Rotational effects of polymeric fluids on shape of filaments in melt extruded net structures

A. Rawal*[1] and J. W. Gonsalves[2]

The present work deals with the net structures, which are produced by replacing the static die (spinneret) with two concentric dies rotating in opposite directions in a melt extrusion process. These dies consist of defined number of slots with non-circular geometries on their peripheries and the filaments are produced when the slots in disk and annulus are offset from each other. The effect of die rotation on the shape of filament is investigated by analysing the polymer flow inside the complex die slots including square and trapezoidal shapes, using computational fluid dynamics (CFD). The die slot shapes have also been predicted using CFD to achieve the desired filament shape.

Keywords: Power law, Computational fluid dynamics, Die slot, Filament, Extrudate, Net

Introduction

Melt extrusion is the most versatile process in polymer technology with diverse applications. The list of applications is extensive and ranges from filaments to net structures. The net structures are produced by replacing the static die or a spinneret normally used for filament production by two counter-rotating dies.[1] In this process, polymer chips are fed to a hopper from which they pass into a single screw extruder. The single screw extruder has two tasks i.e. firstly to melt the polymer and secondly to pump the molten polymer through the die head at a constant rate. The die head is made up from a concentric disk and annulus, which can either rotate, oscillate or be held stationary. Both disk and annulus consist of a defined number of slots on their peripheries. When the slots in disk and annulus are offset from each other the filaments of the net are formed, however, when the slots are adjacent, a joint is formed between the two filaments. Finally, the net structure is drawn under water and given some stretch and orientation by means of drawing rollers. The required quality of net can be achieved with rotation of the die, as the molecules of the polymer align themselves in the direction of flow, enhancing the mechanical properties of net structure. In addition, it has been noted that in order to study these net structures and the manufacturing process and to be able to predict the mechanical behaviour, it is important to develop theoretical models. These models may be generated as a result of process simulation through polymer flow modelling.

A fully predictive computer single screw extrusion model[2] has been developed for the single screw plasticating extruders. The model takes into account five zones of extruders (hopper, solids conveying, delay zone, melting zone and melt conveying) and the die, and it describes an operation of the extruder–die system, which predicts the mass flow rate of the polymer, the pressure and temperature profiles along the screw channel and, in the die, the solid bed profile and power consumption. The required simulation parameters are the material and rheological properties of the polymer, the screw, hopper and die geometry and the operating conditions (screw speed and barrel temperature profile). The model also makes it possible to predict the morphological changes of a polymer blend. After passing through the screw the molten polymer flows into the die or a spinneret where it is pushed into a small duct and tries to achieve the desired shape determined by the die slot shape. The extrudate shape is mainly dependent upon the corresponding die slot shape, however, the shape of the extrudate also depends upon the pressure drop and flow rate of the polymer inside the die slot. The pressure drop and flow rate of the polymer may be studied using Navier–Stokes equations of motion by incorporating one or more variables such as the stress tensor which is produced by various mathematical models.[3,4] In general, the die slot shapes may be classified in two categories: circular and non-circular shapes. In the case of circular shapes,[5] the equations of motion involving non-Newtonian flows (polymer flows) can be solved easily by using simple integration methods. However, in non-circular shapes, the equations of motion may result in non-linear partial differential equations, which are difficult to solve analytically. Therefore, approximate methods such as the variational method[6] are generally used for the non-Newtonian flow problems. Schechter[7] used the application of variational methods to solve the non-linear partial differential equation of pressure drop and flow rate of the polymer in case of non-circular shapes such as rectangle and square. Moreover,

---

[1] National Fibre, Textile and Clothing Centre, Manufacturing and Materials Technology, CSIR, Gomery Avenue, Summerstrand, Port Elizabeth 6000, South Africa
[2] Department of Mathematics and Applied Mathematics, Nelson Mandela Metropolitan University, Port Elizabeth, 6031, South Africa

*Corresponding author, email amitrawal77@yahoo.com

Published by Maney on behalf of the Institute
Received 29 August 2005; accepted 21 October 2005
DOI 10.1179/174328906X79879

Mitsuishi and Aoyagi[8,9] used similar methods for other non-circular shapes such as an isosceles triangle. Similarly, Arai and Toyoda[10] formed the mathematical model to compute the wall shear stresses through pressure drop in a rectangular die slot shape using the power law. These models have been developed for stationary die slots, however, in the case of rotating die slot systems, the extrudate or filament geometry is also influenced by the rotational speed of the die.

