

The Effects Of Thermal Conductivity And Heat Transfer Coefficients On Polymer Processing

Summary

This guide illustrates the effects of thermal conductivity and heat transfer coefficients on polymer processing and how to estimate these parameters using current technology. The important aspects of the measurement of the thermal conductivity of polymers are highlighted and the preferred methods indicated. The transient hot wire and line source techniques are briefly described. The importance of the role of the heat transfer coefficient in polymer processing is discussed and methods used to determine its value are briefly described.

Introduction

The speed of polymer processing is often limited by the rate at which the polymer cools and can, for example, be ejected from the mould in injection moulding or hauled-off in extrusion. The thermal conductivity and heat transfer coefficient parameters control the rate at which heat flows from the bulk of the polymer to the surroundings, for example to the mould tool. The thermal conductivity controls the rate of heat transfer *within* the polymer, and the heat transfer coefficient controls the heat transfer *at the interface* between the polymer and, for example, the mould wall. Apart from its obvious effect on the rate of processing, in injection moulding the heat transfer also influences the manner in which the polymer fills the cavity with effects on filling pressure, temperature distribution and the material structure developed in the moulding. In order to model reliably the flow process, and consequently the product's properties including its shrinkage and warpage, reliable data including the thermal properties data are required.

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Thermal Conductivity

The importance of accurate measurement of thermal conductivity of polymer melts has been investigated [1]. This report examined the thermal material parameters that affect the processing of polymers. It looked at how accurately each parameter could be measured and also at the effect this uncertainty was likely to have on key processing factors such as pressure and temperature. Thermal conductivity was considered to be both one of the least accurately measured parameters and also one of the parameters that has the most effect on industrial processing.

The rate of heat removal from plastic components during moulding determines, to a large extent, the productivity. Although faster cycle times are related to profit margins, a good deal of uncertainty over the values of thermal conductivity and heat transfer coefficient relating to plastics still exists. A study of the literature showed variations in thermal conductivity values of $\approx 50\%$ within a grade and $\approx 200\%$ over the range of polymers studied [1].

The main use of such data is in simulation software such as Moldflow, Fillcalc or C-Mold. As an example of the importance of thermal conductivity, 10% and 50% increases in pressure were predicted using the Moldflow software when thermal conductivity values were increased by 20% and 100% respectively for a nylon 66 grade [1, 2]. Values of thermal conductivity reported in the literature vary by about 50% within a grade of material. Thus

errors of up to approximately 25% in pressure prediction can be expected arising from uncertainties in the measurement of thermal conductivity data and their subsequent use in simulation software. The illustration, [Figure 1](#), shows how a 50% change in the thermal conductivity value can lead to a significant difference in the temperature distribution in the moulding. The higher thermal conductivity value resulted in both a cooler region (by $\approx 15^\circ\text{C}$ below the handle) and a larger hot spot.

Such errors in thermal conductivity values used in flow simulations for mould design could lead to mouldings of unacceptable quality, polymer degradation, high scrap rates and missed opportunities to reduce cycle times. Furthermore, it could be necessary to redesign the cooling system of the mould thus incurring re-machining and delay costs, or to move production to a more expensive (higher clamping force) machine. The need for improved and standardised methods to measure this parameter led NPL to conduct a survey to determine relevant test methods for the plastics processing industry [\[3\]](#)

Temperature and pressure were identified as the parameters having the greatest effect on the thermal conductivity of polymer melts [\[3\]](#). The thermal conductivity of polyethylene decreased up to $\approx 50\%$ on heating from room temperature to 200°C , with a minimum in the value occurring after melting [\[4\]](#). Results of tests investigating the effect of pressure indicated that the thermal conductivity increased by up to $\approx 15\%$ between 20 MPa and 120 MPa [\[5\]](#). Furthermore, the thermal conductivity of solid polymers was identified to be strongly dependent on the degree of orientation, induced by drawing of the specimens [\[6\]](#). The thermal conductivities parallel and perpendicular to the draw direction differed by up to a factor of ≈ 10 .

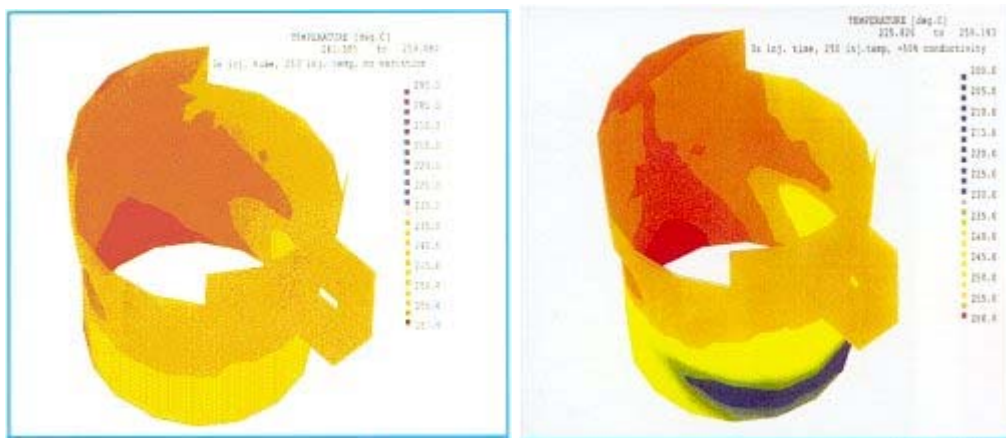


Figure 1: Effect of a 50% increase in thermal conductivity value on predicted temperature profile

