Numerical Simulation of a PA66 Flow Behaviour in a Hot Runner Gate

Alberto Gava, * Giovanni Lucchetta*

Summary: In actual hot runner systems for the injection moulding process, the control of polymers in gate is passive, which means that the melt temperature distribution and associated flow conductance is governed by a balance of heat convection by the flowing melt with heat conduction from the hot melt to the cold mould. This paper examines the rheological and thermal behaviour of a PA66 during freeze-off and melt flow activation. Numerical simulations were carried out according to the Finite Volume Method as implemented in the Ansys CFX® code. Rheological and thermal data were obtained from a careful material characterization conducted on a capillary rheometer and a differential scanning calorimetry (DSC). The analyses indicated that relatively small changes in melt temperature and injection pressure can substantially increase the flow conductance and dynamically control both the gate freezing and the onset of melt flow in the subsequent cycle. Therefore, simple gate thermal actuators were designed and numerically implemented to active control the plastic melt flow. This numerical approach can be used to design and optimize the active control of hot runners gate when the use of mechanical actuation (i.e. valve gates) is not suitable due to excessive cost, critical maintenance or miniaturization of the entire system.

Keywords: computer modelling; differential scanning calorimetry; injection moulding; polyamides; rheology

Introduction

There has been a sustained evolution towards closed loop control in injection moulding. Advances are driven largely by economic concerns since machines can typically operate at higher production rates and with high production yields under closed loop control than with open loop control. By definition, every closed loop control requires a feedback path back to the output being controlled. Most closed loop controls act on feedback regarding machine elements, which do not necessarily provide precise control of the process states that determine the quality of moulded products.

Department of Innovation in Mechanics and Management, University of Padova, Via Venezia 1, 35131 Padova, Italy
Phone: (+39) 049 8276823;
E-mail: alberto.gava@unipd.it

As such, injection moulding is not a closed loop process with respect to the quality of moulded parts. Instead, injection moulding is an open loop process in which many closed loop processes are linked such that the consistency of the moulded products is very high.[1]

This paper deals with the control of plastic freeze-off and melt flow through a conical hot gate. The thermal hot gate functions on a cyclodynamic thermal freeze off cycle and a cold slug forms inside the gate orifice during the cooling time of the part. When the actual plastic part has solidified inside the mould cavity as a result of the mould cooling phase, the mould opens and pulls the cold plastic part away from the gate orifice. The tapered shape of the gate orifice formed by the frustro conical surface causes the cold slug to fracture and to remain inside the gate during this step. This cold slug prevents the plastic melt from drooling out through the gate and also prevents the melt from being pulled into strings. With the next injection cycle, the small cold slug is injected into the mould cavity where it is dissolved by the initial melt pressure impulse from the ram. The temperature of the outer heating arrangements (or alternatively of the inner heat conductive torpedo) and the cooling temperature of the gate metal (steel) follow a thermodynamic cycle in order to achieve the required gate fracture. It will be understood that precise temperature control in both heating and cooling conditions is required and this is achieved by both gate cooling and heating and by micro processor precision temperature controllers with a closed loop feedback of the temperature readings via thermocouples that are placed in the nozzle area. In this regard the nozzle front is thermally insulated from the larger gate area by a pocket that fills with a plastic melt layer.

It has been observed that some residual pressure has been maintained in the barrel of injection moulding machines after plastication and even after decompression.[2] This pressure is typically on the order of 1 MPa, and may be due to the thermal expansion and creeping flow of the plasticating material in the screw, body forces and relaxation of the accrued shot, or idling control signals from the moulding machine. The objective of this research is to provide a thermal control device that guarantees freeze-off during plastication and mould open, but readily admits flow during the filling and packing stages.

Historically injection moulding dedicated analyses have been inaccurate in predicting gate freeze time on hot runners.[3] This is because in the model of a hot runner section the software will not allow that section to ever freeze; it keeps it at the melt temperature throughout the analysis. The scope of this study is to model an externally heated gate giving accurate results with minimal modelling time. A commercial hot gate is modeled with simple geometric shapes, which could be easily modified. Numerical simulations are performed in order to estimate the temperature and pressure distribution along the nozzle and to evaluate the influence of different process parameters on the gate freeze-off. The analysis results are compared to each other based on gate freeze time, fill pressure and fill temperature. The analyses indicate that relatively small changes in melt temperature and injection pressure can substantially increase the flow conductance and dynamically control both the gate freezing and the onset of melt flow in the subsequent cycle.

Rheological and Thermal Characterization

Rheological and thermal data of a polyamide (Vydyne 21 SPC) were obtained from a careful characterization conducted on a capillary rheometer and a differential scanning calorimetry (DSC). Nylon is relevant in injection moulding for its high flowability, low friction, good mechanical properties and high resistance to solvent stress cracking compared to amorphous blends.

Testing plastic melt is necessary since the fluidity of the material is generally not dependent solely on temperature, but also on other parameters, such as shear rate and shear stress. The flow of plastic through a runner is complex since the shear rate and temperature vary throughout the depth of the runner. The shear rate is dictated by the velocity profile. The temperature at any given location is determined by local shear heating, heat transfer and thermal proper-

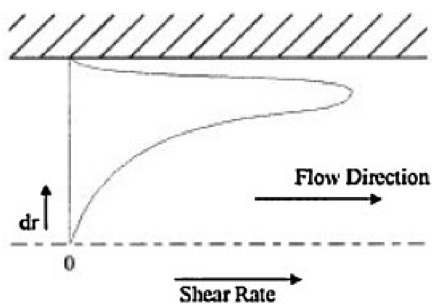

Figure 1.
Shear rate profile from centerline to wall of a circular cross section runner.

ties of the material. The resultant velocity gradient and, therefore, the resultant shear rate reaches a maximum just inside the outermost regions of the flow channel (Figure 1).[4]

The high shear rate region just inside the outermost boundary layer has a combined effect on viscosity. The viscosity in this region is decreased by both shear thinning and frictional heating. It is common in moulding for the frictional heating to increase the melt in the outer most flow laminate to temperatures well above temperature in the center of the melt stream. In hot runner manifolds, the viscosity is decreased even more by the heated manifold and heated mould. This localized frictional heating is dependent on viscosity and shear rate.