This paper reports a series of polymer flow modelling investigations in which the velocity profiles for a range of complex rotating die slot geometries including square and trapezoidal shapes have been computed. This would help in designing the die slot geometries for required filament geometries.

Problem formulation

In the Netlon process[1], the polymer fluid flows in the die slot in which it is sheared in tangential and radial directions by die rotation and in the axial direction by take-up speed and pressure drop. However, the shear in the axial direction can be neglected as the net structures were immediately quenched by water. This shows that the polymer molecules are set in a rigid structure and the take-up speed (axial) is not able to induce its shear on the polymer molecules. Therefore, the effect of die rotation was quantified by analysing the polymer flow in tangential and radial directions using computational fluid dynamics (CFD). In general, there are a defined number of slots on each die, but it is assumed that flow rate in all the slots would be same and, hence, polymer flow can be analyzed for a single slot.

The polymer flow inside the rotating die slots was modelled as a two dimensional cavity flow such that only one of the walls of the die slot was rotating and other three were stationary. This problem was investigated by analysing the polymer flow at the exit of the die slot using finite element modelling based upon computational fluid dynamics (CFD).[11] To simplify the problem, the following assumptions were made during the analysis of polymer flow

- fluid flow is laminar and temperature independent
- fluid flow is incompressible
- direction of the rotation of the die wall is towards the $+x$-axis

Governing equations

The flow fields, i.e. the velocity and pressure are assumed to satisfy the steady Navier–Stokes equations defined as follows

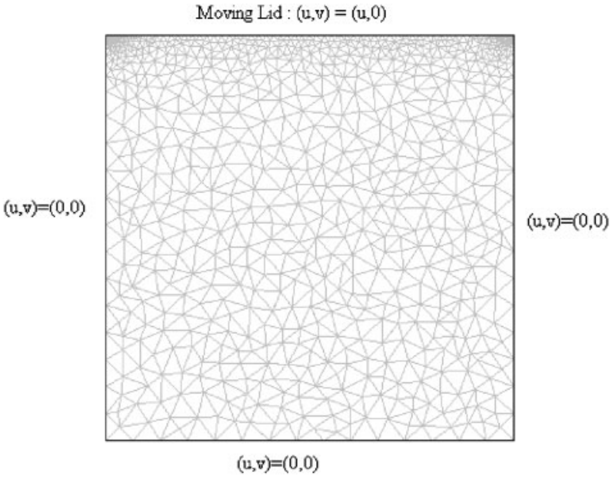
$$-\nabla\cdot\eta(\nabla\mathbf{u}+(\nabla\mathbf{u})^{\mathrm{T}})+\rho(\mathbf{u}\cdot\nabla)\mathbf{u}+\nabla \mathrm{p}=0 \tag{1}$$

and

$$\nabla\cdot\mathbf{u}=0 \tag{2}$$

where ρ defines the density, **u** is the velocity field, p is the pressure and η is the dynamic viscosity.

The above equations can be generalised for non-Newtonian fluids (polymer flows) by incorporating the shear viscosity η as a function of shear rate $\dot{\gamma}$ using various models.[3,4] However, here the power law has been applied as it is commonly used in the polymer industry; this is given by equation (3).



1 Flow in a square cavity

$$\eta=m\dot{\gamma}^{\mathrm{n}-1} \tag{3}$$

where m and n are power law constants characteristic of polymer fluid.

The above equations cannot be solved analytically due to their highly non-linear nature. Hence, the problem has been simplified by reducing the three-dimensional problem to the cavity-driven flow in two dimensions, where the fluid motion is driven by the moving lid.[12] By ensuring that the moving lid is parallel to the x-axis, the associated boundary conditions, to which the governing equations must be subjected, have been introduced. The boundary side representing a moving lid has velocity $\mathbf{u}=(u_0, 0)$, whereas the remaining three sides satisfy non-slip boundary conditions, $\mathbf{u}=(0, 0)$.