The requirements identified for testing polymer melts are:

- need to measure highly viscous materials,
- measurement times preferably of the order of minutes to avoid degradation,
- no sharp, high temperature rises that may cause degradation,
- ability to measure both temperature and pressure dependencies and, to a lesser degree, ability to measure flowing melts, ability to measure orientation dependency of solids,
- error less than 10%.

Steady-state methods, for example parallel hot-plate, concentric cylinder, axial heat flow and radial heat flow all require long periods of the order of hours to reach equilibrium temperature and are thus unsuited to polymer melts as degradation of the material will most likely occur. The main transient techniques for thermal conductivity measurements and their principal advantages and disadvantages related to the measurement of polymer melts are given in [Table 1](#).

Table 1: Summary of transient thermal conductivity and diffusivity methods

	Estimated error [1]	Direct measure of conductivity [3]	Comments (also see notes)
Concentric Cylinder (7,8)	5%	No	Measurement during flow
Transient Hot Wire (9-12)	3%	Yes	Accurate method, fragile wire
Line Source Probe (5,13,14)	10% [2]	Yes	Rapid, robust method.
Laser flash / flash radiometry (15-17)	10%	No	Possible degradation at polymer surface
Forced Rayleigh Scatter (18)	10%	No	Used to examine anisotropy of solids and flowing melts
Differential scanning calorimetry (19,20)	20%	Yes	Poor accuracy
Radial temperature wave (21)	10%	Yes	Reference to measurement of solids only
Plane temperature wave (4,22,23)	12%	Yes	

Notes:

- [1] Estimates of errors obtained from the literature except see [2].
- [2] Estimate of reproducibility obtained from the literature.
- [3] "No" indicates that the method measures diffusivity α from which thermal conductivity λ can be determined using $\lambda = \rho C_p \alpha$, where ρ is the density and C_p the specific heat capacity. However this introduces an additional source of error, that may be as much as 8-10% due to errors in ρ and C_p .

Of these transient techniques the line source probe and transient hot wire methods are favoured for the measurement of thermal conductivity of polymer melts. In the line source probe technique a wire heater and a thermocouple are incorporated into a fine probe which can be inserted into the sample, [Figure 2](#). From measurements of the voltage and current supplied to the heater wire the electrical power and hence the heat energy being supplied to the probe can be determined. The temperature is measured as a function of time. The thermal conductivity is determined directly from the temperature measured at two different times.

The transient hot wire technique works on a similar basis except that the heat source and thermocouple are provided for by a single fine platinum wire, which is suspended in the sample, [Figure 3](#). The temperature of the wire may be inferred from its resistance which varies characteristically with temperature.

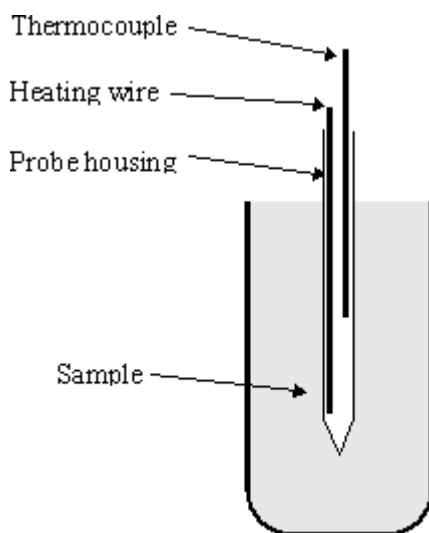


Figure 2: Line source probe

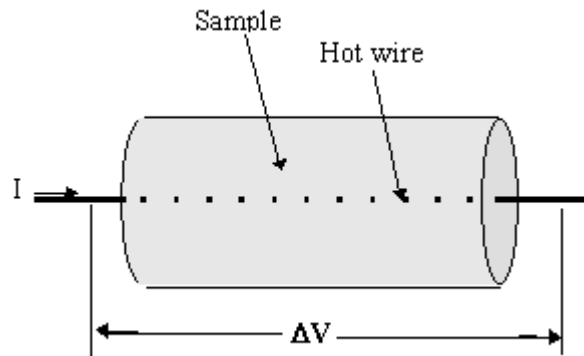


Figure 3: Transient hot wire

The transient hot-wire technique is rapid, accurate, measures thermal conductivity directly and measurements may be made under various conditions of pressure, temperature and flow rate. The problem with this method is that the fine platinum wire is fragile with the consequence that preparing the sample and cleaning the polymer off it may present practical difficulties. In addition, the method is dependent upon a very small heat-emitting area so small bubbles, imperfections or non-wetted sections on the wire may have a significant effect on the results. In order for this technique to be used as a standard technique, appropriate methods must be developed for preparing the sample and removing polymeric residues from the wire without damaging it. Thicker wires may be used, but to the detriment of the accuracy of the technique.

