Comparison of the Mixing Performance of Two Cooling Screw Extruders

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ABSTRACT

The fast growing use of microcellular plastic foams motivates the enhanced design of tandem extrusion lines. In this extrusion process, the cooling screw plays the important role of removing heat from the gas-laden melt. The optimization of the cooling screw design, in terms of the mixing performance and heat transfer efficiency, requires extensive numerical analysis, which is the long-term goal of this study. In this paper, we aim to numerically simulate the polymer melt flow in two common types of cooling screw: "Standard" (ST) and "High Heat Transfer" (HHT). The open source CFD package OpenFOAM is used, in order to handle complex geometries, run on parallel CPU's, and be able to modify the source code. The first part of this paper presents the verification of the OpenFOAM software by comparison of numerical results with analytical solutions for some benchmark problems for power-law fluids. It is shown that the numerical results agree well with the analytical solutions. With the accuracy of the code verified, the simulation of the flow field in the screw extruders is performed. The polymer melt is assumed to behave as a power-law fluid. The full 3D Navier-Stokes equations have been solved. The results are compared with results in the literature demonstrating good agreement. In the next step, the fully developed flow of the polymer melt is subject to cooling from the barrel and screw surface. The coupled momentum and energy equations are solved. As a quantitative measure of mixing, average and maximum temperatures at the screws outlets are compared. It is shown that the periodic displacement of flights in the HHT screw effectively increases the mixing performance compared to the Standard screw. Finally, the effect of flight length on the mixing performance of the HHT screw is presented.

1. INTRODUCTION

The tandem extrusion system shown in Figure 1 is used for the continuous production of high quality structured polymer foams. A tandem extrusion line consists of two serial screw extruders. The first/plasticating extruder melts the polymer pellets and pumps the polymer melt toward the second extruder. At the same time, a blowing agent is fed into the flow, which later results in cell nucleation. The second/cooling extruder is responsible for uniformly cooling the gas-laden melt. Finally, at the end of the line, a micro-cellular plastic foam is formed in the foaming die.

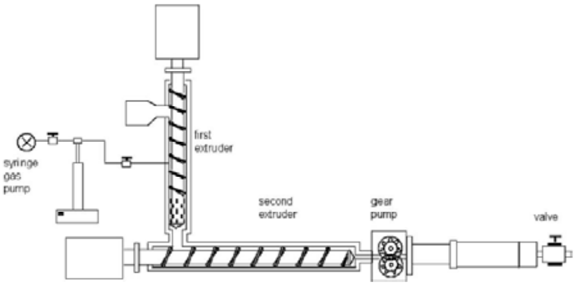


Figure 1. A Schematic of tandem extrusion line

While improvement of the mixing in the plasticating screw extruder has received considerable attention, there is little work on the thermal optimization of the cooling screw extruder. This may be because the optimization of the cooling screw extruder is relatively complex, because enhancing the mixing characteristics of the screw can result in adverse viscous heat generation. The final goal of this study is to solve the coupled momentum and energy equations for cooling screw extruders, to take into account the effects of viscous reheating, and to find a balance between mixing and shear reheating to optimize the cooling efficiency. So far, we have solved the momentum and energy equations without taking the dissipation term into account; hence, this study is focused on mixing performance.

There are many patented screw designs to improve mixing performance, ranging from a “Standard screw” to complicated pin type and multi-flight ones. Among them, the idea of a “Chaos” screw proposed by Kim and Kwon [1], has attracted much attention. They show experimentally that introducing chaos to the flow regime, by adding spatially periodic barriers, dramatically increases the mixing performance. In a separate article [2], the flow field was numerically calculated via a finite element analysis. Yao et al. [3] quantified the mixing performance in a pin mixing screw by a non-isothermal, 3D finite element analysis. They also compared their results with previously conducted experiments [4]. The HHT screw was first introduced by Rauwendaal [5]. The periodic displacement of its flights leads to effective exchange of material from the core of the screw channel to the outer region and vice versa. In the most recent work, Wang et al. [6] studied the effect of different screw geometries on the mixing of polymer melt. They numerically simulated the flow and temperature field for four different screw configurations using the finite element method. Their comparison showed that the more complex the screw geometry, the more efficient mixing is. However, as they didn’t consider the shear reheating effect, it is difficult to come to the same conclusion for cooling efficiency.