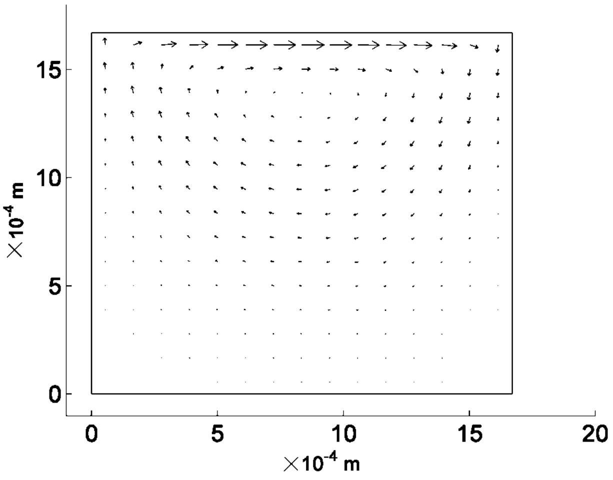
Computational aspects

The multiphysics software package FEMLAB (finite element modelling laboratory) was employed in the research work.[11] Recent benchmark studies have shown FEMLAB is a highly capable tool for handling CFD problems.[13]

In the present work, the domain was partitioned using triangular elements with mesh size ranging between 1000 and 2000 elements. Each mesh was generated with local refinements in the vicinity of the moving lid as shown in Fig. 1. This refinement not only contributes to the accuracy of the solution but also stabilises the convergence process. The problem was further stabilised by a process known as the continuation method. In this method, the solver starts computing the problem for the lowest value of the parameter selected (in our case $u_0=0$), later the solution is determined for higher values of u_0. At each stage, the solution is calculated from the previous value of the parameter as an initial estimate.

Results and discussion

In this paper, two die slot geometries are considered namely square (1·67 mm depth and 1·67 mm width) and trapezoidal (0·73 mm depth and 2·03 mm width with leading and trailing angles of 35° and 55°, respectively) on the periphery of the die having a diameter of 0·20 m. The polymer flow was analysed at linear die speeds of 0·23 m s^{-1} and 0·70 m s^{-1} and the type of polymer used

