HOW DO MULTIPLE FLIGHTS IMPROVE THE EFFECTIVENESS OF A COOLING EXTRUDER SCREW?

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Abstract

As the use of tandem extrusion lines to produce quality structured foams expands, the need for better cooling screws is receiving increased attention. In a tandem extrusion line, the role of the cooling extruder is to efficiently remove heat from the gas-laden melt, without excessive viscous heat generation. There are a variety of design elements that are commonly applied to cooling screws, but the use of multiple flights is the most common method. However, it is not clear how multi-flight configurations lead to a better overall performance. This paper presents a numerical study of the effect of multi-flight screw configurations on the homogenizing and cooling of a polymer melt. Various characteristics of the melt flow and heat transfer in multi-flight screws are compared to those of a corresponding single-flight design.

Introduction

A tandem extrusion system is an extrusion line with a rotating secondary extruder. It is essentially two individual lines in series, offering the flexibility to run as two independent extrusion laminating lines, or as a tandem line [1]. Figure 1 shows a schematic of a tandem extrusion system. The plasticating extruder or first extruder is used to melt and pump pellets so that the polymer is suitable for downstream processing. The second extruder, which is composed of a cold barrel and a cooling screw within, cools and homogenizes the mixture of polymer melt and blowing agent to produce high volume quality foam. A foaming die (connected to the end of the cooling extruder) accomplishes the nucleation and cell growth functions of the microcellular processing system and the shaping function of the sheet processing system.

In a tandem extrusion line, the cooling extruder is designed to remove heat efficiently from the gas-laden melt (GLM) while, at the same time, minimizing the viscous heat generation in the GLM [2]. A standard cooling screw is a long shaft with a thread wrapped helically around it. Between adjacent section of the thread (also called the flight) is the flow channel. It is worth re-emphasizing that the purpose of the cooling extruder is to feed a die with a homogeneous material at low and constant temperature and pressure. This definition highlights one of the primary responsibilities of the cooling extruder while delivering material to a shaping die; i.e., it must homogenize, or satisfactorily mix, the material. It is important that the design of an extrusion system consider mixing, the essential function of the extruder screw [3], to produce a quality product.

The development of a superior design for the cooling screw and the optimization of the process would enable more efficient use of raw materials and energy. As the use of tandem extrusion lines to produce quality structured foams has expanded, there has emerged an increased interest in designing more efficient screws. There are a variety of design elements that are commonly applied to cooling screws, however using two or more flights to provide increased leads with a specified pitch are most frequently used technique in cooling screw design. One design example, described in [4], uses three flights and small holes on the flights to create extra flow paths; a second design uses segmented four flights to divide the flow field into smaller fields [5]; a third example uses two flights with different channel depths to further deform the melt [6]. Although all those designs improve the performance of the screws by using special elements (*e.g.*, slots, segmented channel, and distinct channel depth), multiple flights are used coincidentally.

Multi-flight screws discontinuously provide a partially flighted melt segment along the extruder screw's longitudinal axis. The typical single flight screw inherently produces a non-uniform mix [7]. This is because such model lacks distributing mixing mechanisms, and therefore, complete mixing must depend upon the extent and efficiency of the customary final mixing stage. The concept of multiple flights is direct to a screw design in which a plurality of flightings interacts to divide the flow, and then recombine the flow through a plurality of divisions. Usually, multiple flights provide a higher shear stress within or along the channels as compared to that of the single channel. However, it is not clear to what extent multi-flight element enhances the effectiveness of a screw's mixing and cooling. This paper is the first endeavor to study the efficiency of the multi-flight mechanism and its superiority over a single-flight configuration. This can be done by developing a numerical model based on physical laws and assumptions to predict the melt flow and heat transfer behaviors in response to a given screw geometry with different number of flights.

In the following sections, a mathematical model that describes a typical polymer melt fluid and the numerical algorithm used to solve the model are introduced. Screws with different number of flights are studied numerically, and comparisons between the number of flights are made. Finally, the results of simulations of the flow and heat transfer of a melt flow through screw geometries representative of multi-flight designs are presented.

