PRESSURE AND TEMPERATURE DEPENDENCE OF THERMAL CONDUCTIVITY FOR INJECTION MOLDING SIMULATION

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Thermal conductivity is an important material property as it influences polymer temperature distribution during the whole injection molding cycle. This property is typically measured in the laboratory at pressures which are low (5-10 MPa) compared to those which occur in the injection molding process (30-200MPa). Measurement of thermal conductivity may be for a single temperature or multiple temperatures over the processing range of a material, including the solid state. Implementation of the transient line source technique (ASTM D5930) with bench top twin bore plunger capillary rheometry, allows pressure control of the polymer sample, with two significant enhancements: (i) the ability to improve the contact of the probe with the sample and thus eliminate the effects of contact resistance. This can be significant for semi-crystalline materials, and (ii) allowing the pressure dependence of thermal conductivity to be investigated. Experimental data is presented, outlining the typical effect of pressure on thermal conductivity for both semi-crystalline and amorphous materials. The ultimate aim is to improve the accuracy of injection molding simulations by analytical modelling of thermal conductivity for both temperature and pressure behaviours, providing a method by which experimental error can be reduced, while ensuring the measured behaviour follows theoretical assumptions.

Introduction

Injection molding simulation by the finite-element method began in the 1970's, and has continually developed in sophistication to the present day. The accuracy of injection molding simulation is influenced by many factors such as modelling of part geometry, runner and nozzle, mesh type and density, mathematical finite element solution, process settings and the focus of this paper, material data. Material testing technology is continually evolving to meet the increased demands of simulation as outlined by Speight and Costa (2009). The importance of thermal conductivity in achieving high accuracy simulation is outlined in this paper.

Thermal conductivity (k, W/m.K) defines the heat flux that flows through the material if a temperature gradient exists over the sample. It is defined as the quantity of heat Q, transmitted in time t through a thickness L, in a direction normal to a surface of area A, due to a temperature difference ΔT, under steady state conditions and when the heat transfer is dependent only on the temperature gradient:

$$k = \frac{Heat\ Flow \cdot Distance}{Area \cdot Temperature\ Difference} = \frac{Q}{t} \cdot \frac{L}{A \cdot \Delta T} \quad (1)$$

Considering the case of a cylinder of infinite length, with an infinitesimally thin, infinitely long heating element located along its axis, from Fourier's conduction equation, it is possible to derive an expression for the transient temperature rise at any point in the cylinder. Starting at $t = 0$, a constant finite quantity of heat Q is produced per unit length of the heating element. Lobo and Cohen (1990) explain that at a fixed point of radius r, the change in temperature (T_2 - T_1) in the time interval (t_2 - t_1) is then given by:

$$k = \frac{QCln(t_2/t_1)}{4\pi k(T_2 - T_1)} \quad (2)$$

The transient line source technique uses a probe constant, C, to compensate for theoretical deviations in the experimental set up of the device. The constant is determined by calibrating the probe against a material of known thermal conductivity, such as Polydimethylsiloxane (PDMS) fluid, (60,000 centistokes), with referenced thermal conductivity of 0.16 W/m.K, Chakravorty and Brown (1995). Further investigations are required to determine the stability of thermal conductivity with respect to temperature for Polydimethylsiloxane (PDMS).

To demonstrate the importance of thermal conductivity as outlined by Sridhar and Narh (1999), a sensitivity study is implemented on typical semi-crystalline and amorphous materials. These studies are carried out using Autodesk Moldflow Insight 2010, on a model of a highly instrumented experimental test plaque, dimensions 200x40x2mm. The influence of perturbing thermal conductivity on the prediction of maximum injection pressure and the material freeze time are investigated.

Experimental

The experimentation described uses two laboratory thermal conductivity devices that are present in both our material testing laboratories in Melbourne,

Australia and Ithaca, New York. The first device is an AC-Technology, K-system II. This has been used by our laboratories since the early 1990's, as described by Lobo and Newman (1990), and allows thermal conductivity to be measured in the melt and solid states. The second device is a CEAST SmartRheo 2000 (maximum force 20kN) bench top twin bore plunger capillary rheometer, with transient line-source thermal conductivity option. The CEAST SmartRheo 2000 rheometer has been used since 2008 and allows pressure control of the polymer sample during the measurement of thermal conductivity (up to 200MPa). Experimentation is also presented in this paper from INSTRON - CEAST Division, specifically pressure effect on thermal conductivity data. Transient line source probes for this device were developed together jointly between CEAST and Hukseflux Thermal Sensors B.V., with the capability to measure thermal conductivity in the melt state, Bronzoni and Lanteri (2007).