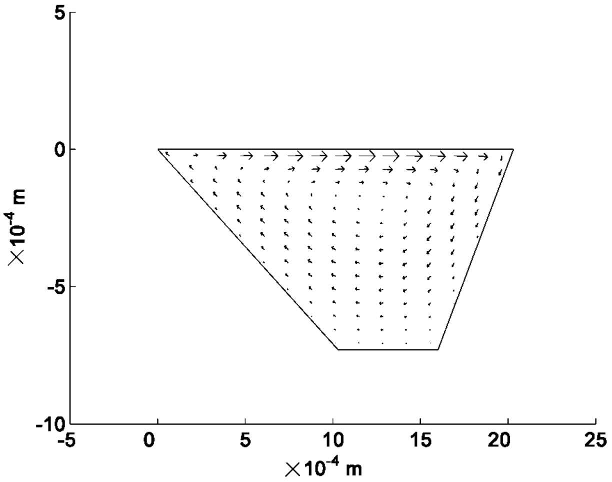


2 Velocity vector in a square die slot

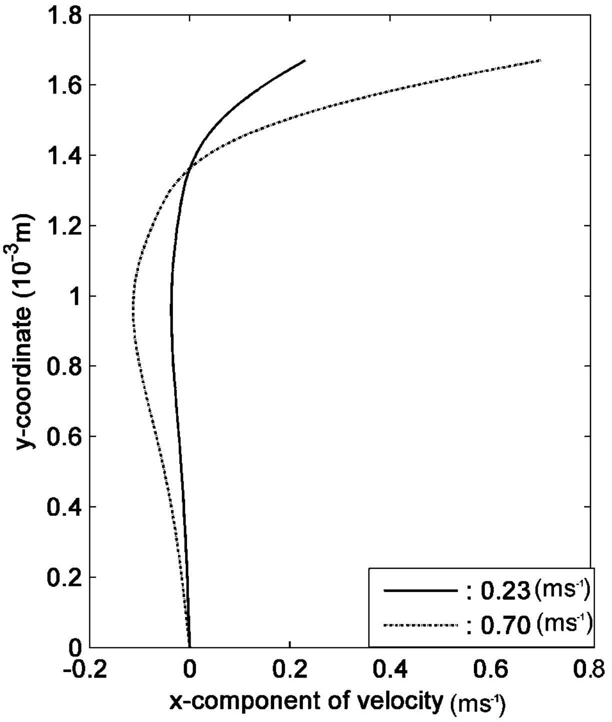
was polyethylene having a viscosity of 150 kg m^{-1} s^{-1} at 190°C and power law constants, i.e. *m* and *n* are 6900 N $s^{1/2}$ m^{-2} and 0·5, respectively.[5]

Numerical results

As mentioned before, the flow of the polymer is computationally defined by a finite domain, i.e. at the exit of the die slot. In general, the rotating wall is accelerating the fluid, however, the fluid resists the force of moving wall as it has a higher extensional viscosity compared with the corresponding Newtonian fluid. Subsequently, the fluid is pushed and decelerated due to the resistance offered by the end corner of the wall and resulting in a recirculation region. Figures 2 and 3 show the vector plot of recirculation region of the fluid caused by the rotating wall in square and trapezoidal die slots, respectively. On increasing the speed of the rotating die wall, the fluid is further accelerated and the resulting recirculation region will have fluid particles of varying velocities along the depth of the die slot. Figure 4 shows the comparison of the velocity profiles of the fluid along the centre-line of flow (*y* axis). It is clearly shown that increasing the rotational speed of the die wall will cause skewness in the fluid velocities along the centre line of the flow. In the case of a trapezoidal die slot, the effect of die rotation is more pronounced as shown in Fig. 5.



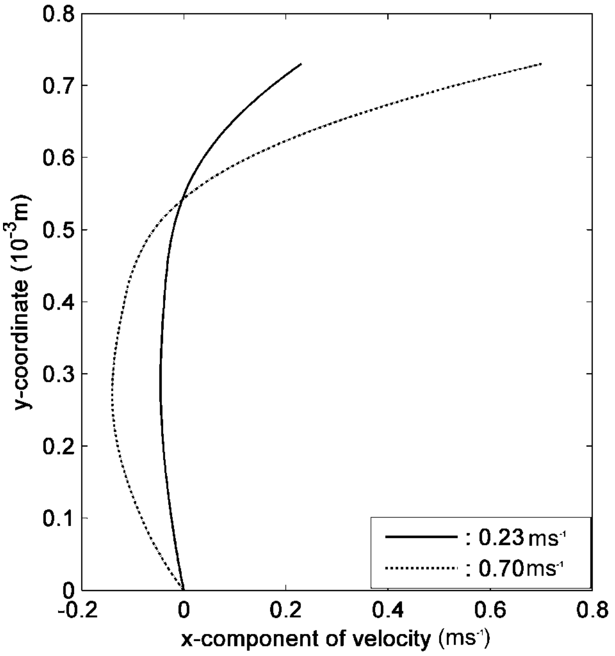
3 Velocity vector in a trapezoidal die slot