Methodology

Conservation Laws

Polymer melt flow in a cooling extruder is assumed to be steady state, incompressible, and to satisfy laws of conservation of mass, momentum and energy, that are in the form of a set of partial differential equations:

$$\nabla \cdot u = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\nabla P + \frac{1}{\mathrm{Re}} \nabla \cdot \left\{ \frac{\mu(\dot{\gamma})}{\mu_N} \cdot \left[(\nabla u) + (\nabla u)^T \right] \right\} \tag{2}$$

$$\frac{\partial T}{\partial t} + u \cdot \nabla T = \frac{1}{Pe}(\nabla^2 T) + \Phi \tag{3}$$

The above equations are in non-dimensional form, and contain two non-dimensional numbers: the Reynolds number $\mathrm{Re} = \rho UL / \mu$, and the Peclet number $Pe = UL / D$, where ρ is the fluid density, μ is the dynamic viscosity, L is a flow characteristic length, U is a characteristic velocity, D is the thermal diffusivity, and Φ represents the viscous heating. For molten polymer flow, the Reynolds number is always very small (<<1) due to the high viscosity of the melt, and so the flow field is diffusion-dominated. On the other hand, the typical Peclet number is large due to the low thermal diffusivity of polymer melt; typical values of D are in the range of $10^{-5} - 10^{-6}\,\mathrm{m}^2/\mathrm{s}$, and this yields a large Peclet number, on the order of 10^5, which makes heat transfer advection-dominated. This large Peclet number effectively insulates melt in the interior of the screw channel from melt near the barrel.

The polymer melt is modeled as a purely viscous fluid, where the shear rate $(\dot{\gamma})$ and temperature-dependent viscosity of the melt is described by a shear thinning model:

$$\mu(\dot{\gamma}) = m(\dot{\gamma})^{n-1} e^{-b(T-T_b)} \tag{4}$$

where m is the consistency index (unit of $Pa \cdot s^n$), b is a constant and n is the power-law index.

In general, equations (2) and (3), for the velocity and temperature fields, are coupled by the viscosity and shear reheating terms, and so the equations are solved simultaneously.

Numerical Algorithm

A finite element solver for three-dimensional non-Newtonian fluid flow and advection-diffusion heat transfer have been developed based on two existing finite element solvers [8, 9]. The governing equations (1) (2) and (3) are spatially discretized using a Galerkin finite element approach in conjunction with P2-P1 tetrahedral Taylor-Hood elements. The unknown velocity and pressure fields are expressed in terms of the shape functions ϕ_j and ψ_j and the nodal velocity and pressure values u_j and p_j:

$$u \ (or\ T) = \sum_{j=1}^{N} u_j \ (or\ T_j) \ \varphi_j \tag{5}$$

$$p = \sum_{j=1}^{N_p} p_j \psi_j \tag{6}$$

where there are $N = 10$ degrees of freedom for velocity (in each co-ordinate direction) and temperature, and $N_p = 4$ degrees of freedom for pressure. Following a Galerkin spatial discretization, the governing equations are written in semi-discrete form as:

$$[M]\frac{d\{u\}}{dt} + ([N] - [N^G]) + [S]\{u\} + [L]^T\{p\} = \int_{\Gamma} (-pn + \frac{\partial u}{\partial n})\, dS \tag{7}$$

$$[L]\{u\} = 0 \tag{8}$$

$$\frac{\partial \{T\}}{\partial t} = D\{T\} + C\{T\} + f \tag{9}$$

where $\{u\}$ and $\{p\}$ are the vectors of nodal velocity and pressure. $[M]$, $[S]$ and $[L]$ are elemental matrices, S is the boundary of the elemental volume, $D = \nabla^2 T / Pe$ is the diffusion operator, $C = -u \cdot \nabla$ is the advection operator, Γ is the boundary of the elemental volume, and n is a normal vector.