Stability of polymer melts can be estimated by both numerical simulation and physical experimentation.[2] Numerical simulation of injection moulding requires viscosity data that covers the temperatures and shear rates encountered in the process. The two most popular devices for obtaining such data are the capillary and the rotational rheometer. The capillary rheometer is the most widely used instrument employed for viscosity characterization. It has the capability of replicating the pressures, rates and flow fields encountered in cylindrical geometries. The rheological quantities that can be obtained from experimental pressure and volumetric flow rate data are the apparent viscosity (Equation 1) and the apparent shear rate (Equation 2):

$$\eta_a = \frac{\Delta P}{\Delta L}\frac{\pi R^4}{2Q} \tag{1}$$

$$\gamma_a = \frac{4Q}{\pi R^3} \tag{2}$$

where Q is the volumetric flow rate, R is the capillary radium, ΔL is the capillary length and ΔP is the pressure drop across the capillary.

Fitting of experimental data to the models such as the Cross model (with WLF temperature dependence) can be employed as a reasonable technique to predict the shear rate of the polymer and hence its behaviour in the injection moulding process. The Cross model (Equation 3) with the WLF temperature dependence (Equation 4) are reported in the following:

$$\eta = \frac{\eta_0}{1 + \left(\frac{\eta_0 \gamma}{\tau^*}\right)^{1-n}} \tag{3}$$

$$\eta_0 = D_1 \exp\left[-\frac{A_1(T - T^*)}{A_2 + (T - T^*)}\right] \tag{4}$$

where n is the power law (or non Newtonian) index, η_0 is the reference viscosity at zero shear rate, γ is the shear rate, τ^* is the shear stress at the transition between the Newtonian and non-Newtonian behaviour of the melt and D_1, A_1, A_2 are WLF model coefficients.

In order to actively control the flow of the polymer melt in cylindrical geometries, accurate rheological characterization of the polymer at low temperature and shear rates was necessary. Therefore, the viscosity and shear rate data were obtained on a commercial polyammide using a CEAST® dual bore capillary rheometer. A recommended die diameter of 1 mm was used for low shear rates (100–1000 1/s); on the other hand, a die diameter of 0,5 mm was used for high shear rates (1000–10000 1/s), because of the high flowability of the melt at high temperatures. To determine the true shear rate γ and the true shear stress τ, capillary dies of the same diameter but having two different L/D ratios were used. Data were obtained at temperatures in the range of 270–300 °C. Due to extremely high melt viscosity, it was not possible to acquire rheological data for the material at lower values of temperature and pressure than was tested with this device. The data obtained from the low temperature testing was fitted to the Cross-WLF model, and is provided in Figure 2. Good agreement was observed between measurements carried on with the two different capillary dies (corresponding results at 1000 1/s are indicated by the dashed line).

Secondly, the material was characterized on a differential scanning calorimetry. The thermal characterization was conducted at

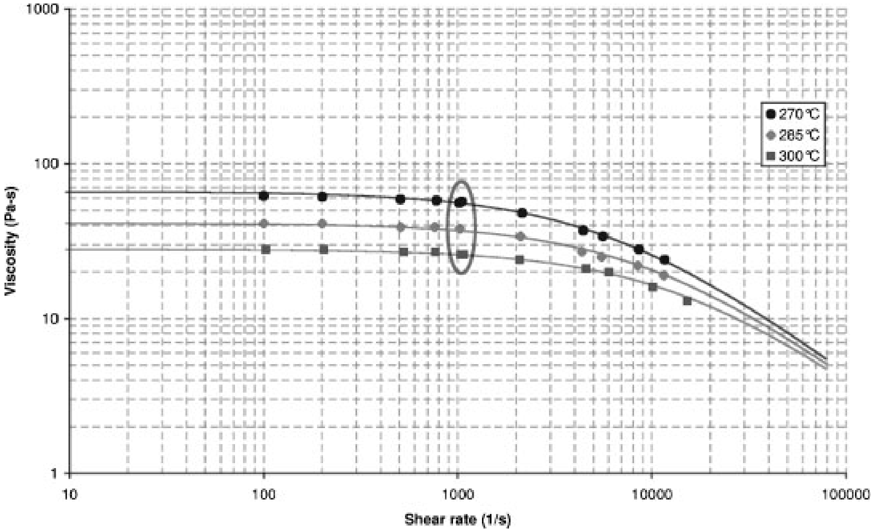

Figure 2.
Rheological characterization of Solutia Vydyne 21 SPC on a capillary rheometer.

the maximum controlled rate of 30 °C/min. The heat of fusion, the heat of crystallization and the specific heat in function of temperature are clearly determined on Figure 3. Due to loss volatiles, the transition temperature was accurately determined only during a second heating rate and it was estimated in 55 °C.

Model Design and 2½D Numerical Simulations

The model considered in this study is a cable tie used for binding several electronic cables together and to organize them into a cable tree. Cable ties are currently produced by injection moulding process in a 52 cavities mould on a BMB injection moulding machine. All runner branches are of trapezoidal cross section in order to machine only the fixed mould part. The actual process production consists of a convenctional technology based on cold runner system. Figure 4 shows the assembly of the nozzle, sprue and mould plate. Due to the symmetry of the runner layout only one-quarter of the mould is modeled.