In this work we aim to introduce a new approach by taking advantage of the open-source OpenFOAM software for numerical analysis. The polymer flow in two commonly used screws: the Standard screw (Figure 2a) and the HHT screw (Figure 2b), is studied and compared. The effect of flight length on the mixing performance of the HHT screw is also analyzed.

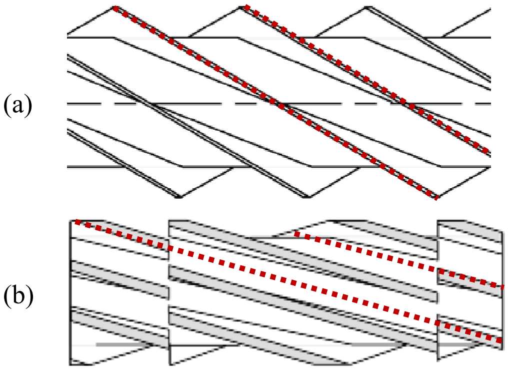


Figure 2. Schematic of (a) a ST screw and (b) a HHT screw. The red dotted lines show the boundaries of the geometries to be modeled.

2. METHODOLOGY

Polymer flow is assumed to be laminar, steady-state, and incompressible. Neglecting the effect of curvature, i.e. assuming an unwound screw channel, the situation to be analyzed becomes the flow in a straight rectangular channel with a top wall (a barrel) moving at a velocity of u at an angle of θ in relation to the screw root. The boundaries of such channels are highlighted in Figure 2 with dotted lines. In addition, we focus on the hydraulic fully-developed region; therefore, ideally, the geometry can be simplified to only one pitch of a screw. However, a longer frame of 4 pitches (as depicted in Figure 3) was used to observe the temperature variation in the thermal developing region.

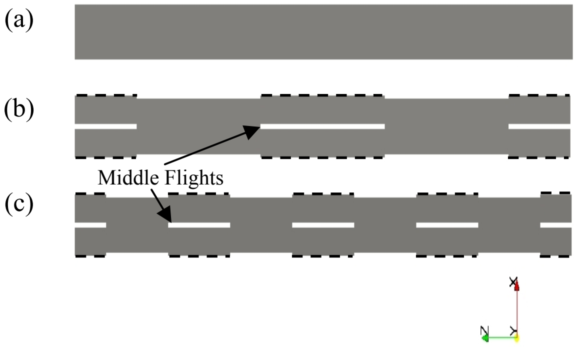


Figure 3. Top view of unwound screw channels
(a) ST (b) HHT_1 (flight length = pitch)
(c) $\mathrm{HHT}_{1/2}$ (flight length = half pitch)

The governing equations in the frame of reference attached to the rotating screw are for mass conservation (continuity):

$$\nabla . \boldsymbol{u} = 0 \,, \tag{1}$$

for momentum conservation:

$$\rho \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \boldsymbol{f_b} \,, \tag{2}$$

and for energy conservation:

$$\rho C_p (\boldsymbol{u} \cdot \nabla T) = \kappa \nabla^2 T + \Phi \,, \tag{3}$$

in which $\boldsymbol{u}$ is the vector of relative velocity with respect to the rotating frame ($\boldsymbol{u} = \boldsymbol{u}_{\mathrm{abs}} - \boldsymbol{\Omega} \times \boldsymbol{r}$), with $\boldsymbol{\Omega}$ and $\boldsymbol{r}$ the vectors of angular velocity and position, respectively. ρ is fluid density, p is pressure, $\boldsymbol{\tau}$ is the stress tensor, and T is temperature. C_p and κ denote the specific heat and thermal conductivity, respectively. The reader may note that the coriolis and centrifugal forces are ignored in the momentum equation as the rotation is very slow, and these two terms are negligible compared with the viscous forces. The term $\boldsymbol{f}_{\mathrm{b}}$ includes the buoyancy forces. The term Φ refers to the heat generation due to viscous dissipation and is of high importance in the study of cooling performance of screw extruder. In this paper, however, the viscous dissipation term is ignored as we just focus on mixing performance.