3D Screw Geometries

A standard screw geometry, Figure 2(a), and three specially designed multiple flights screws, illustrated in Figures 2(b) to (d), were studied. Figures 2(b) to (d) represent a two-flight screw, three-flight and four-flight screw respectively. A summary of geometrical information for all four screw elements is listed in Table 1.

These geometries were spatially discretized using the commercial software ICEM-CFD [10], and then studied by numerical modeling the flow and heat transfer of a polymer melt in the screw channels. The finite element mesh for the two-flight screw channel is shown in Figure 3; it contains 210573 tetrahedral elements and 308893 nodes. Progressively refined meshes each screw channel were constructed to ensure that the simulation results were mesh-independent.

Material Properties

The material studied in this study is WB130HMS polypropylene (PP), which is considered to be a representative of polymers used for extrusion processing. The choice of polymer only affects the constants in the viscosity equation, and the shear-thinning viscosity model is suitable for most of polymer melts (*e.g.*, polystyrene, polyethylene, HDPE, *etc.*). As well, most polymer melts have a low the thermal diffusivity, which leads to a large Peclet number. Therefore, the modeling and the conclusions drown are generally applicable to most of the materials used in polymer extrusion processing. The PP was assumed to enter the screw element at an initial temperature of $220^o C$, while the barrel temperature was maintained at $190^o C$. The screw rotating speed and the polymer melt flow rate are values typical of a laboratory extruder. A summary of material data used for the calculations, and the operating conditions considered, are listed in Table 2 and taken from [11].

Results and Discussion

Pressure Field: a Comparison with Experimental Result

One of the important measures of an extrusion process is throughput. The drag flow arises from the relative motion of the liquid (due to the rotating screw) and the stationary barrel. The pressure flow arises from the back pressure caused by the build-up of pressure in the extruder during the extrusion process, but is a negative contribution to flow, and so reduces the throughput. The pressure profile for the standard screw geometry is plotted in Figure 4. For the standard screw, the pressure rises along the channel (note that the jump in pressure midway along the element is due to the presence of the screw flight). We also conducted a simple experiment, by installing two pressure transducers at each end of a laboratory second extruder with a standard cooling screw. We then divided the overall difference in measured pressure along the extruder by the number of pitches of the cooling screw, to obtain an average pressure variation along one pitch, and we illustrate that difference by plotting two values of pressure on Figure 4. Note that the measured pressure difference is very similar to the calculated one, and indicates that for this case, as given by the operating conditions listed in Table 1, the pressure contributes negatively to the overall throughput for the standard screw.

Velocity Field

To evaluate the mixing of a screw geometry, one can study the flow patterns (velocity profile) within a screw channel, because distributive mixing depends on the affine deformation of fluid particles, and involves stretching, dividing a fluid in order to produce a more homogeneous mixture [6]. Although dispersive mixing, which usually involves intense deformation and requires that a flow locally exceed a critical stress condition to rupture an agglomerate, may not be applicable to a screw without an special design elements (*e.g.*, slots), it has a close connection with the flow pattern [12, 13]. Therefore, the velocity fields were calculated for PP melt flow in the channel between an outside barrel and each of the four screw elements to evaluate mixing. Figure 5 illustrates the axial velocity at cross sections of each of these screw channels. Compared to the more complex screws, the standard single-flight screw yields the simplest flow pattern, Figures 5(a) and 6(a). The two-flight screw, illustrated in Figures 5(b) and 6(b), has two evenly distributed flights which split the flow field into two parts. The streamline trace Figure 6(b), shows that across the channel, the streamlines are also divided and smaller fields are formed between the flights, which are indicative of distributive mixing. On the other hand, the reorienting of the flow fields adjacent to the flights also contributes to distributive mixing. The three-flight screw, Figures 5(c) and 6(c), and four-flight screw, Figures 5(d) and 6(d), with their evenly distributed flights, generate more complicated flow pattern, as more flights force the melt to break into more smaller parts.

The simulation results clearly indicate that the more complex flow patterns in these multi-flight screws are advantageous to mixing, and as a result, we surmise that they are superior to a standard screw.