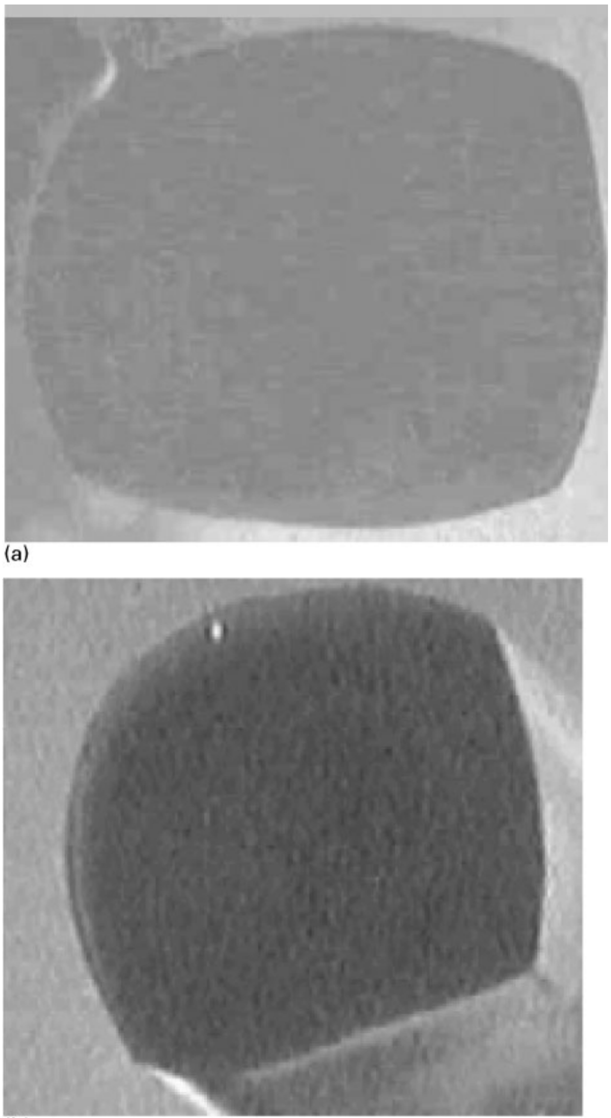
4 Velocity profile in a square die slot along the centre-line of the flow

Comparison with experimental results

A series of net structures were produced using rotating die systems at the collaborating company. Figures 6 and 7 show the comparison of the filaments produced from rotating die systems at different die speeds using square and trapezoidal die slot geometries, respectively. The samples shown in Figs. 6*a* and 7*a* are produced at die speeds of 0·23 m s^{-1} whereas those in Figs. 6*b* and 7*b* are produced at die speeds of 0·7 m s^{-1} by keeping the other variables constant. It has been observed that the filament shapes obtained at a higher die rotational speed



5 Velocity profile in a trapezoidal die slot along the centre-line of the flow



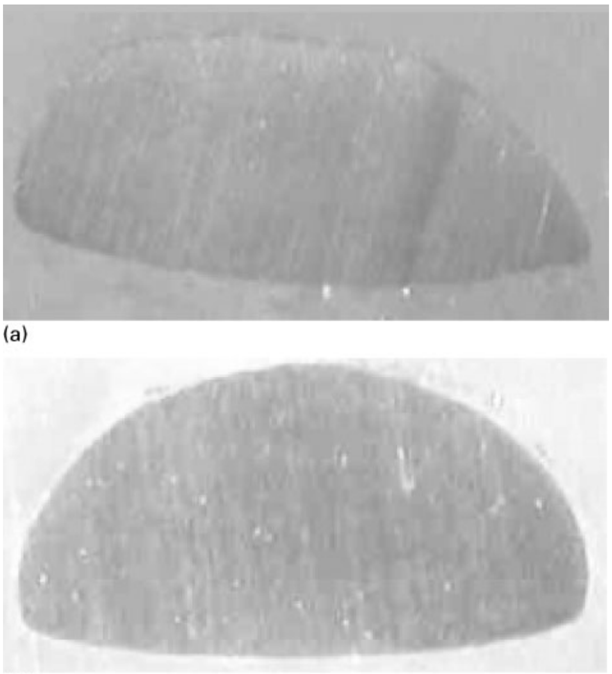
6 Shapes of the filament produced from square die slot *a* 0·23 m s^{-1} *b* 0·70 m s^{-1}

are relatively more circular in geometry as shown in Figs. 6 and 7. Increasing the rotational speed of the die wall causes a deviation in the fluid velocities along the centre line of the flow. The polymer fluid particles having higher velocities will also deviate from their respective locations. Furthermore, the polymer flow emerging out of the die slot is immediately quenched by water and during the transformation of fluid to semi-solid state, the fluid particles having higher velocities tend to move outwards to attain minimum energy. This causes the circularity in the filaments at the positions where the fluid particles have higher velocities, i.e. along the depth of the die slot.

