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Three-dimensional numerical and experimental investigations on polymer rheology in meso-scale injection molding ☆

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ABSTRACT

Three-dimensional simulation and experimental investigation of polymer rheology in a miniature injection molding process is presented. The material used in the study is ABS plastic, Toyolac 250-X10 and tests are carried out at different temperatures of the molten thermoplastic which is injected into the mold cavity. FLUENT 6.3 software is used in the simulation to verify the viscosity model (Cross model) and the Volume of Fluid (VOF) method is applied for the melt front tracking. The model is validated by means of experiments performed by using Davenport High Shear Viscometer with injection nozzle. It has been observed that there exists an optimum combination of temperature viscosity and shear rate for the selected injection molding process. Accordingly, the temperature range 200–260 °C and shear rate 10^2–$10^4\,s^{-1}$ are found good for the process. The mold flow profiles for various temperatures and time steps are also presented. The experimental and the simulation results are in good conformity and the strength of FLUENT 6.3 in handling injection mold filling problems is proved to be excellent.

1. Introduction

Plastic injection molding process demands precise control of melt temperature, melt viscosity, injection speed, injection follow-up pressure, and switch over point from speed to pressure and cycle time. Different polymers have different characteristics and different limitations in processing. Shear rate and shear stress influence melt temperature, viscosity, density and flow behavior of polymer. The change in each parameter has its own influences on other parameters. Hence, process control becomes very complex. Moreover, new polymers and the demand for high-quality electronics, consumer products, automobiles and airplanes have forced engineers and designers to improve mold-tooling efficiency and the quality of final parts. This calls for a careful pre-molding analysis of the physics of the problem and the crucial parameters that influence the quality of the product. Accordingly, researchers have focused on developing efficient computer-aided techniques to replace the cumbersome experimental methods.

Substantial works have been published on injection molding of various materials such as plastics, metals and their composites, but the review of those dealing with thermoplastics only are presented in this article. Chen and Liu [1] presented a two-phase model for simulating the injection mold filling process including the phase change effect of melt solidification. The liquid region was governed by Hele-Shaw flow for a non-Newtonian fluid using a modified Cross model to describe viscosity under non-isothermal conditions. Chen and Hsu [2] had presented numerical and experimental studies of polymer melt flow in the mold filling stage of the coinjection molding process using sequential injection of transparent and colored polystyrene resin. Study on the effects of streamwise convergence in radius on the laminar forced convection in an axisymmetric duct was reported by Lee and Jaluria [3]. Chen et al. [4] had developed algorithms to predict the polymer melt front advancement in the thin plate with ribs of semicircular cross section. A study on the thermal transport in polymer melts flowing through narrow channels with contraction was performed by Lin and Jaluria [5] who focused on the flow and heat transfer of practical polymer melts used in plastic industries, such as low-density polyethylene, which could not be regarded as Newtonian in their behavior. A general finite element solution for three-dimensional mold filling by incompressible viscous fluid was described by Pichelin and Coupez [6]. Bress and Dowling [7] studied the polymer flow during injection molding using a clear mold that allowed optical access from three sides, in a standard commercial machine, under standard molding conditions for polystyrene. An implicit finite volume approach proposed by Chang and Yang [8] could predict the critical three-dimensional phenomena encountered during mold filling more accurately than the existing Hele-Shaw model. Kumar et al. [9] presented a numerical model under isothermal and non-isothermal conditions, using low-density polyethylene. They also performed optimization of the molding conditions based on the simulation results. Injection molding of

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Nomenclature

B	Exponential-fitted constant Pa s
C_p	Specific heat J kg^{-1} K^{-1}
G	Gravity acceleration m s^{-2}
u	Velocity vector m s^{-1}
H	Enthalpy kJ kg^{-1}
k	Thermal conductivity W m^{-1} K^{-1}
N	Power law index –
P	Pressure Pa
T	Temperature K
T_w	Temperature at wall K
T_{in}	Temperature at inlet K
t	Time s
T_b	Temperature-fitted constant K
u	Fluid velocity component in x-direction mm s^{-1}
V	Fluid velocity component in y-direction mm s^{-1}
W	Fluid velocity component in z-direction mm s^{-1}
x, y, z	Cartesian coordinates –