Wall Shear Stress and Average Residence Time

A cooling screw with different number of the flights may produce different mixing. This is because there is a large difference in the shear rate and the residence time in the outer and inner regions of the channel between the flighting. These result in a variation in the shear strain within the channel. The study of wall shear stress plays an important role, because extruders are always designed to increase the flow rate and to keep the flow stable; and it has been found that, in order to meet these two objectives, the stress between the material and the barrel surface should be greater than the stress between the material and the minor circumferential surface of the screw [14]. In this study the wall shear stress was calculated for each case of the screw element with different number of flights, to compare the mixing effect. Figure 7 illustrates the wall shear stress for each screw element. Since the screw is rotating at a fixed speed, the shear rate is zero at the screw root (which refers to all the surfaces on the solid screw) and reaches the highest value at the barrel. The results of the wall shear stress indicate that, the wall shear stress is higher at the barrel surfaces than at the flight tips (still belongs to screw roots) which has a low shear rate; and flows in multi-flight screws are divided into smaller channels which provide a higher shear stress within or along the channels as compared to that of the single channel.

Another measure of mixing is the average residence or dwell time of a fluid element within an extruder, equivalent to the rate at which a polymer melt moves through an extruder at steady state, and equal to the total channel volume divided by the volumetric flow rate:

$$\bar{t} = V / Q \tag{10}$$

Mixing and cooling typically benefit from a longer average residence time.

Figure 8 shows the average residence time $\bar{t}$ for the four screws, for a fixed flow rate. The shortest time is for a standard single flight screw, about 31 seconds, and it increases linearly as the number of the flight increases up to four. The result of the average residence time indicates that melt will remain longer inside the multi-flight screw elements, which promotes both mixing and cooling.

Heat Transfer

To evaluate a screw geometry, one can evaluate the flow patterns within a screw channel, and because polymer melt has a very low thermal conductivity, the heat transfer is largely governed by the flow field, and so mixing can also be evaluated by studying the heat transfer. Heat transfer in an extruder is limited by the low thermal diffusivity of a polymer melt, that results in a large Peclet number Pe (recall that $Pe = UL / D$ characterizes the rate of thermal advection relative to the rate of thermal diffusion). Heat transfer was calculated for all four screw geometries. Figures 9 (a) to (d) illustrate the temperature profiles across screw channels for each screw element respectively. The heat transfer result indicates that the heat within the melt (accumulated in the first extruder) is carried along as the melt flows in the cooling extruder. Only a very thin thermal boundary layer forms, and only a small amount of heat is transmitted to the cooled barrel. Details of the thermal boundary layers and the melt temperature distribution across the flow channel at A-A from the screw root to the barrel are plotted in Figure 10.

For the single flight screw, Figure 10 (a), the temperature across the screw channel from the screw root to barrel is higher than that of multi-flight screws, Figure 10 (b) to (d). Also, as the number of flights increases, the temperature decreases, and three-flight and four-flight screws have a similar temperature distribution across the channel. Figure 11 demonstrates the cooling efficiency for each screw element along axial direction. The melt temperature in a single flight screw decreases a limited value along axial direction of the screw channel, and as the number of flights increases, the cooling improves. The simulation result shows that multi-flight screws are superior to a single flight one by enhancing cooling.

CONCLUSIONS

A finite element analysis for solving three-dimensional polymer melt flow and heat transfer in four cooling screws with different number of flights has been carried out, to investigate the effect of screw geometry on mixing, cooling and overall performance. Polymer melts have a very limited capability to diffuse heat. Therefore, homogeneity in an extruder can be only achieved by providing sufficient mixing of the melt particles, which can be obtained by diversifying the flow pattern by using special screw geometries. Diversified flow patterns can be obtained by using multi-flights

Multi-flight screws are superior to a standard single flight screw because they can split and reorient a melt flow in screw channels which is favorable to the distributive mixing. The higher wall shear stress and longer residence time of a melt in a multi-flight screw promote mixing and cooling. Divided melt between flightings in a multi-flight screw has a more uniform and low temperature distribution compared to a single flight screw, although cooling is limited due to high thermal diffusivity of the polymer melt flow. This study provides a tool for the subsequent design of an optimal technical solution for the elements of an extruder.

