EFFECT OF TYPICAL MELT TEMPERATURE NON-UNIFORMITY ON FLOW DISTRIBUTION IN FLAT DIES

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Abstract

In this study, the influence of non-uniform incoming melt temperature profiles on the flow in a flat die is evaluated. Flat film die flow channels are typically designed to provide uniform flow distribution at the die exit assuming uniform incoming melt temperature profiles. However, in real extrusion conditions, it can be challenging to obtain an ideally uniform melt temperature delivery to the die. There are many reasons why the melt temperature non-uniformity is obtained. Two typical scenarios are evaluated; (i) the temperature profiles generated by an incorrect melt pipe design will be calculated and input in a die flow model as inlet boundary condition and (ii) the influence of a polymer subject to excessive viscous dissipation in the extruder. This work uses 3D computational fluid dynamics (CFD) models.

Introduction

When troubleshooting a film extrusion process, it is sometimes challenging to determine the origin of the problem. Die maker experience suggests that thermal effects and particularly temperature non-uniformity in the melt does have a large impact on the film quality and its mass distribution. In a coextrusion process, such melt temperature gradients can indiscriminately affect individual layer uniformities. Because experiments and measurements to evaluate the effect of melt temperature profiles on the flow behavior in a flat die can be tedious and subject to many influences, flow simulations using a commercial 3D CFD program can be a beneficial tool.

In the first part of the study, the thermal regime of the flow in a melt pipe will be studied. The resulting temperature profile at the exit of the pipe is then used as the inlet temperature profile for the flow through a flat die.

A second study will evaluate the effects of a temperature profile resulting from excessive viscous dissipation in the extruder.

Extrusion layout and die geometry

This work deals with a monolayer polypropylene cast film extrusion scenario as illustrated by Figure 1. A typical extrusion tooling for this application is made of a melt pipe, which feeds the melt from the extruder to the die and a flat die equipped with a vacuum box that improves the contact between the web and the chill roll. In this study, we consider a monolayer die with a two-stage preland[1] designed by Cloeren Incorporated for the process parameters presented in Table 1 and for the material specifications detailed in the following section. The die is 2032 mm wide and a view of the flow channel is shown in Figure 2.

Table 1: Process parameters

Process parameter	Value
Die wall temperature	260°C
Initial melt temperature	260°C
Extrusion output	453.6 kg/h

Polymer and rheology

The polymer used for this study is a cast film grade isotactic homopolymer polypropylene (Ho-PP) manufactured by Borealis, with a Melt Flow Rate (MFR) of 8.0 g/10 min (230°C, 2.16 kg) and density of 0.905 g/cm^3. No data was available for thermal properties of the melt and the following generic properties were used: melt density ρ = 0.74 g.cm^{-3}; thermal conductivity k=0.20 W.m^{-1}.K^{-1} and specific heat C_p= 1.50 J.g^{-1}.K^{-1}.

The shear viscosity behavior was determined by measurements tested by capillary rheometry at temperatures of 210°C, 230°C and 250°C. The data was corrected according to Bagley[2] and Rabinowitsch[3] methods. The shear viscosity data is summarized by the viscosity master curve at a reference temperature (T_{ref}) of 230°C, resulting from the Time Temperature Superposition (TTS) principle[4] and shown in Figure 3. Acceptable superposition was achieved with the shift factor values shown in Table 2.

Table 2: TTS shift factors

Temperature [°C]	TTS shift factor a_T
210	1.0
230	0.70
250	0.50

The shear rate and temperature dependency of viscosity was modeled according to the well accepted combination of the Cross model[5] and the Williams Landel Ferry (WLF) model[6] respectively, given by the two following equations:

$$\eta(\dot{\gamma},T)=\frac{\eta_0\times a_T}{1+\left(\frac{\eta_0\times a_T}{\tau_*}\dot{\gamma}\right)^{1-m}} \quad (1)$$

$$a_T=\exp\left(-\frac{C_1\left(T-T_{ref}\right)}{C_2+\left(T-T_{ref}\right)}\right) \quad (2)$$

Where η is the shear viscosity (Pa.s), $\dot{\gamma}$ is the shear rate (1/s), T is the temperature (K), η_0 is the zero shear viscosity (Pa.s), τ^* is the characteristic shear stress (Pa) and m is the pseudo-plastic index. η_0, τ^* and m are the Cross model parameters and are determined by curve fitting. The TTS is included in the Cross model through the shift factor a_T, which follows a WLF model. The model parameters C_1 and C_2 (K) are also determined by curve fitting (Table 3). Both curve fittings were done using the KaleidaGraph 4.1.0 software[7] and the resulting parameters are summarized in Figure 3.

Table 3. WLF parameters from curve fitting

WLF Parameters	Value
C_1	12.237
C_2 (K)	666.19
T_{ref} (K)	483.15

Flow simulations

Literature dealing with elastic effects on the flow distribution in mono-layer cast film dies is sparse. A flow simulation study however showed that the effects of elongational viscosity may slightly affect the velocity distribution at die exit for highly branched polymers like low density polyethylene (LDPE)[8]. In the case of linear polymers such as a homopolymer polypropylene, it is reasonable to neglect the elastic or elongational behaviors for purposes of mass flow distribution. Finally, an a priori dimensional analysis shows that the consideration of viscous dissipation and coupled thermal and flow solutions are necessary, especially when strong temperature gradients are involved. For these reasons, a generalized Newtonian non-isothermal approach was taken.