Prediction of die slot geometries

In general, the filament shape is affected by die rotation as mentioned above. Therefore, the required filament shape can be achieved in the following two ways.

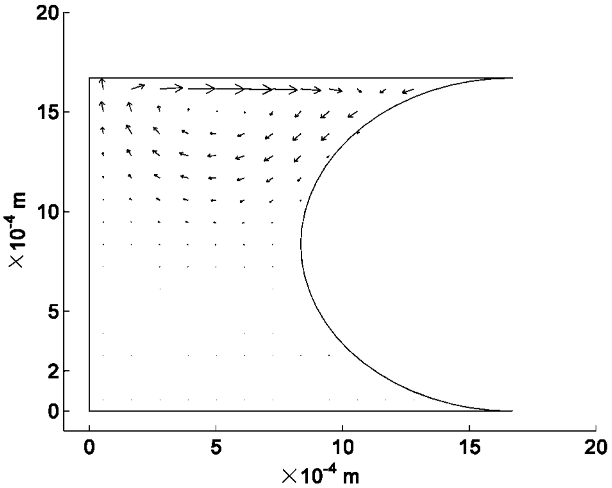
- First, the die speed can be reduced, which will induce minimum shear into the flow particles and, hence, the extent of the circularity in the filament shape will be low. However, it will reduce the production rate of the net structures.



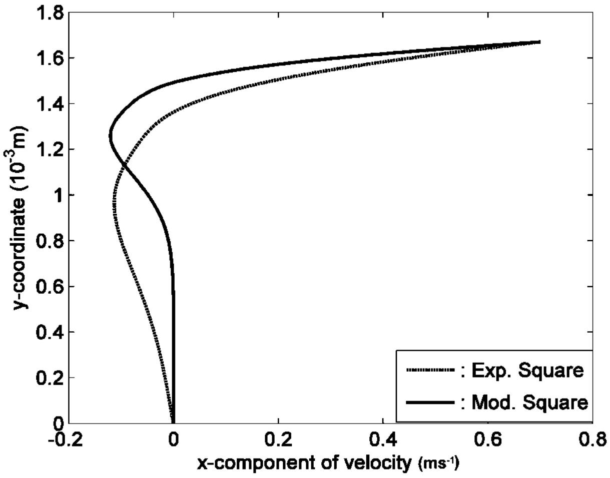
7 Shapes of the filament produced from trapezoidal die slot *a* 0·23 m s^{-1} *b* 0·70 m s^{-1}

- Secondly, the die should be designed in such a way that the filament emerging from the slot should have minimum circularity at a higher die speed. This will lead to less deviation in filament shape from its corresponding die slot shape.

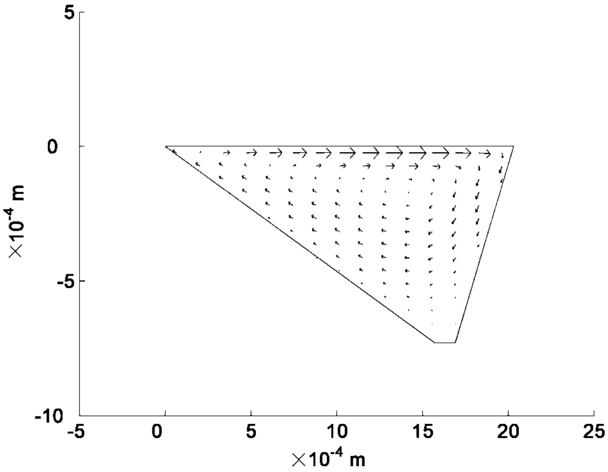
Therefore, die shapes were predicted using the FEMLAB package, based upon the fact that the deviation in the fluid velocities along the centre line of the flow should be at a minimum. In a square die slot, one of the straight stationary walls was replaced by a convex wall and referred to as a 'modified square' die slot. Figure 8 shows the velocity vector of the flow in a modified square die slot. It was found that in a modified square die slot, even at the higher die wall speed (i.e. 0·70 m s^{-1}), the fluid velocity at the lower half of the die slot remains constant (shown in Fig. 9). However, it is expected that the corner of the filament will be slightly more circular than the corresponding filaments



