough. This can not be explained by experiments alone because of the sensitive nature of food dough. Selection of inlet velocity (assumed to be screw speed) into the die is very important as it affects all the process parameters.

Dough temperature has no effect on flow rate within the temperature range of 120°C to 180°C. The temperature of the dough decreases as it flows through the die. With increased inlet velocity, minimum temperature in the die decreased. The temperature differences between maximum and minimum values obtained are 37°C, 28°C, 132°C and 134°C for dies 1, 2, 3 and 4 respectively. The pressure increases with screw speed.

The simulated values of flow velocity and experimental values for flow velocity correlation coefficient, r obtained are die 1 (0.954), die 2 (0.983), die 3 (0.919), and die 4 (0.966). Similarly, the simulated values of die pressure obtained compare favorably with the experimental results. The correlation coefficient, r for die 1 (0.955), die 2 (0.976), die 3 (0.994), and die 4 (0.981) respectively. The values of temperature obtained for die exit temperature by simulation and experiment compare favorably. This shows that the simulation procedure employed using ANSYS FLOTRAN computer simulation package is reliable enough to accurately predict the dough flow velocity, die pressure and temperature of the corn dough at any point in the die.

Studies are needed on the simulation and modeling of influence of changes in viscosity and density of corn dough during extrusion on process parameters, flow and heat distribution. Analysis may be extended to 3-dimensional analysis for flow in food extruder analysis to enhance further understanding of the die internal mechanism.

References

Adekola, K.A. 2015. Influence of food extruder die dimension on extruded products

expansion. *Agricultural Engineering International,* 17(1): 255-263.

Adekola, K.A. 2014. Analytical engineering designs for twin-screw extruder die. *International Journal of Engineering Innovations and Research,* 3(5): 713-717.

Adekola, K. A. 1999. Studies into twin screw food extruder die. Ph.D Thesis. Changchun, China. Jilin University of Technology, Department of Agricultural Engineering. Pp. 135 –158

Adekola, K.A., C.L. Ma and C.C. Zuo. 1998. Estimation of temperature profile in food extruder dies. *Transactions of Chinese Society of Agricultural Engineering,* 14(3): 226-230.

ANSYS / FLOTRAN 1998. Operating Manual (Analysis and Theory Guides).

Chen, H.Y. and A. Friis. 2010. Modelling extrudate expansion in a twin-screw

extrusion cooking process through dimensional analysis methodology. *Food and Bioproducts Processing,* 88(2-3): 188-194.

Della Valle, G.., C. Barres, J. Plewa and B. Vergnes. 1993. Computer simulation of

starchy products transmission by twin-screw exrusion. *Journal of Food Engineering,* 19(1): 1-31.

Eise, K., J. Curry and J.F. Nangeroni. 1983. Compounding extruders for improved polybends. *Polymer Engineering Science,* 23(4): 642-646.

Emin, M.A. and H.P. Schuchmann. 2013. Analysis of the dispersive mixing efficiency in a twin screw extrusion processing of starch based matrix. *Journal of Food Engineering,* 115(1): 132-143.

Kim, M.H. and J.L. White. 1989. Simulation of flow in modular tangential counter-rotating twin screw extruders: screw flight staggering and backward pumping elements. SPE ANTEC Technical Paper, 35: 49.

Ollet, A.L., Y. Li, R. Parker and A.C. Smith. 1989. A comparative study of the conveying performance of screw in a twin screw co-rotating extrusion cooker. *Journal of Food Engineering,* 10(3): 165-181.

Sastrohartono, T., V.K. Mukund, Y. Jaluria and H.K. Tai. 1991. Numerical simulation of fluid flow and heat transfer in a twin screw extruder. Publication no. F10544-5-91 of the New Jersey Agricultural Experimental Station, 89-104.

Szydlowski, W. and J.L. White. 1987. An improved theory of metering in an intermeshing co-rotating twin screw extruder. *Advanced Polymer Technology,* 7(2): 177.

Van Der Wal, D.J., D. Goffart, E.M. Klomp, H.W. Hoogstraten and P.B.M. Janseen. 1996. Three-dimensional flow modeling of a self-wiping corotating twin screw extruder. Part II: The kneading section. *Polymer Engineering Science, 36(7): 912-924.*

Yang, H.H. and I. Manas-Zloczower. 1992. Flow profile in kneading elements in the intermeshing corotating twin screw extruder. *Polymer Engineering Science*, 32(3): 1411.

Morgan-Sagastume, F., B. E. Sleep, and D. G. Allen. 2001. Effects of biomass growth on gas pressure drop in biofilters. *Journal of Environmental Engineering-Asce,* 127(5): 388-396.

O'Neill, D. H., I. W. Stewart, and V. R. Phillips. 1992. A review of the control of odour nuisance from livestock buildings: Part 2, the costs of odour abatement systems as predicted from ventilation requirements. *Journal of Agricultural Engineering Research,* 51(?): 157-165.

Phillips, V. R., I. M. Scotford, R. P. White, and R. L. Hartshorn. 1995. Minimum-cost biofilters for reducing odors and other aerial emissions from livestock buildings .1. Basic air-flow aspects. [Article]. *Journal of Agricultural Engineering Research,* 62(3): 203-214.

Poulsen, T., G. Minelgaite, T. Bentzen, and R. Andreasen. 2013. Minor losses during air flow into granular porous media. *Water, Air, & Soil Pollution,* 224(9): 1-11. doi: 10.1007/s11270-013-1666-2

Pugliese, L., T. Poulsen, and R. Andreasen. 2013. Biofilter media gas pressure loss as related to media particle size and particle shape. *Journal of environmental engineering,* 139(12): 1424-1431. doi: doi:10.1061/(ASCE)EE.1943-7870.0000771

Ryu, H. W., K. S. Cho, and D. J. Chung. 2010. Relationships between biomass, pressure drop, and performance in a polyurethane biofilter. *Bioresource Technology,* 101(6): 1745-1751. doi: 10.1016/j.biortech.2009.10.018

Schiffman, S. S., E. A. Sattely Miller, M. S. Suggs, and B. G. Graham. 1995. The effect of environmental odors emanating from commercial swine operations on the mood of nearby residents. *Brain Research Bulletin,* 37(4): 369-375.

Scotford, I. M., C. H. Burton, and V. R. Phillips. 1996. Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings .2. A model to analyse the influence of design parameters on annual costs. *Journal of Agricultural Engineering Research,* 64(2): 155-163.

Swanson, W. J., and R. C. Loehr. 1997. Biofiltration: Fundamentals, design and operations principles, and applications. [Proceedings Paper]. *Journal of Environmental Engineering-Asce*, 123(6): 538-546.

Tabase, R. K., D. Liu, and A. Feilberg. 2013. Chemisorption of hydrogen sulphide and methanethiol by light expanded clay aggregates (leca). *Chemosphere,* 93(7): 1345-1351. doi: http://dx.doi.org/10.1016/j.chemosphere.2013.07.068