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Improvement of heat transfer analytical models for thermoplastic injection molding and comparison with experiments

Baptiste Pignon *, Vincent Sobotka, Nicolas Boyard, Didier Delaunay

Université de Nantes, CNRS, Laboratoire de Thermique et Energie de Nantes, UMR 6607, La Chantrerie, rue Christian Pauc, BP 50609, 44306 Nantes cedex 3, France

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ABSTRACT

The aim of analytical models presented in this paper was to provide a first set of data for choosing thermal conditions during thermoplastic injection molding. Two different models allowed the quick determination of the cooling/solidifying time, the mold surface temperature variation and the heat flux densities exchanged between the polymer and the mold. The first model specific to amorphous polymers was based on the 1D heat conduction equation. The second model dedicated to semi-crystalline polymer was based on the adaptation of the solution of the Stefan problem for part with a finite thickness. For each case, the influence of the thermal contact resistance between polymer and the mold on the cooling/solidifying time was highlighted. Then, the description of heat transfer in the mold allowed to determine the time needed to produce reliable parts when the mold was in periodic steady state. The attenuation of the periodic temperature variation through the thickness of the mold was evaluated through the penetration depth. Parameters calculated from these analytical models were compared with experimental results obtained with an instrumented mold or with data computed with a coupled model. The good agreement between them validated the interest to these models to get quickly reliable characteristic parameters of injection molding.

1. Introduction

Injection molding is the most used process in amorphous and semi-crystalline polymers forming. This is a cyclic process, in which each cycle can be decomposed in several steps: The filling step consists in injecting the melted polymer in the molding cavity during a short time. During the packing phase, a pressure is applied to the polymer to compensate the thermal and crystallization shrinkages until the freezing of the gate. The cooling of the part continues until the part is solidified enough to be ejected. The cooling phase being the most significant step of the process cycle in terms of time, its determination is of primary importance to estimate production capabilities and costs. Heat transfer in the process can be described in a first approach by designers' experience and the use of simple formulas [1] even for the design of conformal cooling channel [2]. This approach can be completed using simulations such as commercial software, especially for complex geometry parts. However, their use may be time-consuming in terms of computation and also requires input data especially boundary conditions and material properties, which are sometimes difficult to obtain. In this context, different analytical models have been developed to provide quickly a first set of data for mold designers.

Simplified modeling [3,4] used for cooling time calculation is based on the heat conduction equation. Indeed, natural convection does not occur due to the very high viscosity of melted polymer (more than 1000 Pa·s). Moreover, even during the filling (less than 5% of the cooling time), the thermal shock of the melted polymer on the mold induces a high conductive heat flux (more than 3.10^5 W/m^2) which is several orders of magnitude higher than the convective heat flux [5]. The assumptions of these models include the use of average thermophysical properties as well the boundary conditions that are assumed constant and uniform.

Nevertheless, these methods cannot be used for semi-crystalline polymers since they do not consider the crystallization. Indeed, heat transfer and crystallization are strongly coupled: the crystallization depends on the temperature, pressure and mechanical stresses, while the temperature field is influenced by the crystallization enthalpy released and by the dependence of thermophysical properties according to the crystallinity and temperature. The coupling can be simplified if the Deborah D_e number is low (Eq. (1)), what means that the solidification half-time $t_{solid}/2$ is small compared to the characteristic conduction time e^2/a_p, as proposed by Bénard and Advani [6] (Eq. (1)). In this case, the phase

* Corresponding author.
E-mail address: baptiste.pignon@univ-nantes.fr (B. Pignon).