Objective of this work is to develop a new technological solution based on hot runners system and active thermal control. Such a tecnology will confer clear advantages in terms of both process cycle time reduction and thermoplastic material waste. These respectively translate into faster time to market and lower production costs. Futhermore, new advances in nozzle tip design and materials can provide wider operating windows and longer service life. On the other hand the cold runner technology offers advantages when considering mould complexity and cavity machining costs. Numerical simulations of the process were performed in Moldflow Plastic Insight® enviroment to estimate the cycle time reduction in the case of a technological solution based on hot runners system as alternative to the conventional cold runner solution.

Two and half numerical simulations were performed implementing:

- the melt temperature as equal to the barrel temperature (300 °C);
- the mould temperature as the mean value of the mould surface acquired by temperature transducers mounted in the fixed mould part (40 °C);
- the real ram speed profile given by the machine;
- the same packing pressure profile implemented in the machine;

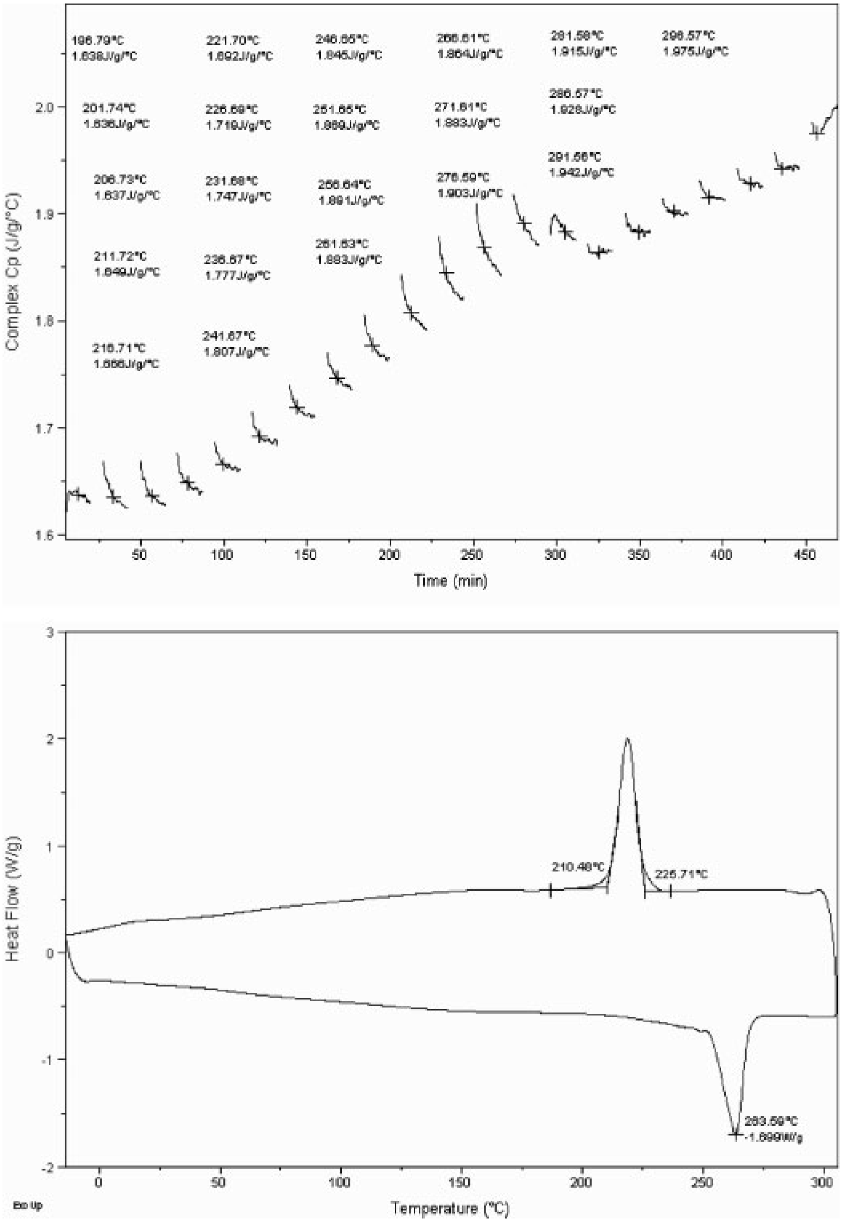

Figure 3.
Thermal characterization of Solutia Vydyne 21 SPC conducted on a DSC: specific heat (above) and endothermic/exothermic processes (below): melting temperature (263 °C), no-flow temperature (225 °C), crystalline melting point (218 °C), ejection temperature (210 °C), glass transition temperature (55 °C).

- a mould-open time of 2 seconds;
- thermal and rheological properties obtained from the material characterization conducted on capillary rheometer and differential scanning calorimetry. The melt compressibility is modeled with a double domain Tait equation, extracted directly from the Moldflow® material database.