For a steady state problem, the continuity (3) and momentum balance (4) equations for an incompressible flow with negligible inertia and gravity effects write:

$$\nabla\cdot\mathbf{v}=0 \quad (3)$$

$$\nabla\cdot\boldsymbol{\tau}-\nabla p=0 \quad (4)$$

For a generalized Newtonian fluid, we have:

$$\boldsymbol{\tau}=2\eta\dot{\boldsymbol{\varepsilon}} \quad (5)$$

$$\text{Where } \dot{\boldsymbol{\varepsilon}}=\frac{1}{2}\left(\nabla\mathbf{v}+(\nabla\mathbf{v})^{\mathrm{T}}\right) \quad (6)$$

The fluid viscosity depends on temperature and shear rate as described by the Cross and WLF models detailed earlier. The energy balance for a steady state problem writes:

$$\rho C\left(\mathbf{V}.\nabla T\right)=k\Delta T+\boldsymbol{\tau}:\dot{\boldsymbol{\varepsilon}} \quad (7)$$

A commercial CFD software, SolidWorks Flow Simulation 2011 SP1.0[9] was used to solve the coupled thermal-flow problem and a mesh with brick elements was built. The boundary conditions for this model are: (i) a symmetry condition at the centerline for flow and temperature; (ii) a fully developed flow at the entrance ; (iii) a tabulated fluid radial temperature profile and a flow rate (453.6 kg/h for the total geometry) are imposed at the entrance; (iv) at the outlet surface, the pressure is set to 1 atm and; (v) finally, on the flow channel walls, we assume a non-slip condition (v=0) and a uniform temperature (260°C) is applied.

1- Uniform melt temperature at inlet

First, a reference flow simulation of the die with uniform incoming melt temperature was carried out. The main results are shown as follows:

- Velocity contour plot on the parting plane of the die (Figure 4)
- Temperature contour plot on the parting plane of the die (Figure 5)
- Velocity and melt temperature profiles at the die exit on the parting line (Figure 6).

As expected, the die flow is well balanced as the total amplitude of flow variation of 1.60 % is predicted for exit velocity. Shear heating is also well controlled as the average melt temperature at the exit on the parting line of the flow is 261.46°C for an initial entrance temperature of 260°C.

2- Non-uniform melt temperature resulting from poor melt pipe design

An initial study was carried out to determine the type of temperature profile that could result from a poor melt pipe flow channel design. It is not uncommon to see poorly designed melt pipe adaptors in the field due to lack of attention to design details. A typical design mistake is the combination of a small flow channel diameter with a long flow length. This situation was simulated with a melt pipe length of 4m and channel diameter of 19.05 mm. A

3D flow simulation was run for the material specified earlier and the process parameters detailed in Table 1. The resulting melt temperature profiles at 0.5m length increments are shown in Figure **7**. This simulation predicts substantial viscous dissipation with a maximum temperature of 292.5°C at the exit of the 4m-long pipe, for an initial melt temperature of 260°C. The result of the pipe flow simulation agrees with literature for thermal regimes that are not fully developed [10,11] as the maximum of temperature develops initially very close to the wall, which corresponds to the high shear stress region. Downstream, as the thermal regime develops, the temperature maximum moves gradually away from the wall toward the center. This is explained by the increasing importance of radial conduction as the temperature gradient from wall to center becomes large.

The radial temperature profile resulting from the pipe flow simulation at a flow length of 4.0 m (Figure 8) was used as a new boundary condition at the entrance of the film die. The achieved velocity and temperature contour plots on the parting plane at the exit of the flat die are shown in Figure 9 and Figure 10 respectively. Excessively non-uniform temperature and velocity profiles are found in the preland section as well as in the land region. A comparison of the velocity and temperature profiles at die exit for all three studies is summarized in Figure 14 and Figure 15.

3- Non-uniform melt temperature resulting from poorly performing extruder screw

Poorly performing extruder screw is another well-known cause of melt temperature non-uniformity and, generally, melt quality issues. Typically, thermocouples that are used to measure melt temperature are mounted in the wall of the extruder barrel. Consequently, the resulting measurements are predominantly influenced by the barrel temperature and give only a rough idea of the actual melt temperature[11]. Recent experimental work using a thermocouple mesh technique has been done to map the temperature profile of a melt coming from an extruder at various operating conditions[12]. Inspired by these results, a temperature profile representative of a poorly performing extruder screw was created. For sake of comparison with the previous study, a similar temperature deviation of +32.5°C was included, as shown in Figure 11. The 3D flow simulation of the die with this incoming temperature profile was completed and the resulting velocity and temperature contour plot are shown in Figure 12 and Figure 13 respectively.

Discussion

While the die provides relatively uniform temperature and velocity profiles when the incoming melt temperature is uniform, the situation changes when the melt temperature is not uniform.