8 Streamline flow in a modified square die slot



9 Comparison of modified and experimental square die slots along the centre line of the flow



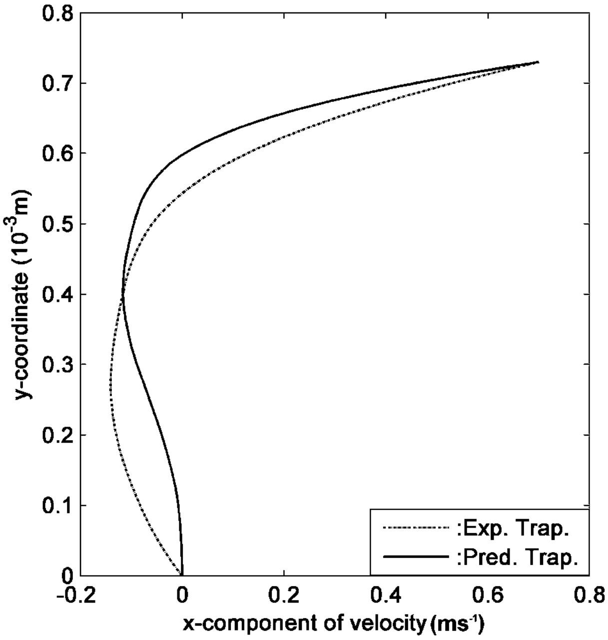
10 Streamline flow in a predicted trapezoidal die slot

produced from regular square die slots. In the case of trapezoidal die slot shape (as shown in Fig. 10), it was found that by changing the leading angle (25°) and the trailing angle (65°), the deviation in the fluid velocities along the centre line of the flow was found to be a minimum, as shown in Fig. 11. Hence, the trapezoidal die slot shape can be designed by optimising the leading and trailing angles. This will reduce the extent of circularity in the polymer shape even at higher speeds and the filament shape produced should be similar to their corresponding die slot shape.

The authors recognise that the predicted die slot shapes (specifically for square die slots) are complex to manufacture and further work would be required to design these die slot geometries based on our prediction.

Conclusions

A multiphysics finite element package was used for the analysis of polymer flow at the exit of rotating square and trapezoidal die slot shapes. This has demonstrated that deviation in the fluid velocities along the centre-line of the flow contributes to the circularity in the filament. Therefore, the shapes of die slots have been predicted in order to achieve the desired filament shape.



11 Comparison of predicted and experimental trapezoidal die slots along the centre line of the flow

Acknowledgements

The authors are extremely thankful to Tensar International Ltd, UK for their support in this research work.

References

1. F. B. Mercer: 'Improvements relating to the production of net or netlike fabrics by extrusion methods', GB Patent No. 836,555, June 1, 1960.
2. K. Wilczynski: *Polym-Plast Technol. Eng.*, 1999, **38**, 581.
3. E. C. Bingham: 'Fluidity and plasticity'; 1922, New York, McGraw–Hill.
4. P. J. Carreau, PhD Thesis, University of Winsconsin, Madison, 1968.
5. R. B. Bird: 'Dynamics of polymeric liquids'; 1977, New York, John Wiley & Sons.
6. L. V. Kantorovich and V. I. Krylov: 'Approximate methods of analysis'; 1958, New York, Interscience Publishers.
7. R. S. Schechter: *AIChE J*, 1961, **7**, 445.
8. N. Mitsuishi and Y. Aoyagi: *J. Chem. Eng.*, 1973, **6**, 402.
9. N. Mitsuishi and Y Aoyagi: *Chem. Eng. Sci.*, 1969, **24**, 309.
10. T. Arai and H. Toyoda: Proc. 5th International Rheological Congress, Kyoto Japan, 1970, 461–470.
11. 'FEMLAB 3·0a: User and Reference Manual', Stockholm, Sweden, 2004.
12. A. M. Grillet, B. Yang, B. Khomami and E. S. G. Shaqfeh: *J. Non-Newtonian Fluid Mech.*, 1999, **88**, 99–131.
13. http:www.maths.lth.se/na/staff/olivier/BenchmarkReport2.pdf