Acknowledgments

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Table 1. Geometrical Dimensions of Screw Elements

Geometry Dimensions	I (Standard)	II	III	IV
Number of flights	1	2	3	4
Barrel diameter (in)	0.65	0.65	0.65	0.65
Pitch (in)	1.65	3.30	4.95	6.6
Revolution	3.48	2.3	1.49	1.14
Channel height (in)	0.1	0.1	0.1	0.1

Table 2. Material data and operating conditions

Parameters	**Values**
Screw revolution speed (rpm)	8
Mass flow rate ($g / \min$)	20
Barrel temperature ($^{\circ}C$)	190
Inflow temperature ($^{\circ}C$)	220
Newtonian viscosity (μ_N)	6000.0
Thermal diffusivity (m^2 / s)	1.2×10^{-7}
Density (g/ml)	0.910
Power-Law Index (*n*)	0.4
Reynolds Number (*Re*)	1.0×10^{-4}

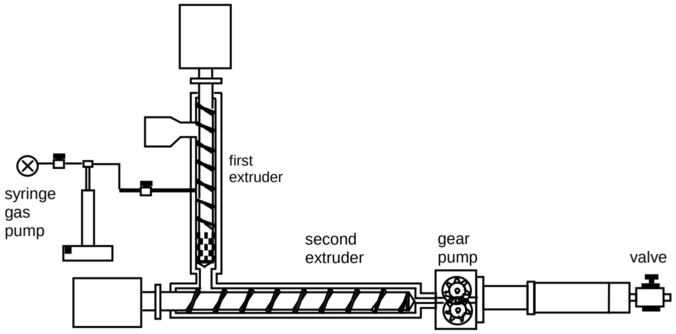

Figure 1. A schematic of a tandem extrusion system

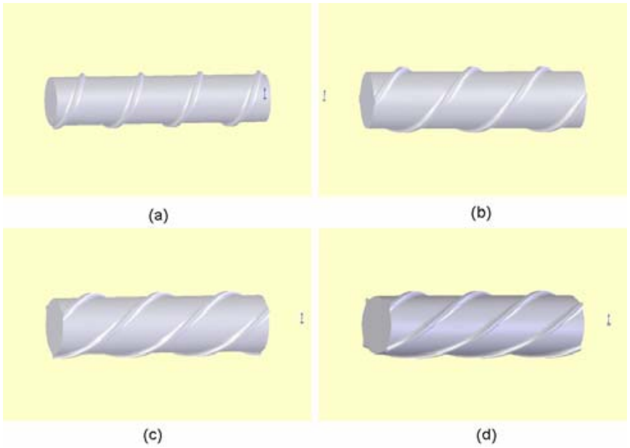

Figure 2. Screw elements (a) single flight (standard screw) (b) two-flight (c) three-flight (d) four-flight

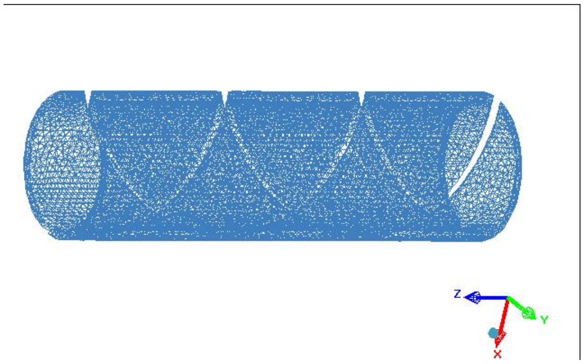

Figure 3. Finite element mesh for the screw element depicted in Figure 2(b)