When excessive viscous dissipation occurs in a melt pipe, the resulting melt temperature profile exhibits a strong radial temperature gradient with a maximum temperature near the wall. This ultimately affects the flow in the flat die characterized by a flow increase near the die ends. This is explained by the reduced polymer viscosity (by temperature) flowing along the path of higher flow resistance, i.e. toward the end regions of the die flow channel. The magnitude of the flow imbalance at the exit of the die is found to be about 10%. This number can seem small in contrast to the initial melt temperature gradient at the entrance. This can be explained by the thermal boundary condition at the wall of the die, which is very strong with an imposed uniform wall temperature of 260°C. While an imposed temperature at the wall is a typical boundary condition applied by most 3D die flow simulation work found in literature [13 - 16], it may not be perfectly reflect real conditions. In practice, the excessive heat from the melt is dissipated to the wall of the die, and may show a thermal over-ride by the die thermocouples.

When excessive viscous dissipation occurs in the extruder, the incoming melt temperature profile also shows a radial gradient. It is however characterized by a maximum temperature at the center with a temperature plateau from the center to about half of the radial profile, followed by a sharp decrease near the wall. The 3D die flow simulation taking this incoming melt temperature profile into account shows less flow variation compared to the previous case. Figure 13 shows that the melt stream distributes somewhat uniformly in the flow channel. Consequently, the amplitude in flow variation at the exit is only 5.4%.

Conclusion

3D coupled thermal-flow simulations were built and computed using a commercial CFD program to investigate the response of non-uniform melt temperature profiles fed into a polypropylene cast film die. The two cases of non-uniform temperature investigated are somewhat representative of two common extrusion issues: excessive shear heating in melt pipe or by an extruder screw. In both cases, the flow is found to be affected as both temperature and velocity exhibit non-uniform profiles at the exit. Ultimately, this could explain some of film quality issues observed in a process, such as gauge non-uniformity.

Acknowledgement

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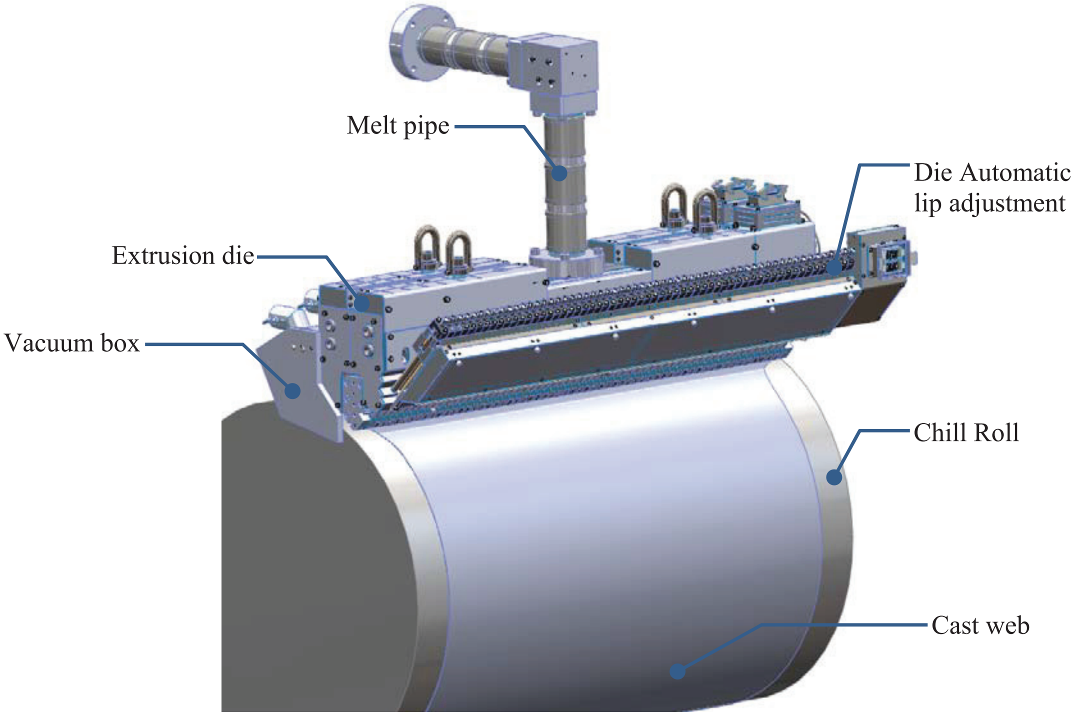

Figure 1. Typical monolayer cast film layout (Note: extruder is not shown)