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Nomenclature

a	thermal diffusivity [m^2/s]
B_i	Biot number
b	thermal effusivity [$J{\cdot}K^{-1}{\cdot}m^{-2}{\cdot}s^{-1/2}$]
c	parametric constant
C_p	specific heat capacity [$J{\cdot}kg^{-1}{\cdot}K^{-1}$]
D_h	hydraulic diameter [m]
D_e	Deborah number
e	part thickness [m]
g	parametric constant
Gz	Graetz number
k	thermal conductivity [$W{\cdot}m^{-1}{\cdot}K^{-1}$]
K_{Nak}	Nakamura coefficient [s^{-1}]
L	length of the channel [m]
l	length between the molding cavity and cooling channels [m]
l_{eq}	equivalent length between the molding cavity and cooling channels considering the constriction field [m]
n	Avrami exponent
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Ste	Stefan number
t	time [s]
$t_{cooling}$	cooling time [s]
t_{cycle}	cycle time [s]
t_{solid}	solidification time [s]
TCR	thermal contact resistance [$m^2{\cdot}K/W$]
T	temperature [°C]
T_c	contact temperature [°C]
T_{ej}	temperature in the center of the part at the ejection [°C]
$\overline{T}_{ej}$	average temperature at the ejection [°C]
T_f	phase change temperature [°C]
T_{inj}	injection temperature [°C]
T_{mi}	mold temperature before injection [°C]
$\overline{T}_s$	mean mold surface temperature [°C]
u	root of transcendental equation
V	velocity [m/s]
x_f	crystallization front [m]
z	length between two cooling channels [m]

Greek symbols

α	relative crystallinity
ΔH	crystallization enthalpy [J/g]
μ	dynamic viscosity [Pa·s]
ξ	root of transcendental equation
ρ	density [kg/m^3]
τ	mold time contact [s]
φ	heat flux density [W/m^2]
φ_{msi}	heat flux density obtained with the semi infinite medium assumption [W/m^2]

Subscripts

fluid	fluid in cooling channels
l	polymer in amorphous state
m	mold
p	polymer
s	polymer in semi-crystalline state

change can be solved with a front tracking method at a constant temperature. This temperature is chosen as an effective phase change temperature of the polymer, which is highlighted by the crystallization quasi-plateau observed during the cooling of parts [7–9]. The only available analytical solution in the literature is the so-called Stefan one [10,11] based on the semi-infinite medium assumption. The method was extended by Sobotka et al. [12] to finite medium from the parameterization of the ratio between the half-thickness of the finite part and the solidified thickness in the semi-infinite medium.

$$D_e = a_p \frac{\frac{t_{solid}}{2}}{e^2} \tag{1}$$

All models presented above considered a perfect contact between the polymer and the mold. Actually, heat transfer at the interface between the polymer and the mold is impeded by the non-perfect contact due to the roughness of the mold surface. Between asperities, an interstitial gas is trapped and its volume evolves during the cooling of the part due to pressure variations. The constriction field induced is modeled by the thermal contact resistance *TCR*, characterized by the temperature drop between the surface temperatures of the polymer T_p and the mold T_m and the heat flux density crossing the interface φ (Eq. (2)). The *TCR* could be estimated by indirect methods [8,13] or measured with specific instrumentations [14,15]. Some authors developed models to compute TCR during the process [16,17]. However, this parameter was rarely considered for the rapid estimation of cooling time in injection molding, due to the need to know a large number of parameters. Even if analytical solutions [18] exist to determine the temperature field in amorphous part, the problem is more complicated for semi-crystalline polymers and is not solved analytically in the literature. Nevertheless a parametric model developed by Merlin [19] was proposed for phase-change slabs to take the surface *TCR* into account.

$$TCR = \frac{T_p - T_m}{\varphi} \tag{2}$$

In this context, the present paper proposes two different methods to determine analytically the cooling/solidification times, mold temperature variations and heat flux densities at the interface for amorphous and semi-crystalline polymers. The influence of the thermal contact on the cooling time is evaluated for both polymers. Heat transfer in the mold is also considered to analytically determine the time required to produce parts in the steady periodic regime. The attenuation of the periodic temperature variation through the thickness of the mold is evaluated. For each case, the results of the simplified models are compared with experimental ones using an instrumented mold, or with a model coupling heat transfer and crystallization if the information is not directly available.

2. Experimental study

2.1. Mold instrumentation

The mold used in this study has been developed few years ago in the framework of the SWIM project (Shrinkage and Warpage in Injection Molding) [7,20]. As illustrated in Fig. 1, the part is a square slab which dimensions are 60 mm × 60 mm × 3 mm. A special feeding system was designed to ensure unidirectional flow through a 1.5mm thick gate. The molding cavity is instrumented with a pressure sensor Kistler© (type 6157B) positioned at 17 mm from the gate in the fixed mold side and with two heat flux