The stress tensor $\boldsymbol{\tau}$ is required to obey the constitutive equation and takes the form;

$$\boldsymbol{\tau} = 2\mu(\dot{\gamma})\boldsymbol{d}\,, \tag{4}$$

where $\mu(\dot{\gamma})$ is the dynamic viscosity and $\boldsymbol{d}$ is the rate of deformation tensor:

$$\boldsymbol{d} = \frac{1}{2}[\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T]. \tag{5}$$

The local shear rate is defined as

$$\dot{\gamma} = \sqrt{2tr(\boldsymbol{d}\cdot\boldsymbol{d})}, \tag{6}$$

where *tr* is the trace. The polymer melt is modeled as a pure viscous fluid with the viscosity described by the power-law model:

$$\mu(\dot{\gamma}) = k(\dot{\gamma})^{n-1}, \tag{7}$$

in which k (Pa.s^n) is the consistency index and n is the power-law index.

The governing equations must be matched to proper boundary conditions. From the observer point of view, the screw is fixed and the barrel is rotating at the same velocity, but in the opposite direction, of the real screw rotation. The no-slip no-penetration boundary condition is assumed on the barrel and screw surfaces. The cyclic boundary condition is used to link the flow field at the inlet and outlet, which mimics the fully developed condition (note that the flow is purely driven by the moving barrel). A cyclic boundary condition is also applied at the boundaries marked by dash lines in Figure 3b & c. The polymer melt with uniform temperature of 493.15 K enters the screw channel. The barrel and the screw root temperatures are set at 418.15 K.

The following table lists the operating conditions, geometrical parameters, and fluid properties considered in this simulation. They are presented in the fashion that appear in the OpenFOAM dictionary files.

Parameters	Value
Channel length (one pitch) (mm)	240
Channel height (mm)	17
Channel width (mm)	64
θ, Helix angle (degree)	17.66
u_z, barrel axial velocity (m/s)	0.044
u_x, barrel transverse velocity (m/s)	-0.0141
Screw flight width (mm)	6
ρ, density (kg/m3)	1050
k, consistency index (Pa.s^n)	6922
n, power-law index	0.4
β, thermal expansion coeff. (1/K)	8×10^{-5}
Pr, Prandtl number	10^7

Table 1. Geometrical and fluid parameters

The geometry of the screw channels (Figure 3) were modeled by SolidWorks (2010) and imported into the commercial meshing software ICEM-CFD from ANSYS (13.0) and meshed using hexahedral elements. The momentum equations were solved using the OpenFOAM solver: simpleFoam, a Finite-Volume solver based on the SIMPLE algorithm. Then, the flow field was fed as an initial condition to the coupled energy-momentum solver, buoyantBoussinesqSimpleFoam. The thermal expansion coefficient is so small that the buoyancy is not comparable to the viscous forces. Consequently, there is no significant change in the flow field as a result of natural convection.

3. VERIFICATION OF THE CODE

To study the accuracy of the OpenFOAM solver simpleFoam for the simulation of power-law fluids, three basic problems were solved and the results compared to the analytical benchmark solutions presented by Bird et al. [7]. Figure 4 illustrates these three problems.