The transient line-source method can produce very precise results when good contact between the sample and the probe is achieved, eliminating effects of thermal contact resistance. Measurements are typically for a period of 45 seconds, sampled at 10Hz. Radial losses can be seen: (i) in the initial region of the transient through a non-linearity of the curve, and are due to the initial heat wave propagating through the walls of the probe, and (ii) for sample periods that are too long.

The probe casing (hypodermic needle) is 50 mm in length, 1.3 mm diameter; as shown in figure 1. Constantan wire is used for the heater element because of its low temperature coefficient of resistivity. A single thermocouple is used for the temperature measurement (either Type J or K), where the thermocouple bead is halfway down the length of the probe and is in physical contact with the walls. The wires are fixed in place using a high-temperature ceramic cement to maintain electrical continuity.

For injection molding simulation, thermal conductivity may be measured using the following test methods: (i) single point at recommended melt temperature; (ii) multi-point, over a temperatre scan from melt to solid, where the average thermal conductivty is determined, or (iii) where the multi-point thermal conductivty data series, with respect to temperature, and (iv) where the multi-point thermal conductivty data series, with respect to both temperature and pressure. Thermal conductivity is typically reported as a temperature scan of up to 12 points, where the test procedure involves multiple scans to ensure accuracy. Intra-laboratory testing on a Polystyrene (PS) sample shows a repeatability of 3%. However, this result is highly dependent on ensuring good sample contact resistance.

Results and Discussion

The mean transient temperature delta during 6 separate runs is shown in figure 2, using Polydimethylsiloxane (PDMS) at 30C, plotted against natural logarithm (time). The output of the transient line source technique is theoretically a straight line on a semi-log plot of temperature against time. The initial portion of the transient displays some curvature, as the heat moves through the metal wall of the probe, between -2.0 and 1.50 ln(seconds). Since the mass of the probe is finite the temperature difference across the steel wall becomes constant quickly and the termperature sensor will thereafter reflect the temperature rise of the polymer. The temperature rise at the line-source varies linearly with the logarithm of time in the region where the process is dominated by conduction and other effects can be neglected, between 1.70 and 3.70 ln(seconds). This linear zone is characteristic of the sample properties. The different regions of the temperature versus time diagram of the probe are illustrated in figure 2 by review of the coefficient of variation. During the linear region the measurements on PDMS are within 0.1% variation, demonstrating the potential accuracy of the device.

Polymers will shrink during cooling, therefore it is necessary to maintain a constant pressure on the probe to prevent voids forming and gaps at the surface interface when in the solid phase. This is especially important for semi-crystalline materials. Figure 3 highlights that the experimental variation in the solid stage (<110C) is higher then the melt stage (> 150C). These result are measured using the K-System II. Future experimention will investigate the performance of the CEAST SmartRheo 2000 during polymer transitions from melt to solid state under pressure control.

Figures 4 and 5 show the effect of perturbing thermal conductivity, as the input to an injection molding simulation, for a typical unfilled Polypropylene and Acrylonitrile-butadiene-styrene. For this research, thermal conductivity was variated by $\pm$50%, so that the trends are clearly observable. For materials such as the Polypropylene as shown in figure 3, a 20% change in thermal conductivity between melt and solid states will account for a difference in injection pressure and freeze time (cycle time) calculations.

Bronzoni and Lanteri (2007) showed the effect of pressure on thermal conductivity for Low Density Polyethylene (LDPE), Polystyrene (PS) and Polycarbonate (PC), refer Figure 6. At the same test temperature, LDPE and PS show a different behaviour, in particular, LDPE exhibits a near linear pressure dependence on conductivity, compared to the response of the PS. The thermal conductivity data obtained for PC at 300°C are similar in response to the LDPE. The percentage increase in thermal conductivity between 60

to 200MPa for LDPE, PS and PC are 29%, 20% and 14% respectively. These results are presently being validated in our own laboratories.