Moldflow® provides a good prediction of both the magnitude and shape of the

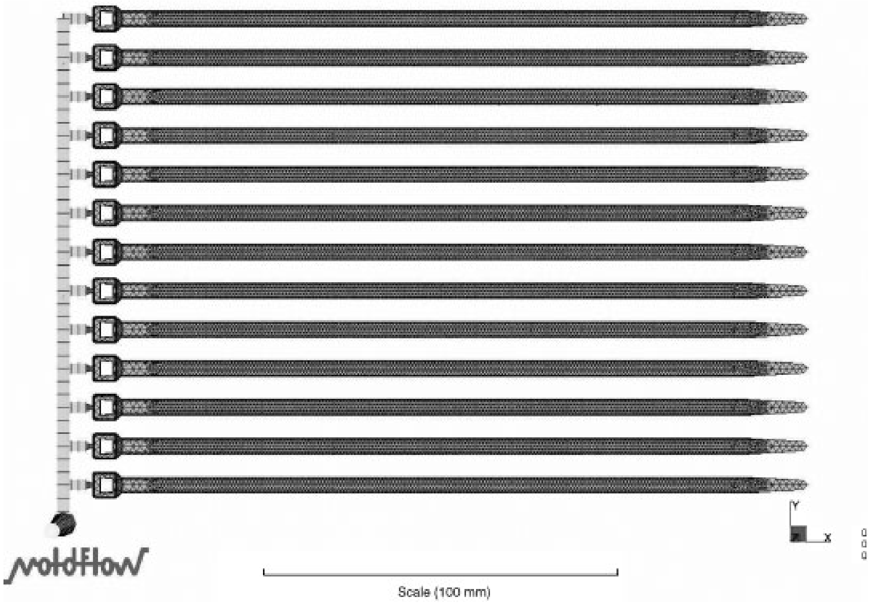

Figure 4.
Test mould used to determine melt flow conditions in a 52 cavity cold runner system.

pressure evolution during injection moulding of the material adopted in this work. Estimated injection, packing and cooling times are in good agreement with industrial case. The same software was therefore adopted in this work to analyze the evolution of the frozen layer at gate position (i.e. hot runners system solution), at sprue position (i.e. cold runners system solution) and in a point inside the cable tie. Figure 5 shows how hot runners system solution confers clear advantages in terms of cooling time reduction. Compared results are reported in Table 1.

Total cycle time estimated in the case of hot runner system didn't take into account for the gate freeze-off time during plastication and for melt flow activation. Futhermore injection moulding flow simulations use shell models of the thin walled mould cavity to represent the cavity geometry. The shell elements use a high-order interpolation through the shell thickness to accurately represent the non-linear temperature distribution in this direction. Convection is assumed to occur only in the plane of the shell. These assumptions served well, since in most cases flow velocity fields are laminar, but lose validity in thick regions, at sudden changes in thickness and at junctions, such as at gate location or at branch in a multi cavity feed system. In the following gate freeze-off and melt flow activation are simulated using a 3D fluid dynamics analysis on Ansys CFX® enviroment.

Analisys of Gate Freeze-off and Melt Flow Activation

Evolution of solidification inside the gate is a quite complex phenomenon, which involves several aspects. During the filling step, cooling inside the gate is counteracted by the continous incoming of new hot material from the runner. At the beginning of the packing step, the convective term in the energy balance is still high. However, it gradually fades, since the cooling rate inside the cavity reduces with time and a decreasing flow rate of material is required to balance the polymer density increase. If the effects of convection were not signifi-

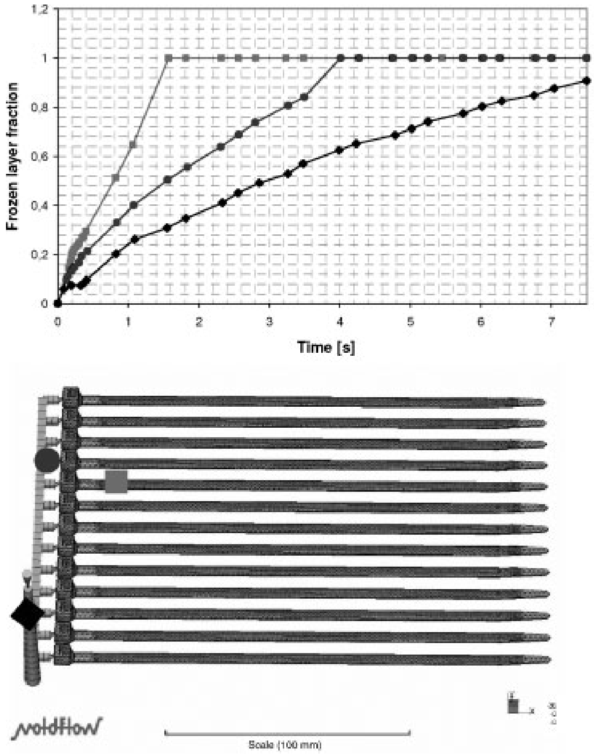

Figure 5.
Frozen layer fraction in three different zones of the mould.

cant inside the gate, cooling rate at gate position would be much quicker and gate solidification time much shorter. Gate solidification takes place when the heat lost through gate walls by conduction overcomes the energy entering the gate from the runner because of convection.[5] The gate freeze-off time can be therefore intended as the sum of three terms:

- a time at which the flow front reaches the gate;
- a ''convective'' period, when convection is high enough to reduce substantially the cooling rate;
- a ''conduction'' period, when the heat lost by conduction through gate walls gives rise to a rapid cooling to solidification temperature at gate midplane.

Commercial 2½ simulation softwares have been historically inaccurate in predicting gate freeze time on hot runners.[3,5] Therefore, this paper presents on the use of general purpose and extrusion flow analysis programs with injection moulding runner analysis. It also reports on the 3D extrusion software's suitability to integrate itself into injection moulding approaches. A numerical analysis is performed using the fluid

Table 1.
Estimated and experimental cycle time.