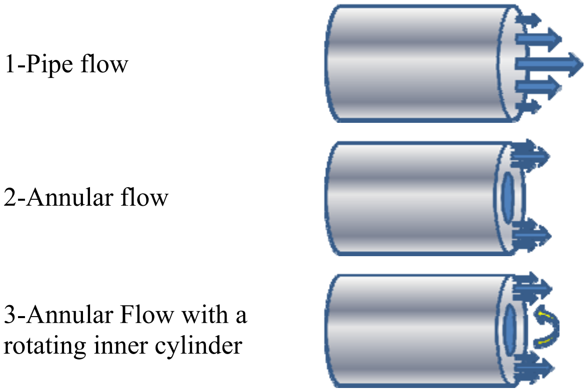
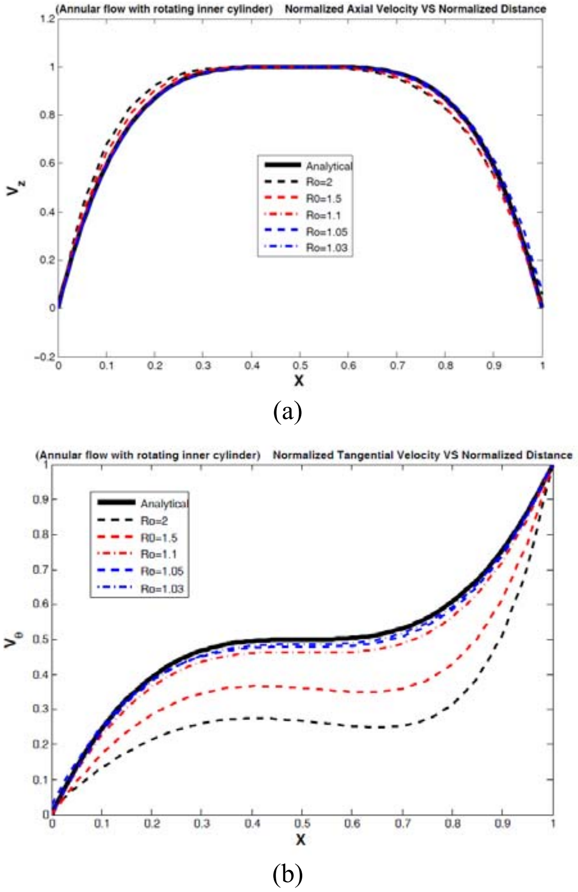


Figure 4. Schematic of the three benchmark problems

All of the numerical results agreed very well with the analytical solutions. Here, we just present a comparison of the results for the third case. The dimensionless axial and tangential velocities across the channel opening are depicted in Figure 5a & b. The analytical solution (the solid line) corresponds to the asymptotic situation of a very thin annulus. The numerical results (dashed lines) correspond to the annuli with inner radius r_i=1 and outer radius r_o ranging from 2 to 1.03. It can be seen that as the outer radius decreases (channel gets thinner), the numerical results approach the asymptotic analytical solution, and there is good agreement for the case of r_o=1.03.



(a)

(b)

Figure 5. Dimensionless (a) axial and (b) tangential velocity profiles versus normalized distance from the outer cylinder.

4. DISCUSSION OF RESULTS

4.1 Flow Field

Having obtained good solutions to simple problems using the simpleFoam solver, simulations of isothermal fully-developed flow in screw channels were set up. The most simple flow field belongs to the Standard screw. The moving barrel applies a viscous drag force to the polymer melt in both the axial and transverse directions. Figure 6 represents the profiles of velocity components along the channel height at the middle of the channel opening. For the relatively shallow channel, the axial velocity tends to couette flow. The profile of u_x has a change of sign suggesting a circulating transverse flow in the plane perpendicular to the axial direction.

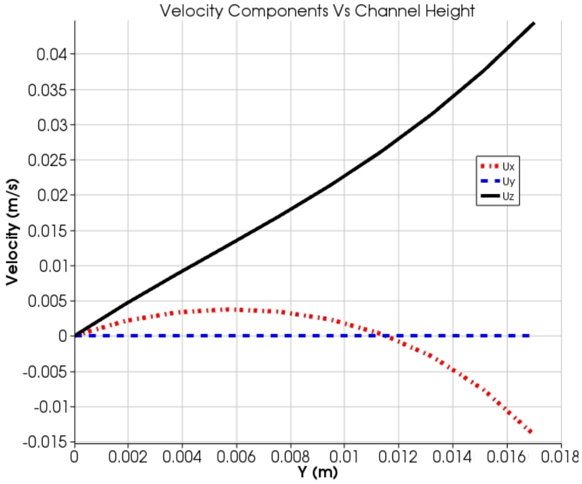


Figure 6. Profile of velocity components along channel height. (ST screw)

The stream lines of transverse flow form a series of co-rotating orbits as depicted in Figure 7. At first glance, this secondary rotating flow seems to effectively improve the mixing of the polymer melt; however, a more detailed analysis contradicts this hypothesis.