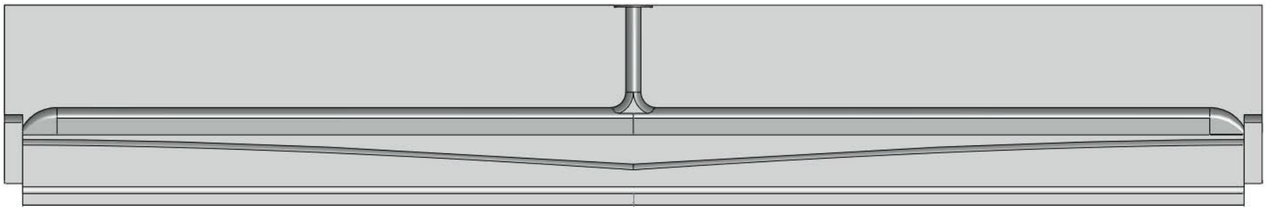

Figure 2. Die flow channel featuring a two-stage preland used for the study

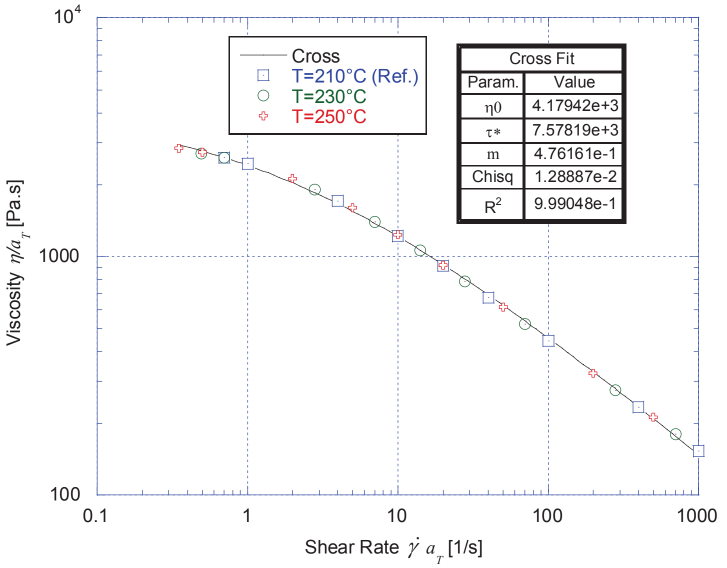

Figure 3. Master curve of viscosity and Cross fit for 8.0 MFR Ho-PP

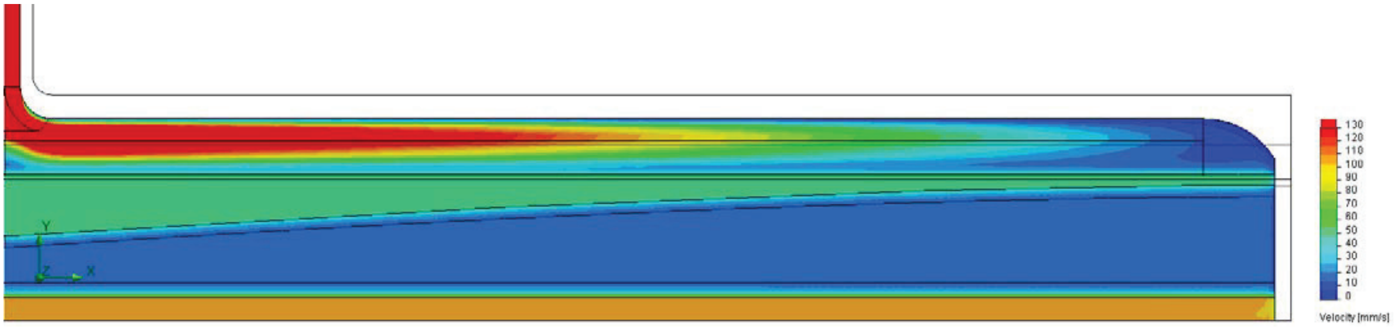

Figure 4. Velocity contour on parting plane for uniform entrance melt temperature

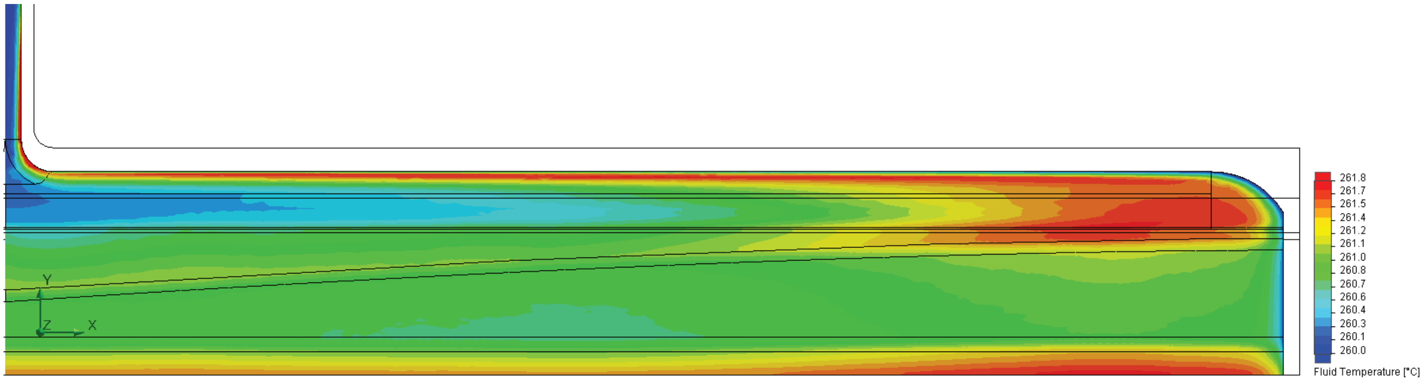

Figure 5. Melt temperature contour on parting plane for uniform entrance melt temperature