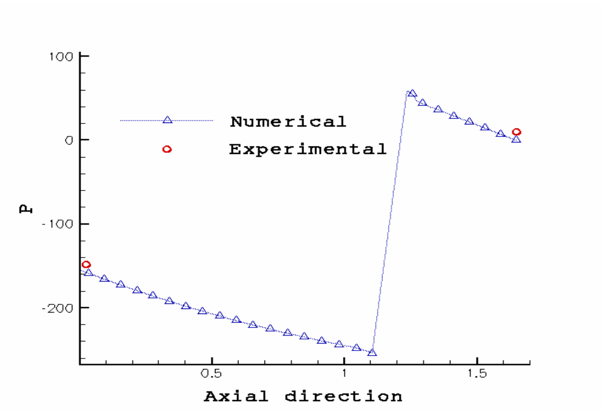

Figure 4. Pressure profile for the standard screw geometry: comparison with experimental result

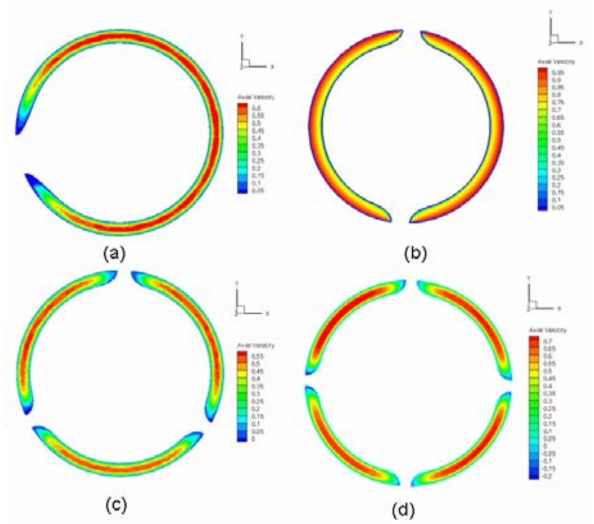

Figure 5.Axial velocity contours (a) single flight (standard screw) (b) two-flight (c) three-flight (d) four-flight

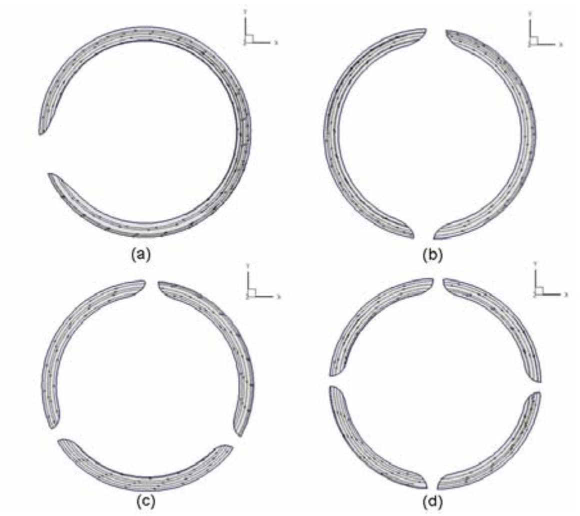

Figure 6. Velocity streamlines at the cross section (a) single flight (standard screw) (b) two-flight (c) three-flight (d) four-flight

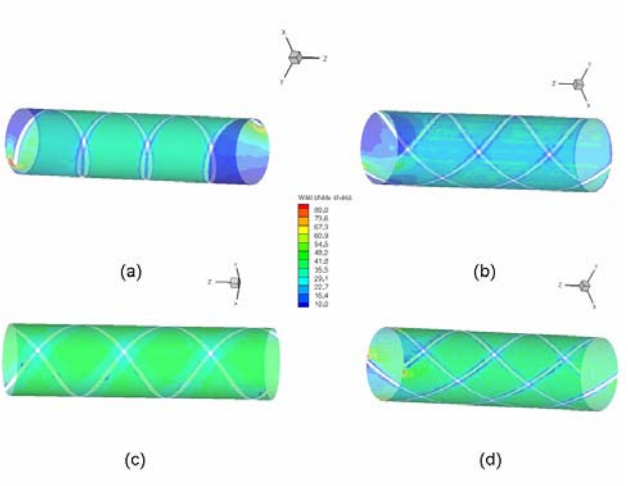

Figure 7. Wall shear stress (a) single flight (standard screw) (b) two-flight (c)three-flight (d) four-flight