Extending the sensitivity study as outlined in figures 4 and 5 to a range of materials, typical grades are selected and the relative importance of changes in thermal conductivity can be observed. Figures 7 and 8 show comparative data for injection pressure and material freeze time, for a range of materials. These results are for the specific material grades selected from the Autodesk Moldflow Insight 2010 database and may not be representative of all grades. Thermal conductivity variations will account for a difference in injection pressure and freeze time (cycle time) calculations.

Conclusions

Accuracy of injection molding simulation is influenced by thermal conductivity. The transient line source method has the potential to provide accurate thermal conductivity data, when good contact resistance between the probe and material is maintained. Experimental practice for thermal conductivity measurement will improve by pressure control of the plunger ensuring: (i) the ability to improve the contact of the probe with the sample and thus eliminate the effects of contact resistance, and (ii) allowing the pressure dependence of thermal conductivity to be investigated. Together with these experimental improvements, it is proposed that an analytical model for thermal conductivity be introduced, thereby ensuring experimental data complies with the expected material behaviours.

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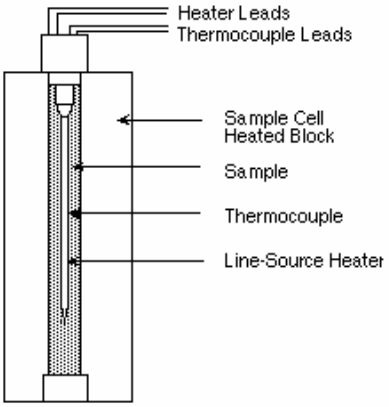

Figure 1, Schematic diagram of AC Technology K System II, transient line source thermal conductivity test cell, bore diameter 12.8mm, probe length 50mm.

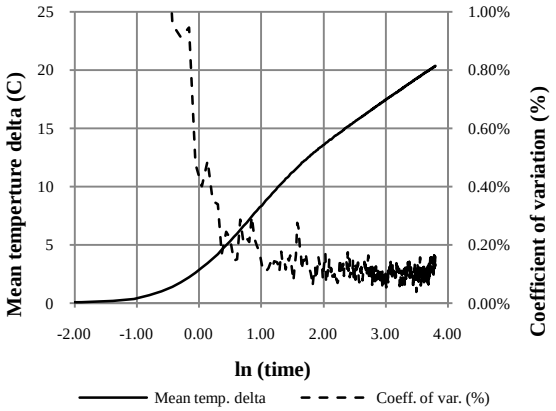

Figure 2, Mean output tranisent temperature delta and coefficient of varation, for of 6 samples, of Polydimethylsiloxane (PDMS) fluid at 30C.

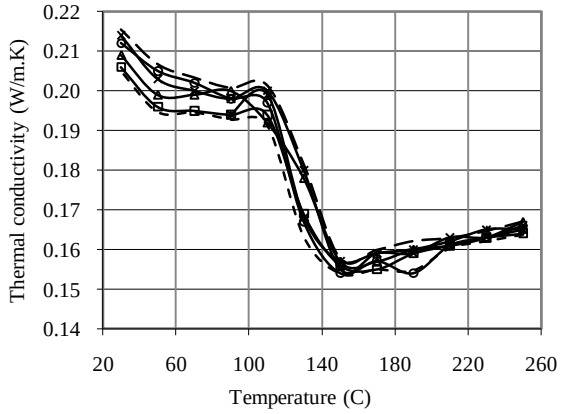

Figure 3, Thermal conductivity against temperature, showing typcial experimental variation for a typical unfilled Polypropylene (PP).