	Injection time [s]	Packing time [s]	Cooling time [s]
Actual process production	0,55	2,2	4,3
Simulation: cold runner system	0,65	2,5	4,5
Simulation: hot runner system	0,4	2	0,5

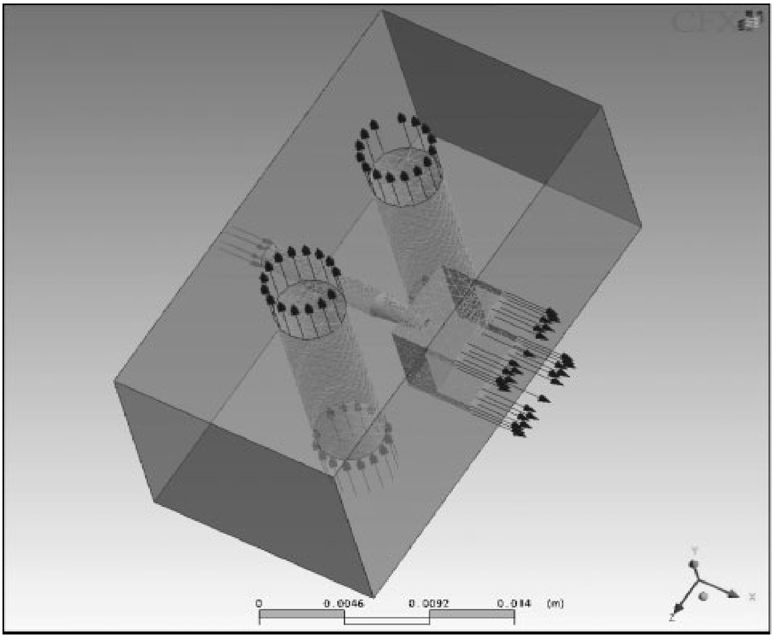

Figure 6.
3D mesh of flow domain used to determine gate freeze-off.

dynamics package Ansys CFX®, to solve for temperature and flow within the runner and gate system. Figure 6 shows the assembly of part of the runner system, part of the cable tie and the water line system. The 3D meshes are graded with a finer mesh near the outer most boundaries of the melt and water channels to capture the high thermal gradients. The gate is modeled as a three dimensional cone. Its dimensions are determined according on flow rate and admissible shear rate of the melt, as recommended on easy-to-read diagrams published by hot runner systems suppliers.[6] A flow rate of 5 cm^3/s is selected as input according to Moldflow® simulation results.

The rheological behaviour and the temperature distribution predicted via experimentation are used to evaluate the control of the plastic melt and freeze-off in cylindrical geometries. The Vydyne 21 SPC material is modeled as a non-Newtonian fluid with viscosity calculated according to the WLF-Cross model. In order to predict the viscosity at lower temperature and pressures the equations for continuity, momentum and energy are solved by numerical integration as per standard simulation practice.[7] By using a three dimensional tetrahedral mesh to represent the solid geometry, the limitations of shell based analyses can be avoided. Convection is performed using the full three component velocity vector and without geometry based restriction.

The boundary conditions for the simulations are summarized below:

- prescribed pressure or melt flow rate at inlet of the fluid domain;
- uniform inlet melt temperature equal to 290 °C in the fluid domain;
- adiabatic wall boundary at the runner/mould interface;
- conservative heat transfer at gate/mould interface;
- zero pressure at the cable tie exit (according to end-packing conditions);
- no slip condition at the mould walls;
- uniform inlet water temperature and mass flow rate in the cooling system.

Table 2.
Geometric and flow conditions during injection moulding process through the gate.

Parameter	Value
Gate diameter	0.8 mm
Cooling channels diameter	4 mm
Melt inlet pressure	1.5, 2, 2.5 MPa
Water inlet temperature	30, 40, 50, 60, 70 °C

The initial boundary value problem at hand is solved by the Finite Volume Method as implemented in Ansys CFX® software. Numerical simulations are performed in order to estimate the temperature and pressure distribution along the nozzle/gate and to evaluate the influence of coolant temperature and inlet melt pressure on the gate freeze-off. The temperature of the coolant system and the inlet pressure of the melt (i.e. residual pressure maintained in the barrel after plastication and even after decompression) are established with the aim of keeping a realistic industry perspective. The geometric specific sizes and the process parameters levels are given in Table 2.

Analysis of the temperature distribution of the nozzle contacting the mould shows a significant temperature distribution as a function of the axial and radial position in the metal and polymer. The temperature of the polymer melt determines the viscosity and subsequent flow through the nozzle. Figure 7 and 8 show the results of the transient temperature analysis, both for fluid and solid domain.

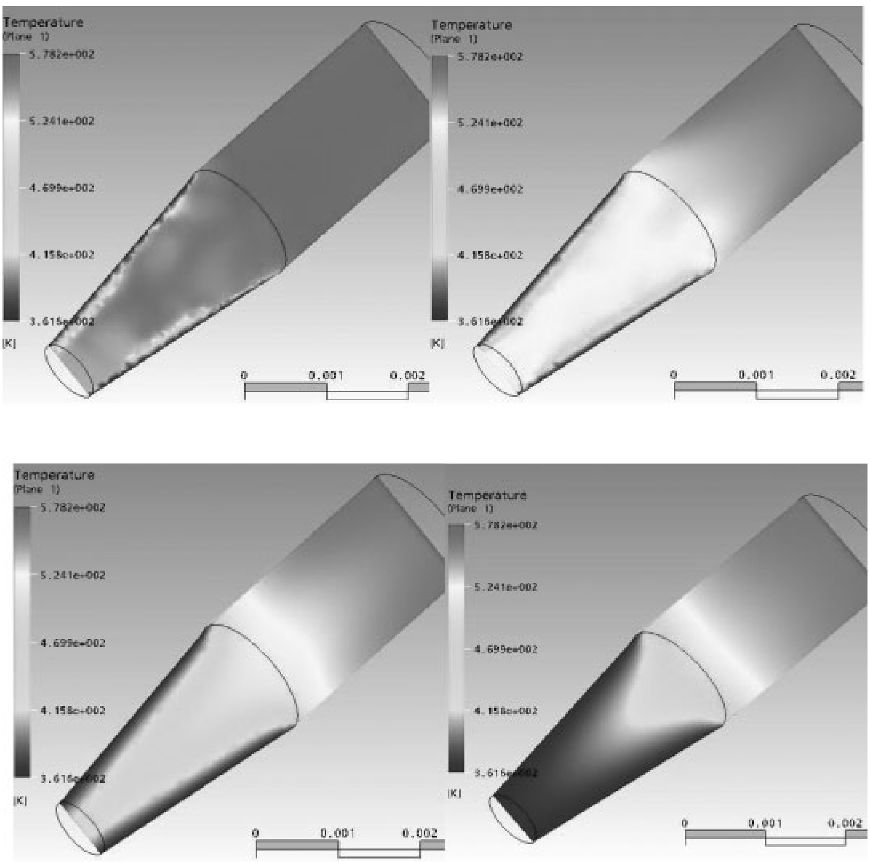

Figure 7.
Gate freeze-off considering a time step of 0,45 seconds. Inlet melt pressure and inlet water temperature are respectively set at 1,5 MPa and 70 °C.