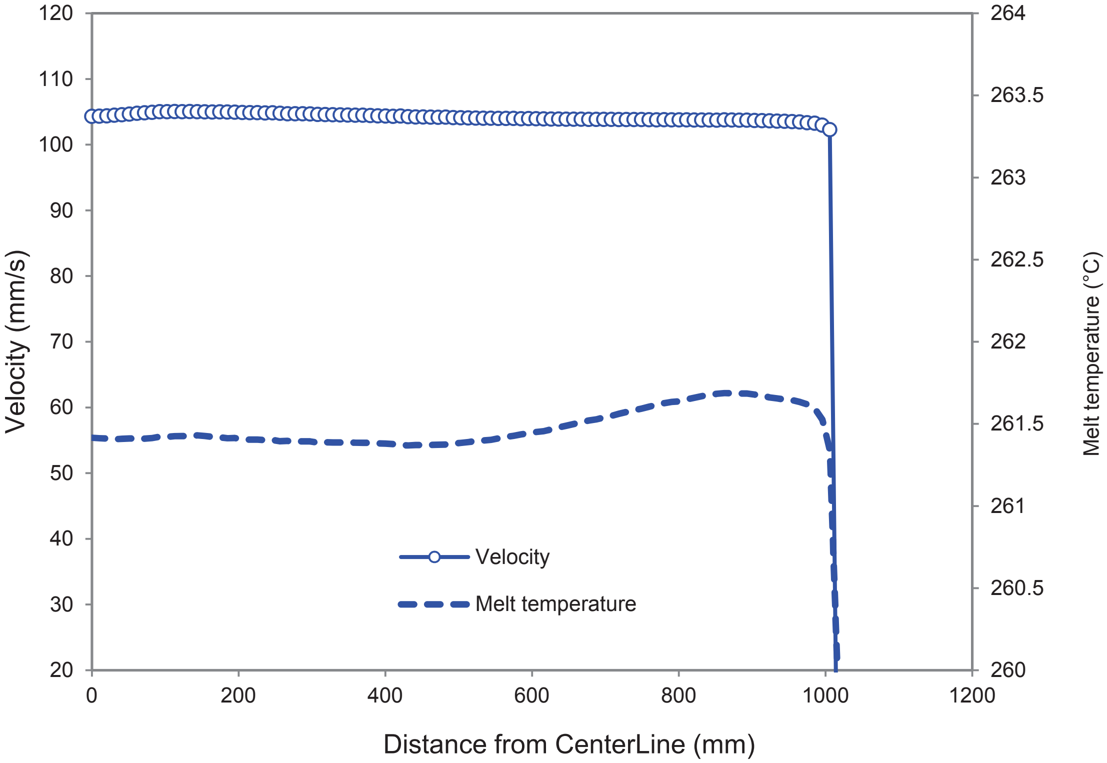

Figure 6. Velocity and temperature profile at die exit for uniform entrance temperature conditions