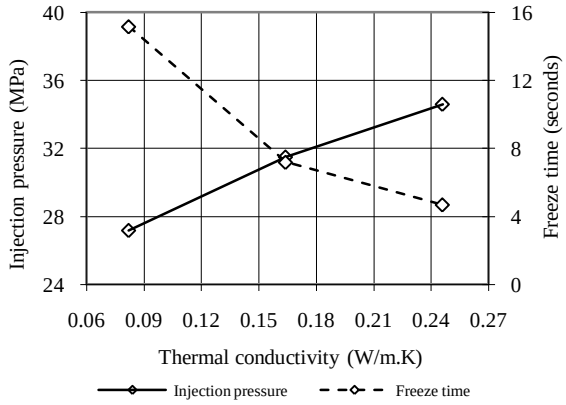

Figure 4, Influence of thermal conductivity on injection pressure and freeze time for a typical unfilled Polypropylene (PP).

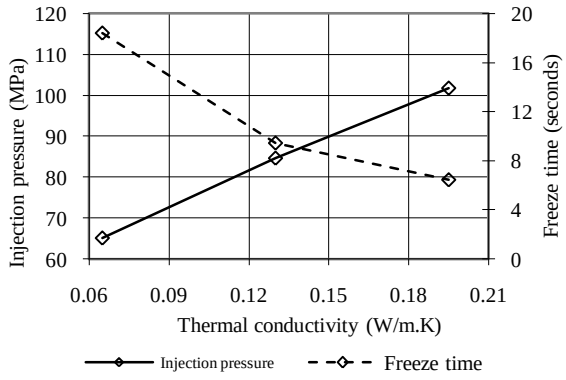

Figure 5, Influence of thermal conductivity on injection pressure and freeze time for a typical Acrylonitrile-butadiene-styrene (ABS).

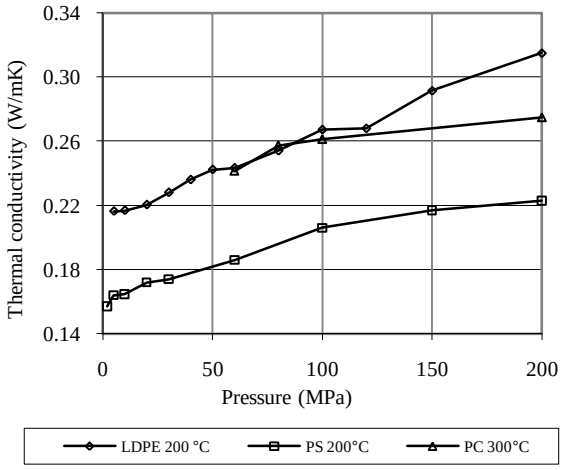

Figure 6, Influence of pressure on the thermal conductivity of LDPE, PS and PC.

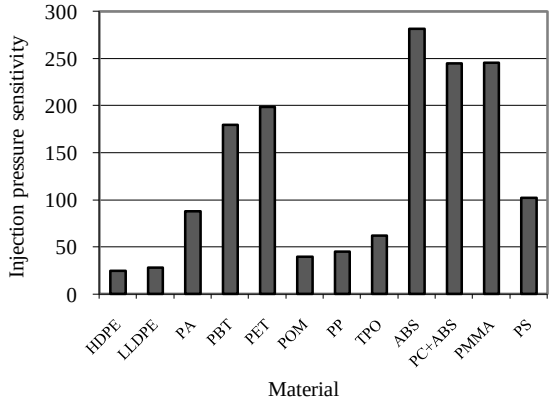

Figure 7, Injection pressure sensitiviy to thermal conductivity (MPa / W/m.K) for a range of materials.

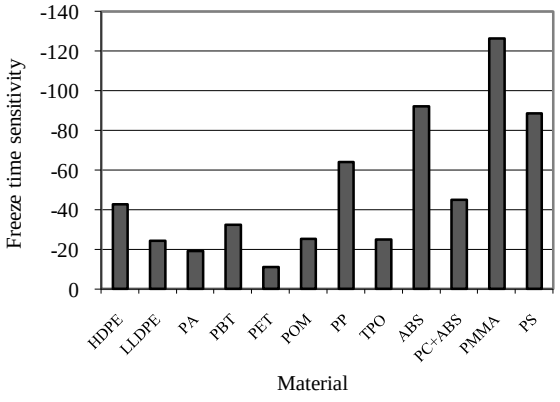

Figure 8, Freeze time sensitiviy to thermal conductivity (Seconds / W/m.K) for a range of materials.