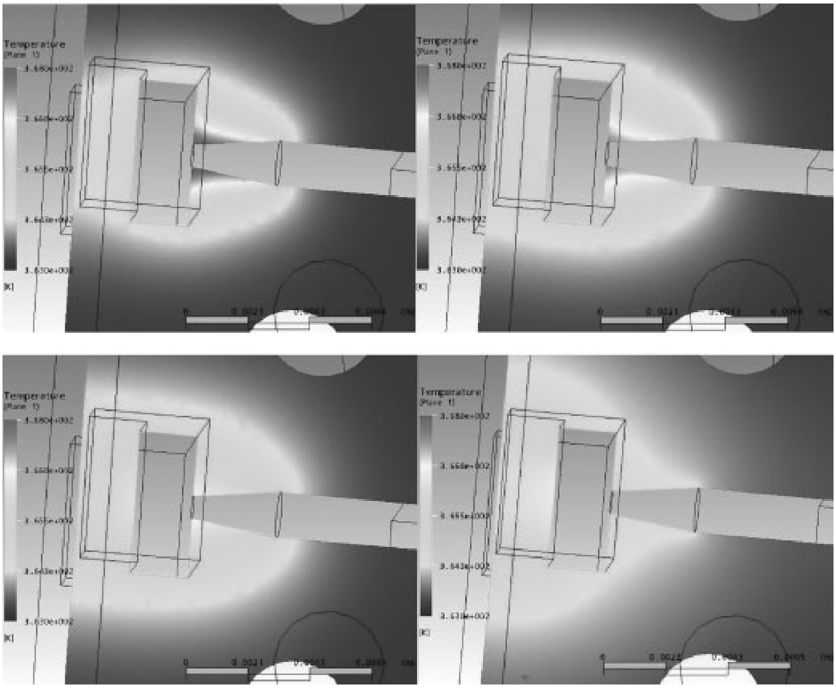

Figure 8.
Mould heating considering a time step of 0,45 seconds.

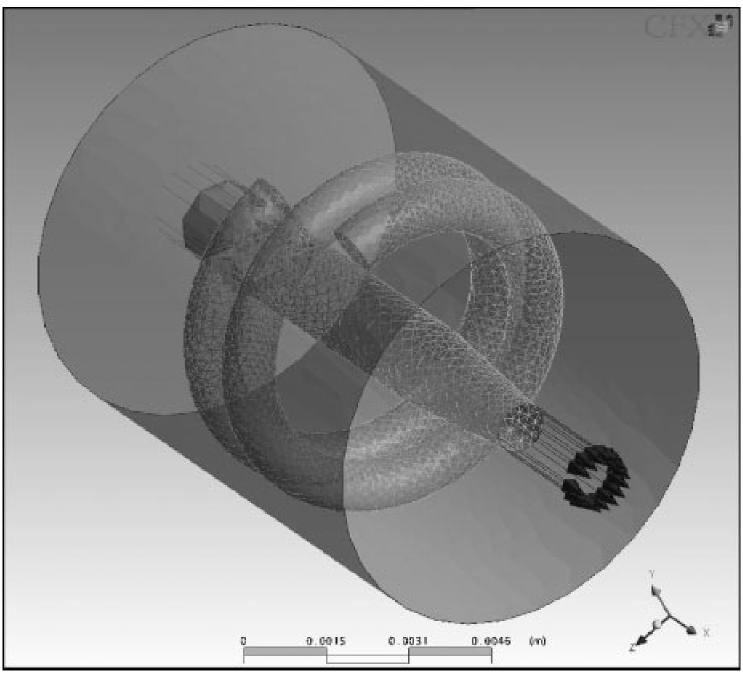

Figure 9.
Model of heat exchanger implemented in Ansys CFX® simulation.

The second objective of the paper is to evaluate the flow activation in the subsequent cycle. A hot runner system for injecting polymer material from a plasticating unit into an injection mould for moulding very small plastic devices, includes a hot runner manifold having an inlet for receiving melted polymer material from the plasticating unit and a heater for maintaining the manifold at an elevated temperature. To efficiently and rapidly control the flow of freeze-off and flow of the polymer