Figure 7. Stream lines of transverse flow. (ST screw)

Once a particle locates on one of these orbits, it remains on that orbit and never crosses to another orbit as it moves downstream. To visualize this 3D phenomenon, the streamlines of total velocity and transverse velocity are superimposed, as shown in Figure 8. The flow field consists of elliptical layers sliding on each other without mixing together. This not only reduces the mixing performance but also acts as thermal resistance. Polymer melt has a very small thermal conductivity; therefore the dominant heat transfer mechanism is convection. The outer layer of flow cools down in contact with the cold barrel and screw root, but at the same time the core region is insulated within a low conductive layer of polymer melt, and remains hot.

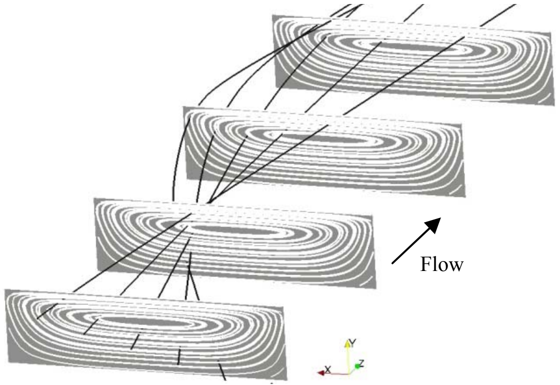


Figure 8. Streamlines of total velocity (black lines) and transverse velocity (white lines). (ST screw)

The design of the HHT screw with periodically displaced flights is based on the idea of mixing the core region and outer layers. Figure 9 presents how mixing occurs as the polymer melt flowing along the HHT screw is displaced by the flights. If one follows the streamline number 1 (Figure 9), it can be seen that the streamline initially starts in the core region, but ends up in the outer layers.

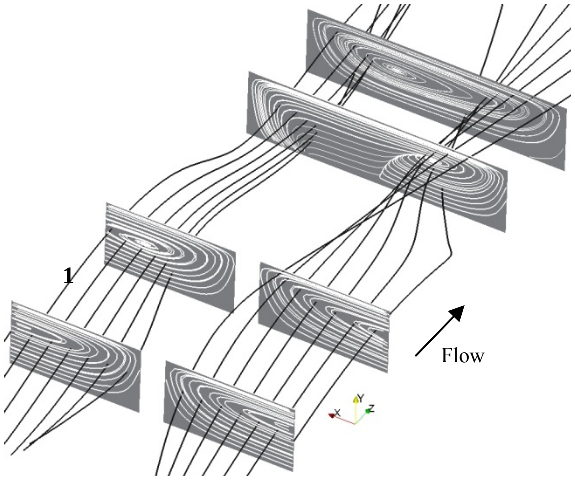


Figure 9. Streamlines of total velocity (black lines) and transverse velocity (white lines). (HHT_1)

4.2 Temperature Distribution

So far, we have qualitatively compared the mixing performance of Standard and HHT screws. There are some methods in the literature to measure the mixing ability of continuous mixers based on the local mixing efficiency distribution [8] and residence time distribution. In this paper, however, the temperature has been used to assess the mixing efficiency. It is assumed that uniformly heated polymer melt (493.15 k) is fed to the extruder, and that all of the surrounding surfaces are kept at constant temperature (418.15 k). As mentioned before, conduction plays only a small role in the cooling of the polymer melt, and convection is proportional to the mixing performance. The viscous dissipation term is not considered in order to simply assess the temperature changes related to convection. In this case, temperature is a precise measure of mixing. Figure 10 compares the temperature distributions of the Standard and the HHT screws. While the core region remains insulated and hot in the Standard screw, the effective mass exchange between the center and outer regions of the HHT screw results in a more uniform temperature distribution.