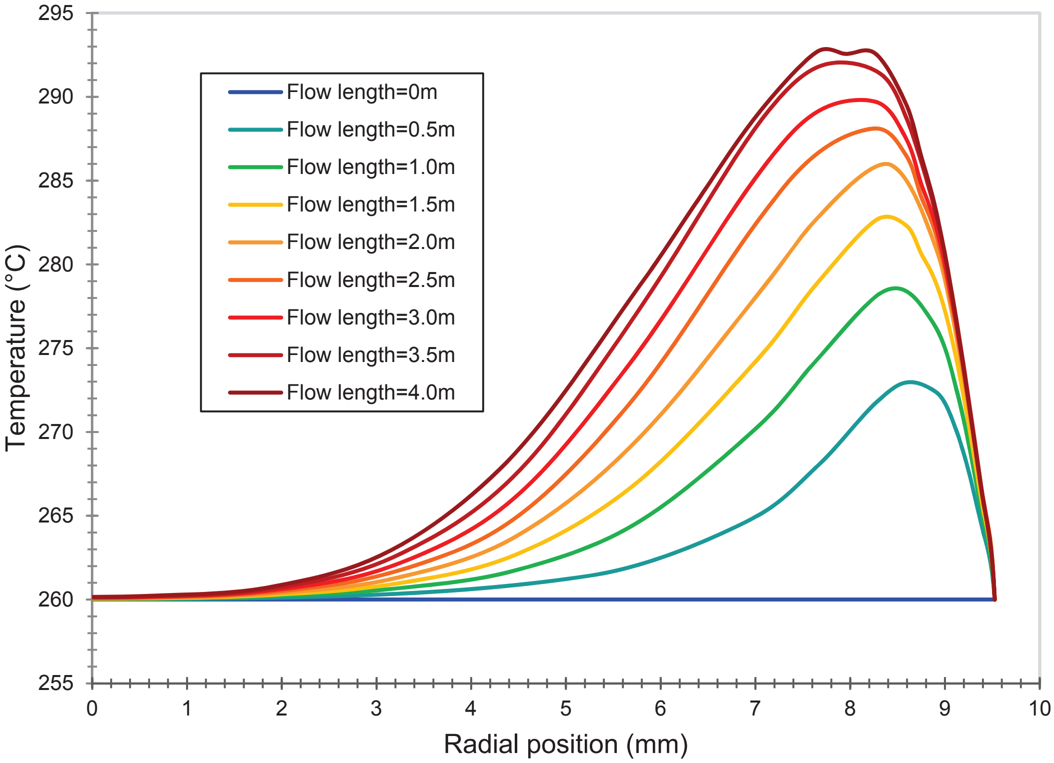

Figure 7. Melt temperature profiles as a result of the melt pipe flow simulation

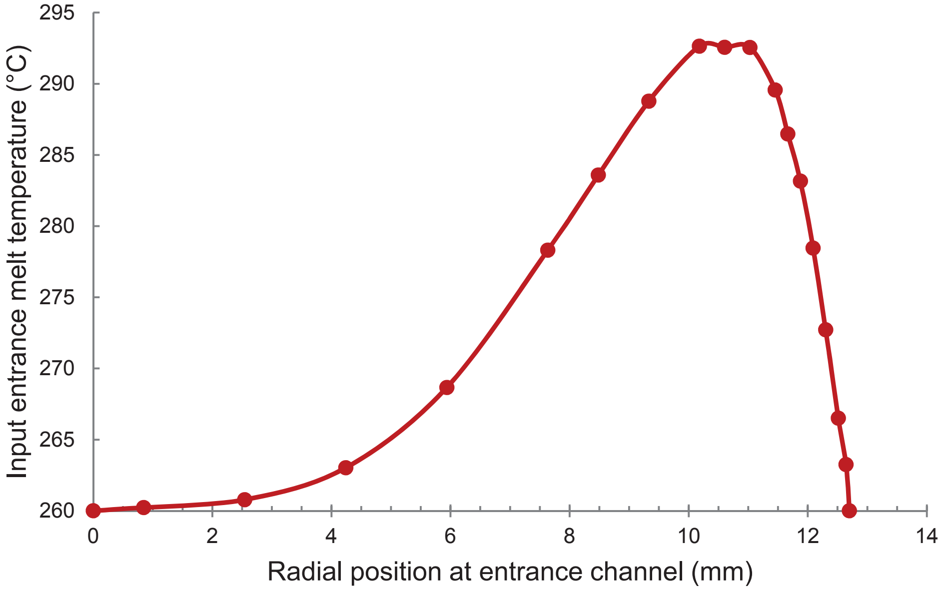

Figure 8: Entrance temperature profile input as a boundary condition (pipe shear)

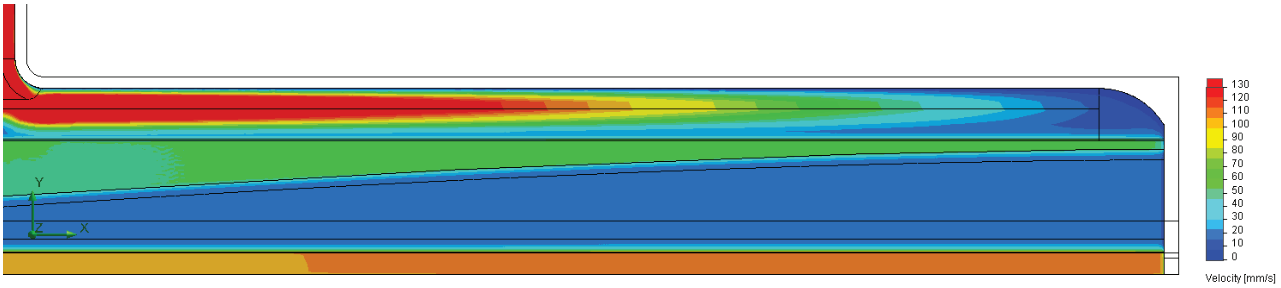

Figure 9. Velocity contour on the parting plane with non-uniform entrance melt temperature resulting from excessive shear in the melt pipe

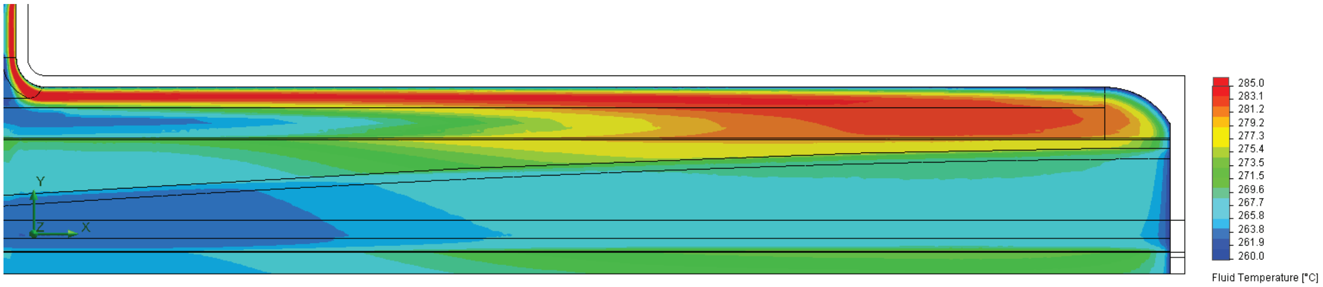

Figure 10. Temperature contour on the parting plane with non-uniform entrance melt temperature resulting from excessive shear in the melt pipe