Greek letters

η	Viscosity Pa s
η_0	Zero shear rate viscosity Pa s
P	Density kg/m^3
τ	Shear stress Pa
$\dot{\gamma}$	Shear rate 1/s
E	Energy source term J
τ^*	Parameter that describes the transition region between zero shear rates and the power law region of the viscosity curve Pa

thin plates of micro sized features was studied by Yu et al. [10] in order to manufacture micro-fluidic devices for bioMEMS applications. It was found that the injection speed and mold temperature in injection molding greatly affect the replication accuracy of microstructures on the metal mold inserts. Simulation of a coining type of injection–compression molding was performed by Fan and Kazmer [11]. A hybrid finite element finite difference method was employed to model the temperature and pressure fields of the process using a non-isothermal compressible flow model. Zhou et al. [12] investigated the relationship between velocity and pressure and a 3D control volume was built to track the flow front in numerical analysis using finite element model. Geng et al. [13] presented a 3D mathematical model and numerical method to perform accurate simulations of injection mold flow. The model employed an equal-order velocity–pressure interpolation method. Liou and Chen [14] studied the injection molding characteristics of polymer micro- and sub-micron structures using demonstration mold inserts with micro- and sub-micron channels with high-aspect ratios. The effects of the injection molding parameters on the achievable aspect ratio of the micro- and sub-micron walls were investigated. Wang et al. [15] had proposed the adaptive mesh refinement (AMR) technique to one-dimensional three-phase flows in heterogeneous porous media, including phase change. The influence of the processing temperature on the rheology, morphology, and mechanical properties of injection-molded microcomposites has been studied by Kalkar et al. [16]. A numerical approach was introduced by Cao et al. [17] to solve the viscoelastic flow problem of filling and post-filling in injection molding. The governing equations were in terms of compressible, non-isothermal fluid, and the constitutive equation was based on the Phan–Thien–Tanner model. Study on polymer rheology in mold filling during encapsulation of electronic packages has been reported by Abdullah et al. [18,19]. Hassan et al. [20] studied the effect of the viscous dissipation on the temperature distribution throughout a rectangular channel for different polymers at different inlet velocities and temperatures. A hybrid GA and gradient method for the optimization of injection molding conditions such as melt temperature, mold temperature and injection time was proposed by Lam et al. [21] The hybrid optimization process was elaborated and a case study was conducted to test the effectiveness and efficiency of the strategy and its implementation algorithm. The rheological properties of thermoplastic polyurethane were studied by Hernández [22] at small and large deformations via three different types of rheometry: dynamic shear, capillary, and torque (an instrumented batch mixer). Recently, Boronat et al. [23] investigated the effects of reprocessing on the processability of two Acrylonitrile–Butadiene–Styrene (ABS) grade thermoplastic polymers. The flow properties of virgin and reprocessed materials have been evaluated by capillary rheology. Low viscosity grade showed a reduction of viscosity upon increasing the number of processing cycles, thus confirming the degradation of this polymer. High viscosity grade, conversely, showed an increase of melt viscosity as the number of injection molding cycles was increased. It has been confirmed that applied shear rates in injection molding process affect material behavior as well as applied temperatures.

In the present study an attempt is made to simulate the three-dimensional mold filling to study the polymer rheology of ABS plastic in a meso-scale injection molding. The VOF technique is used for the melt front tracking and the numerical simulation is performed by FLUENT 6.3. Modeling and meshing are performed by using Gambit 2.3 software. Navier–Stokes equations are solved by finite volume method and SIMPLE segregated algorithm. As far as the authors are aware, the use of 'FLUENT' which is appreciably cheaper than most of the softwares used by the previous workers to study the injection mold filling, has not been reported so far. To validate the model experiments are performed by means of Davenport High Shear Viscometer with injection nozzle. The effects of viscosity, temperature and shear rate on mold flow are plotted and studied.

2. Mathematical model

In the simulation model, molten ABS plastic and air are assumed incompressible and the governing equations describing the fluid flow are conservation of mass, conservation of momentum and conservation of mass, conservation of momentum and conservation of energy. FLUENT normally solves the governing equations using Cartesian spatial coordinates and velocity components.

The conservation of mass or continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0. \tag{1}$$

Eq. (1) is the general form of the mass conservation equation and is valid for incompressible and compressible flows.

Conservation of momentum in i-th direction in an inertial (non-accelerating) reference frame is described by:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \tag{2}$$

where, P is the static pressure, τ_{ij} is the viscous stress tensor and g_i and F_i are the gravitational acceleration and external body force in the i direction, respectively.

The energy equation cast in terms of h (static enthalpy) can be written as,

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_i}\right) + \eta\dot{\gamma} \tag{3}$$

where T is the temperature, k is the thermal conductivity, η is the viscosity and $\dot{\gamma}$ is the shear rate. The molding compound was assumed to be a generalized Newtonian fluid (GNF). The Cross model used with