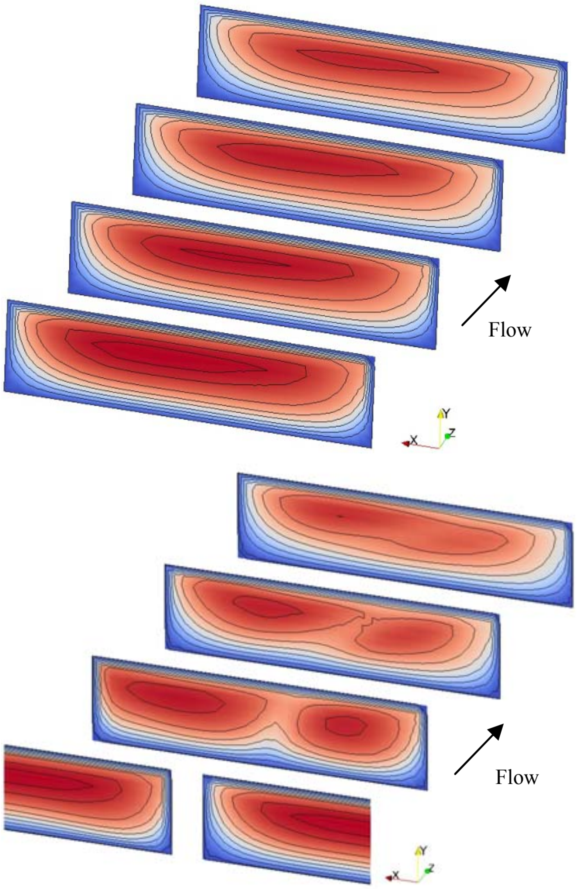


Figure 10. Temperature distribution on four transverse sections of the screw channel
(a) ST (b) HHT_1

The variation of the average temperature along the screw channels is illustrated in Figure 11. The average temperature of the Standard screw smoothly decays as the flow moves downstream. The wavy trend of the curves for the HHT screws is associated with the periodic flights in the middle of the channel. Based on the minimum average temperature at the outlet of the channel, one can order the screws from the most to the least cooling efficient as $HHT_{1/2}$, HHT_1, and ST, respectively.

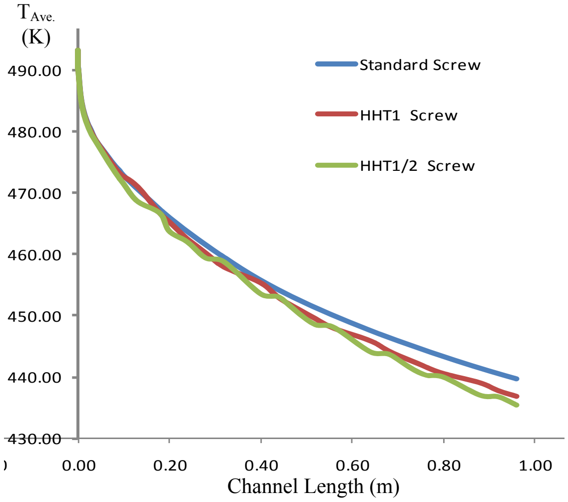


Figure 11. Variation of bulk temperature along screw channel

Table 1 summarizes the average and maximum temperatures at the outlet of the three screws. The difference between the maximum and the average temperature at the outlet of the $HHT_{1/2}$ is almost half that of the Standard screw. This confirms that the introduction of periodic flights significantly increases the mixing and mass exchange between the layers. The uniformity of temperature is of high importance in a cooling screw extruder as it directly affects the quality of the polymer foam. The more uniform the temperature, the better the quality of the product.

Table 1. Average and maximum temperatures at the outlet of the screw channels

Type	$T_{Ave.}$ at outlet (K)	T_{Max} at outlet (K)
ST	439.8	460.1
HHT_1	436.9	451.8
$HHT_{1/2}$	435.3	446.8

5. CONCLUSION

The flow of polymer melt through Standard and HHT screw extruders has been solved using the OpenFOAM software. The accuracy of the OpenFOAM solver simpleFoam to handle non-Newtonian fluid models was verified by solving three classical problems of power-law fluids. The good agreement between the numerical results and analytical solutions for these benchmarks confirms the capability of the solver. The polymer melt flow inside a screw extruder channel was also compared to previous studies, which quantitatively matched with those obtained with the same operating conditions. The developed approach can be used for the simulation of other screw designs and geometries.

It has been shown that the mixing performance of the HHT screw is better (compared with the Standard screw) due to the introduction of displaced flights and consequently, the added chaos of the system. The comparison between two HHT screws with different flight lengths confirms that as the length of flights decreases, i.e. more flight displacements per unit length, the mixing increases.

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