The line-source probe technique is also rapid, measures thermal conductivity directly and can be used under a range of conditions and has the added advantages that it is robust and the probe is easily calibrated and cleaned. Its principal disadvantage is that its accuracy is relatively poor compared with that of the transient hot-wire technique.

Heat Transfer Coefficient

A further complication in process modelling arises when characterising the boundary between the polymer and, for example, either the mould wall in injection moulding or air in fibre spinning and film blowing or water in extrusion. Heat transfer coefficients are used to model the transfer of heat at the interface. However, the accuracy of determination of this property is poor compared with that of thermal conductivity. The large uncertainties are considered to be due to inadequate temperature measurement methods and the need for complex models to determine values from the available temperature measurements.

The most popular approach reported in the literature for determining heat transfer coefficient values for polymer melts is through the combined use of modelling and measurements. The value, or values, of the heat transfer coefficient used in the process simulation are adjusted until a best-fit to experimental temperature and/or heat flux measurements is obtained. This lumped-parameter approach is appealing in that all factors affecting the heat transfer coefficient such as pressure, temperature and surface finish are taken into account. However, using this approach the heat transfer coefficient may not always be determinable as independent functions of fundamental parameters, e.g. pressure and temperature, with the consequence that the ability to extrapolate reliably from one case to another is questionable. However, where the modelling is such that only a single value for the heat transfer coefficient can be used, then this lumped-parameter approach is perhaps preferable. Examples of the determination of heat transfer coefficients and their use are referenced in [Table 2](#). In comparison, few laboratory based measurement techniques for polymeric materials were reported in the literature: coaxial cylinders for a flowing rubber [\[24\]](#), and by quenching instrumented plate specimens for rubbers [\[25\]](#) and for a crystallising polymer [\[26\]](#).

The relatively low thermal conductivity of polymers and the large section thicknesses and high pressures involved in injection moulding have the consequence that the heat transfer coefficient does not appear to be a very critical parameter for that process. However, there are other processes for which the heat transfer coefficient has a much more significant effect, for example in film blowing and fibre spinning. Heat transfer coefficients are considered to be important where the polymer thicknesses are small (e.g. films and fibres) or where heat transfer is to another poor conductor. The relative importance of thermal conductivity λ and heat transfer coefficient h can be assessed using the dimensionless Biot number Bi , where $Bi = xh/\lambda$ and x is a characteristic length e.g. film thickness [\[27\]](#). For $Bi > 100$ there would typically be good heat transfer across the interface and errors in h would be unimportant. For $Bi < 0.1$ there would typically be poor heat transfer across the interface and errors in h would be significant. Between these values the relative importance of the heat transfer coefficient varies from insignificant to significant.

For various polymer processes the relative importance of the heat transfer coefficient and the experimental and empirical approaches used to determine suitable values are indicated in [Table 2](#).

Table 2: Relevance of the heat transfer coefficient to polymer processing

Process	Process description	Bi	Key parameter	References
Injection and compression moulding	good contact with a good conductor, length > mm	high	λ	28
Film blowing	heat transfer to air, length < mm	low	h	29, 30
Fibre spinning	heat transfer to air, length < mm	low	h	31-34
Film casting	heat transfer through a layer of solid polymer to a chilled roller, length < mm	low	h	27, 35-37
Profile extrusion and sheet forming	heat transfer to air or water, lengths > mm	mid	h, λ	27, 37, 38
Melting	heat transfer from metal to polymer, variable lengths mm	low	h	39-43

Conclusions

Heat transfer is an essential part of polymer processing which is basically a melting-flow-solidification process. Thus the thermal conductivity and heat transfer coefficients are essential parameters in modelling polymer processing. The accuracy of their measurement directly affects the accuracy of predictions made using process simulation software.

Techniques for measuring the thermal conductivity of materials are relatively well established. For polymer melts the preferred option is for transient methods principally to avoid material degradation. The transient hot wire and line source probe techniques were identified as being suitable for polymer melts, the line source probe being the more robust but less accurate of the two.

The relative importance of the heat transfer coefficient varies from process to process: it is more important for processes such as fibre and film production for which the critical dimension, e.g. film thickness, is small. Methods for determining heat transfer coefficients are not well established, compared with those for thermal conductivity. The preferred route, as evident in the literature, is to determine, using process simulation, the values to obtain a best-fit to measured data.

Acknowledgements

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