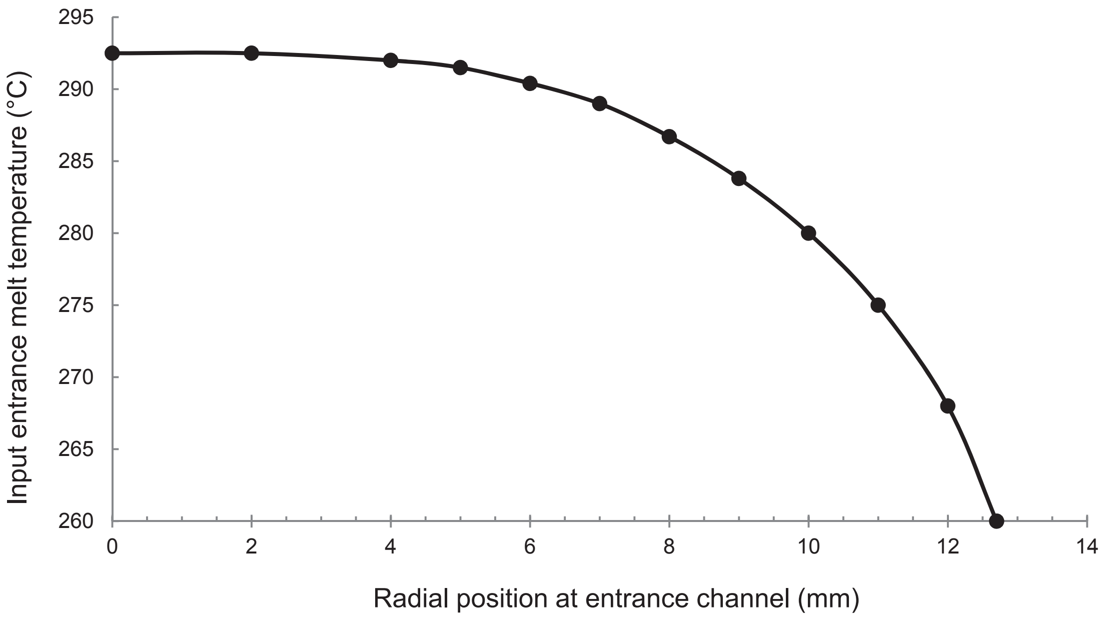

Figure 11. Entrance temperature profile representative of poorly operating extruder input as a boundary condition

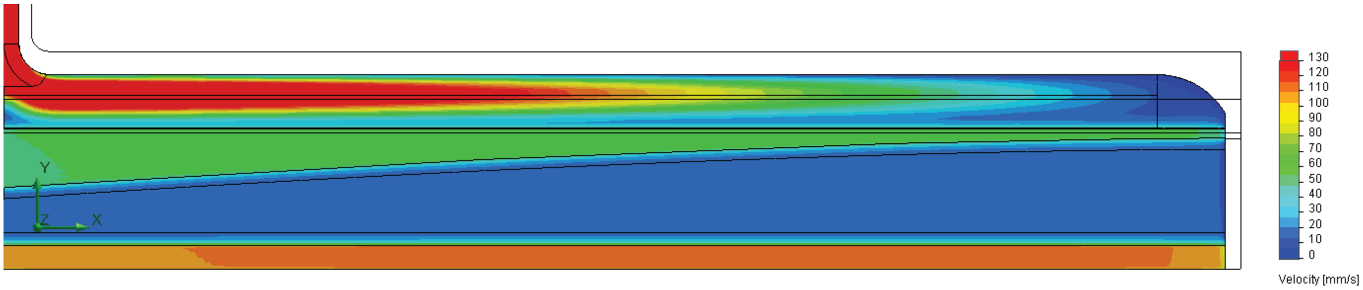

Figure 12. Velocity contour on the parting plane with non-uniform entrance melt temperature resulting from excessive shear in the melt pipe

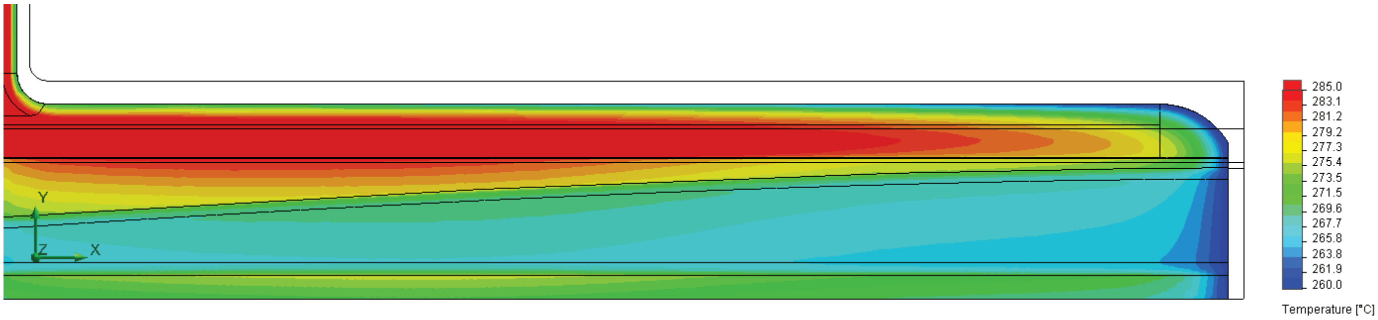

Figure 13. Velocity contour on the parting plane with non-uniform entrance melt temperature resulting from excessive shear in the melt pipe