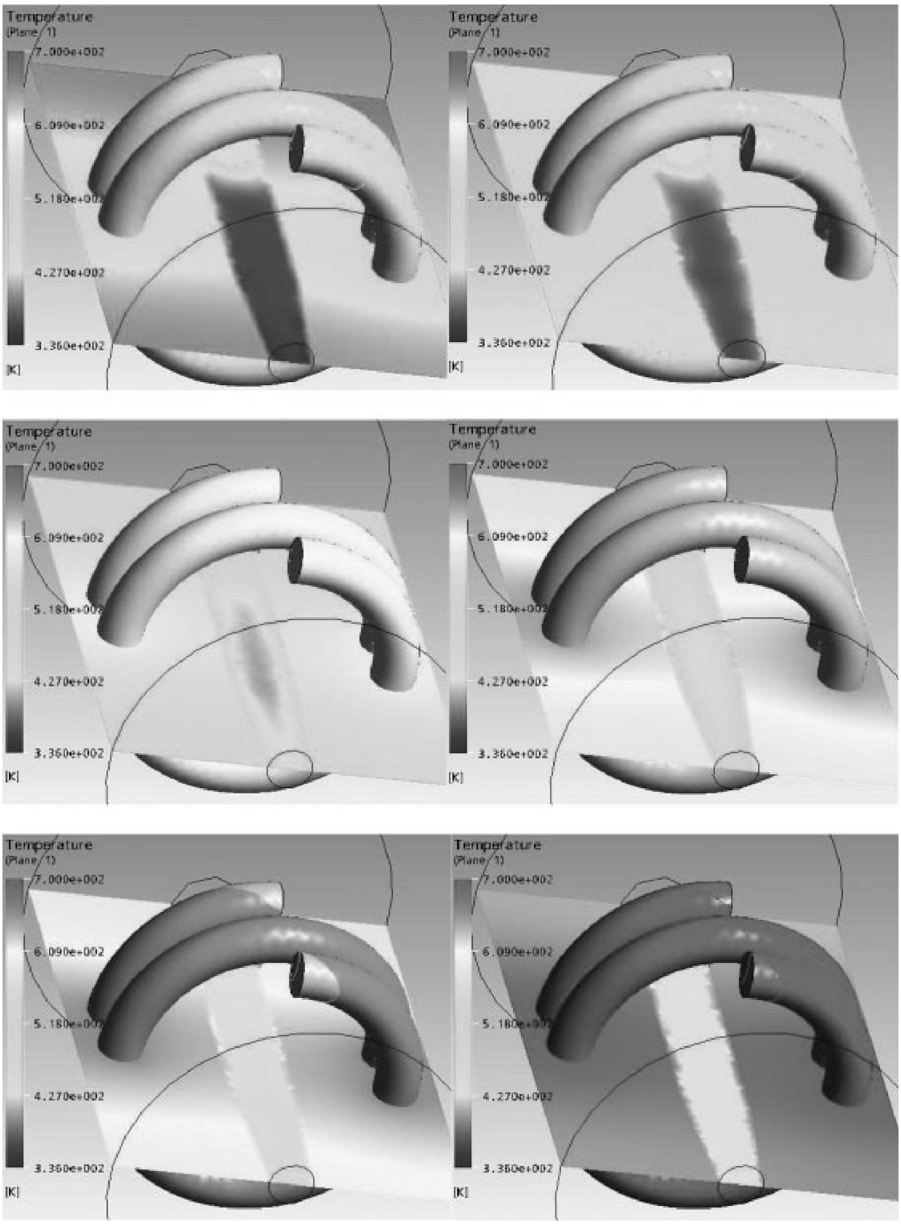

Figure 10.
Melt flow activation considering a time step of 0,35 seconds. The inlet melt pressure and the heater power density are respectively set at 10 MPa and 1.0E + 07 W/m^3.

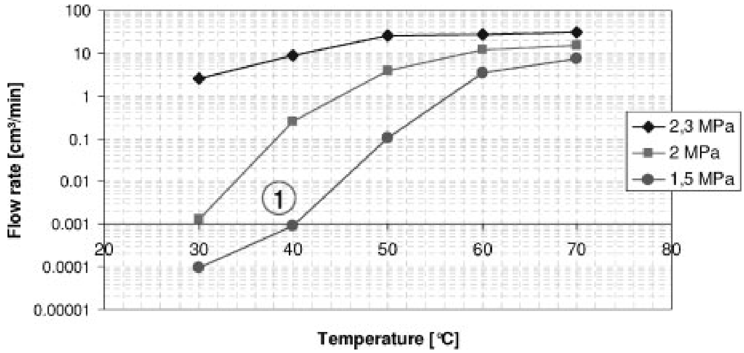

Figure 11.
Effect of temperature and pressure on the average flow rate after 1 second.

melt in the subsequent cycle, it is desired to change the heater temperature by a small amount across which the flow conductance of the polymer is greatly increased. In this case part of the model of a simple heat exchanger is used to model the heat transfer from a solid domain to a fluid domain (Figure 9). The heater is a solid Ni-Cr coil modelled as a constant heat source. The temperature of the heater is initialised at 275 °C. The heater power density and the inlet pressure of the melt are varied in order to determine their influence on melt flow activation.

Analysis of the temperature distribution of the nozzle contacting the mould is reported in Figure 10. Thermal degradation of the melt as a result of excessive residence time or high temperature has to be considered in order to avoid burning and black streaks.

Results and Discussion

The previous analysis results are compared to each other based on gate freeze time, fill pressure and fill temperature. Figure 11 and 12 plot the flow rate through the gate at varying reference temperatures and pressures, respectively after 1 and 1,5 seconds. The flow rate is plotted on a logarithmic scale given the significant increase in the flow rate with increases in melt temperature or injection pressure. Point 1 in Figure 11 establishes a baseline no-flow condition of

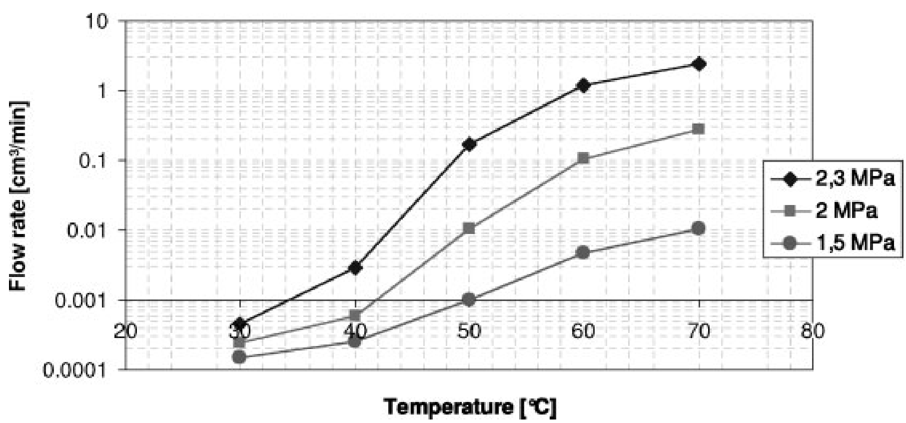

Figure 12.
Effect of temperature and pressure on the average flow rate after 1.5 seconds.