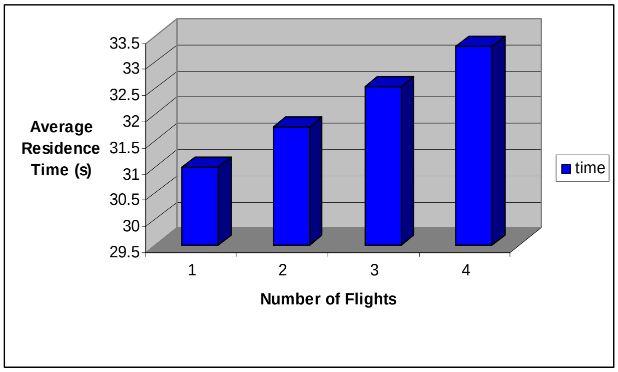

Figure 8. Average residence time for each case

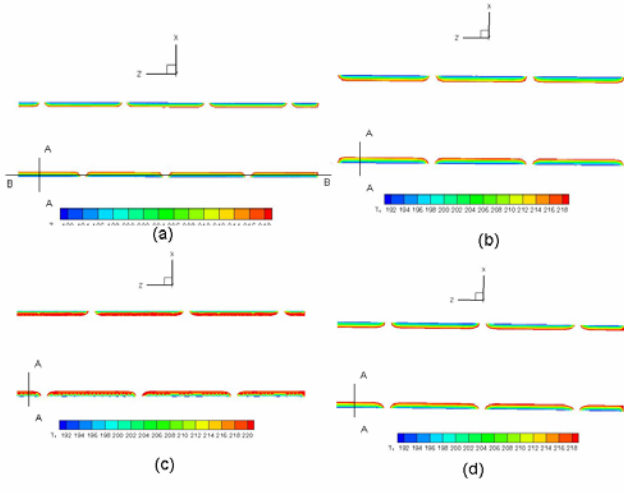

Figure 9. Temperature field at the cross section

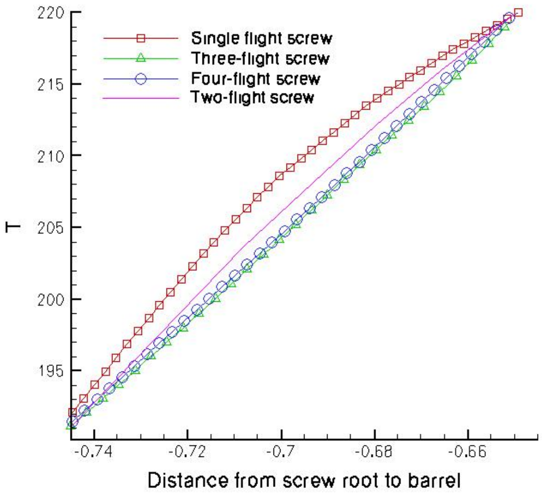

Figure 10. Temperature across the channel, at cross sections along A-A as depicted in Figure 9

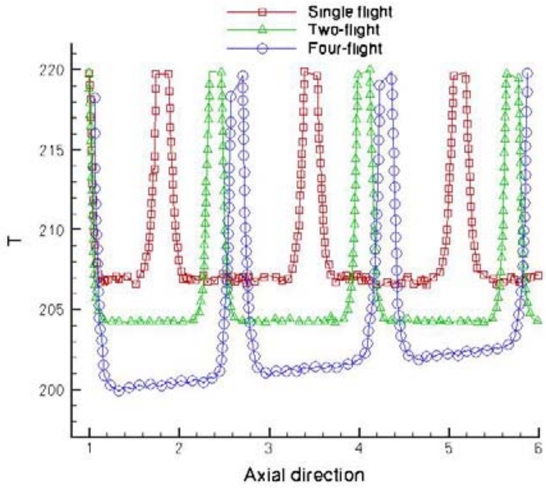

Figure 11. Temperature across the channel, at cross-sections along B-B as depicted in Figure 9