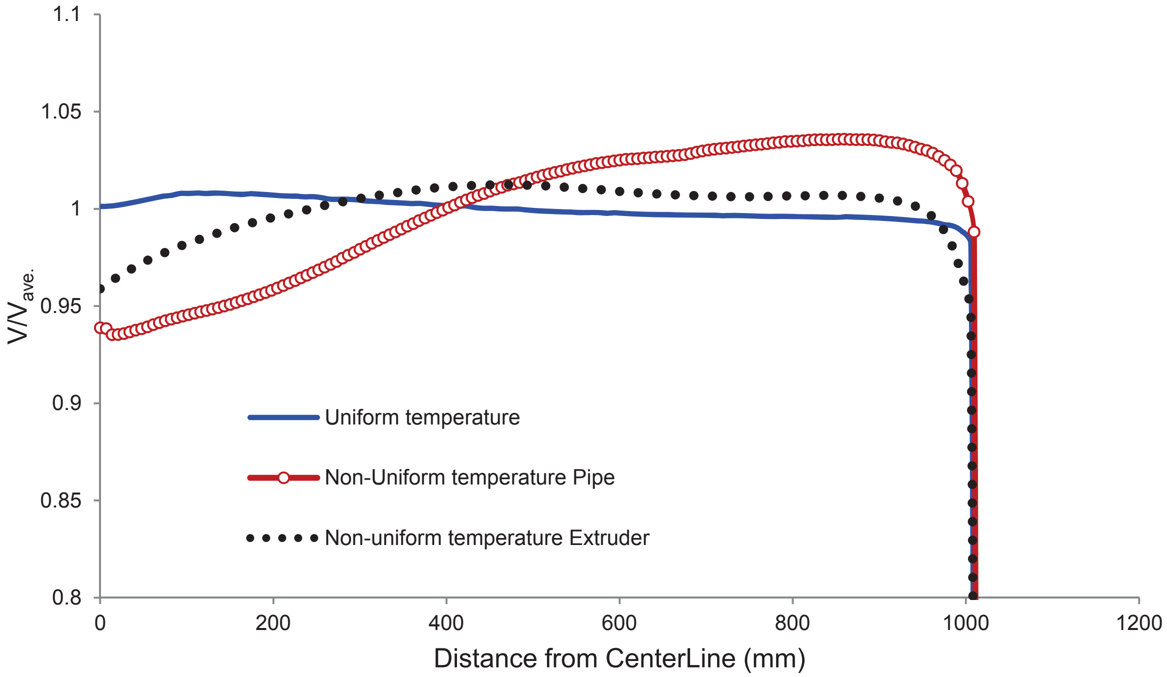

Figure 14. Normalized exit velocity profiles on parting plane with different incoming melt temperature conditions

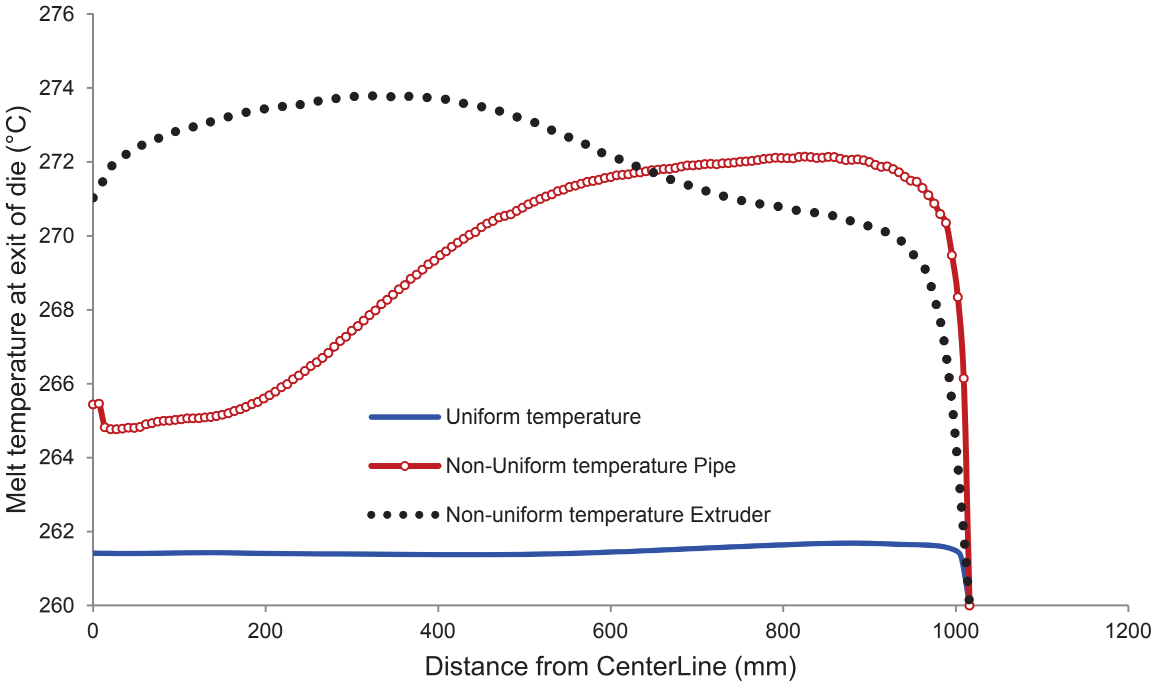

Figure 15. Resulting exit melt temperature profiles with different incoming temperature conditions