0.001 cm^3/min at a coolant temperature of 40 °C and a pressure drop across the nozzle of 1.5 MPa. Such a no-flow condition may be specified to guarantee the prevention of leakage during plastication or mould open condition. In Figure 12 it should be noted that the no-flow condition may be made even more conservative by requiring a lower coolant temperature to prevent leakage at high pressure drops.

To enable melt flow, it is necessary to either increase the melt temperature in the nozzle or apply a much greater pressure drop. Once melt flow is induced, the convection of the heated melt and internal viscous dissipation will further increase the bulk melt temperature, thereby further increasing the flow conductance and sustaining continued melt flow. To efficiently and rapidly control the flow of freeze-off and flow of the polymer melt, it is desired to change the temperature by a small amount across which the flow conductance of the polymer is greatly increased. The primary issue, then, is how to enable initial melt flow. Most moulding practitioners have observed attempts to clear a plugged nozzle or gate by increasing the injection pressure. Depending on the geometry of the gate and temperature distribution, these attempts can lead to a clear gate at relatively low applied pressure, a bullet exit at relatively high applied pressure, or no clearance at any pressure.[2] In this paper it is assumed that a flow rate of 0.1 cm^3/min is needed to initialize steady flow through the nozzle (Figure 13).

Point 2 indicates that 0.1 cm^3/min of flow can be accomplished in 1.3 s with a pressure of 15 MPa by selecting a heater power density of 7 W/mm^3. Alternatively, point 3 indicates that the same flow rate can be accomplished in 6 s by an injection pressure of 2 MPa and a heater power density of 0.2 W/mm^3. Specifically, the energy required to increase the melt temperature is defined as:

$$E = \varepsilon\, m\, c_p\, \Delta T \quad (5)$$

where m is the mass of the polymer, c_p is the specific heat of the polymer, ΔT is the required temperature change of the melt, and ε is the actuation efficiency (percentage of heater power that enters the melt, dependent on nozzle and heater geometry and thermal properties) on the order of 10%. To reduce actuation energy and response time, it is clearly desirable to reduce the diameter of the nozzle as well as the required temperature change. How-

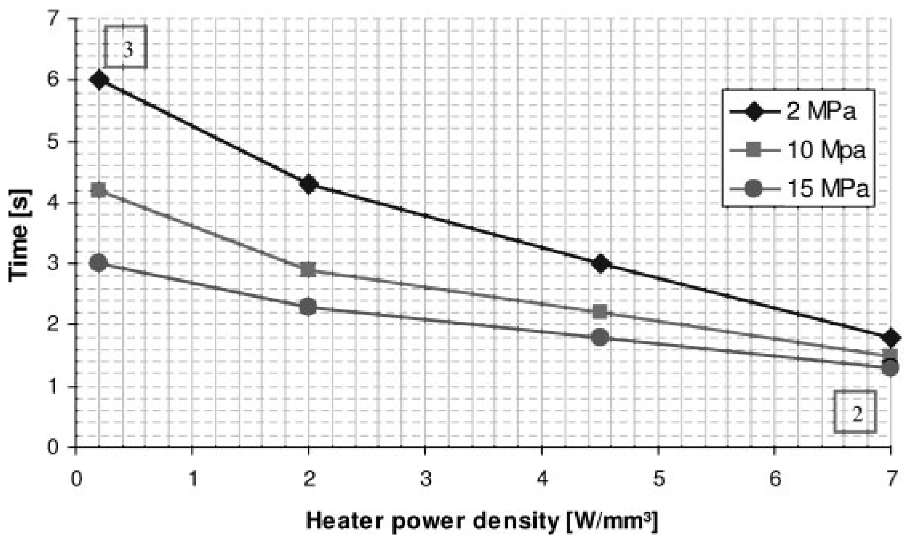

Figure 13.
Effect of heater power density and melt pressure on flow activation.

ever, reducing the diameter will further reduce both the initial and steady state flow conductance, such that the minimum diameter is dictated by the maximum allowable pressure drop across the nozzle during the filling stage. Clearly, further increases in melt temperature would require proportionally greater power and longer heating times. While a 1.3 seconds delay (point 2) during mould closure would likely not extend the cycle time of the process, a 6 (point 3) seconds delay would be economically crippling. A good combination of melt pressure and heater power density has to be defined in order to avoid material degradations (high shear rate or high temperature maintenance) and reduce the cycle time length.

Conclusion

This paper examined the rheological/thermal, melt flow and freeze-off behaviour for a polyammide material. The analysis indicated that relatively small changes in coolant temperature and injection pressure can substantially increase the flow conductance and dynamically control the onset of melt flow. Gate freeze-off and flow activation times are evaluated by monitoring the flow rate at the gate exit. The further development and deployment of the present technology could proceed in a number of directions. In the interest of further validating and clarifying the knowledge produced to date, it is planned to:

- conduce experimental trials in order to validate the 3D flow extrusion simulations;
- conduce a series of simulations to investigate the flow behaviour for different dimensions and shapes of gate;
- perform testing with additional materials;
- develop an automated methodology for design of injection moulds and moulding control profiles to ensure low risk, low cost, lights out manufacturing;
- validate the required operating temperature and pressure changes for various amorphous and semi-crystalline resins;
- perform thermal characterization at higher cooling rate.

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