DEPC-MN-035

Measurement Note

Measurement of heat transfer properties for polymer processing

SUMMARY

Polymer processing is fundamentally a heat transfer – mass transfer process, with heat being initially added to and finally removed from the polymer. Heat transfer is a key to increasing throughput particularly as, due to the low thermal conductivity of polymers, the cooling phase often dominates the cycle time. Furthermore, a better understanding of heat transfer, resulting in improved predictive capability, can lead to reductions in scrap rates due to the elimination of hot spots and excessive temperature gradients that lead to materials degradation and high internal stresses causing warpage and shrinkage of the product.

A new instrument has recently been developed at NPL to measure heat transfer across interfaces and can, for example, simulate the mould-polymer interface during injection moulding. The instrument can also be used to determine the thermal conductivity of polymers. The instrument (right) is described and results on thermal conductivity and the effect of an air gap on heat transfer are presented.

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INTRODUCTION

Ensuring efficient processing and optimal properties of plastics requires good control over heat transfer during both the preparation of the material charge (e.g. plastication) and the cooling of the formed product, for example to avoid phenomena such as hot and cold spots.

Heat transfer in polymer processing is comprised of two principal components that can be defined by the properties of thermal conductivity λ ($W.m^{-1}.K^{-1}$) and the heat transfer coefficient, h ($W.m^{-2}.K^{-1}$). The heat transfer coefficient characterises the contribution that the interface makes to the overall thermal resistance of the system. The heat transfer coefficient, h, is defined by:

$$h = \frac{q}{T_1 - T_2}$$

where

h = heat transfer coefficient ($Wm^{-2}K^{-1}$)
q = heat flux at surface ($W.m^{-2}$)
T_1 = temperature on 'hot' side of interface (K)
T_2 = temperature on 'cold' side of interface (K)

An instrument has been developed at NPL to study heat transfer through polymer specimens mounted between two plates, thereby enabling the effect of interfaces to be investigated. This will enable investigation of, for example, the effect of different mould finishes or mould materials on moulding cooling rates. The instrument can also be used to measure the effect of an air gap between the mould surface and the polymer. This replicates the formation of air gaps or voids in moulding where the material shrinks away from the mould wall on cooling due to material shrinkage.

METHOD

The apparatus consists of two parallel, circular plates sandwiching the polymer specimen, Figure 1. The bottom plate is temperature controlled (electrically heated), and the top plate acts as a heat sink. Heat flux sensors and thermocouples are located in both upper and lower plates to measure heat fluxes and temperatures from which thermal conductivities and heat transfer coefficients are calculated.

An optical fibre temperature sensor can be used to monitor the internal temperature of the specimen. This sensor does not significantly affect the temperature field within the specimen due to low heat conduction along the fibre in comparison with thermocouples.

Properties can be measured at elevated pressures by installing the instrument in a press.

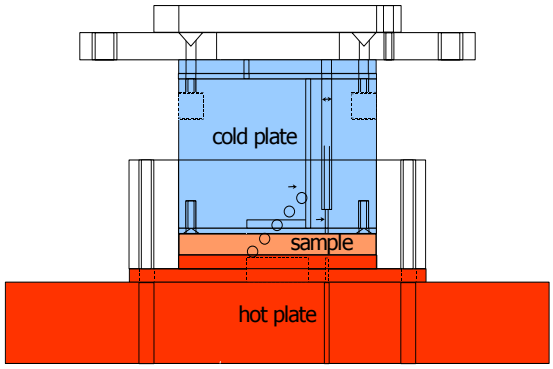

Figure 1: Schematic of NPL's heat transfer equipment

The separation between the plates can adjusted to accommodate test specimens of different thickness or to introduce air gaps of known thickness.

Test specimens can be either in pre-moulded sheet form or produced using the instrument as a compression moulding tool.

The instrument was calibrated by measuring a material of known thermal conductivity to determine the instrument factors. PMMA with a thermal conductivity value of 0.195 W/(m.K) was used as the reference.

It is convenient to analyse the experimental data in terms of thermal resistances. For a multi-layer system with heat flow in the through-thickness direction, as is the case for this experimental set-up, the total thermal resistance R ($m^2.K.W^{-1}$) is the sum of the thermal resistances of the individual layers r_i

$$R = \frac{\delta T}{Q} = \sum r_i = \sum_i \frac{1}{h_i} + \sum_j \frac{x_j}{\lambda_j}$$

where the subscript i represents the interfaces of heat transfer coefficient h_i and j represents the layers of thickness x_j (m) and thermal conductivity λ_j.

By using this approach the layers and interfaces can be compared on the basis of their thermal resistance. The results for the effect of an air gap have also been presented in terms of the equivalent thickness of a polymer having the same thermal resistance (PMMA has been chosen for consistency of presentation). This provides a more easily understood measure of the relative effect of an air gap on the heat transfer, compared with the polymer.

RESULTS AND DISCUSSION

The instrument has been used to measure the thermal conductivity of samples at elevated temperatures, e.g. from the effect of insertion of the PMMA specimen at a time of 18:00 in Figure 2. Initial results are shown in Table 1 for PTFE and PS samples tested in the temperature range ≈ 60 °C to 70 °C and compare reasonably well with literature values, the observed discrepancy being similar to that expected due to the temperature dependence of thermal conductivity [1].

Table 1: Thermal conductivities

Material (thickness, mm)	Thermal conductivity, W/(m.K)	Literature value[2] W/(m.K)
PTFE (1.03)	0.25	0.25
PTFE (2.15)	0.28	
PTFE (3.02)	0.27	
PS (2.50)	0.17	0.14

The effect of introducing an air gap between the mould surface and the polymer, simulating the formation of a gap due to shrinkage of the polymer away from the mould surface, is illustrated in Figure 2. The insertion of the air gap at a time of ≈ 20:10 resulted in a significant step increase in the thermal resistance, reducing by one-third the heat flux passing through the measurement system (Figure 2). The thermal resistance of a 0.36 mm thick air gap was found to be equivalent to that of a polymer layer ≈ 3 mm thick.

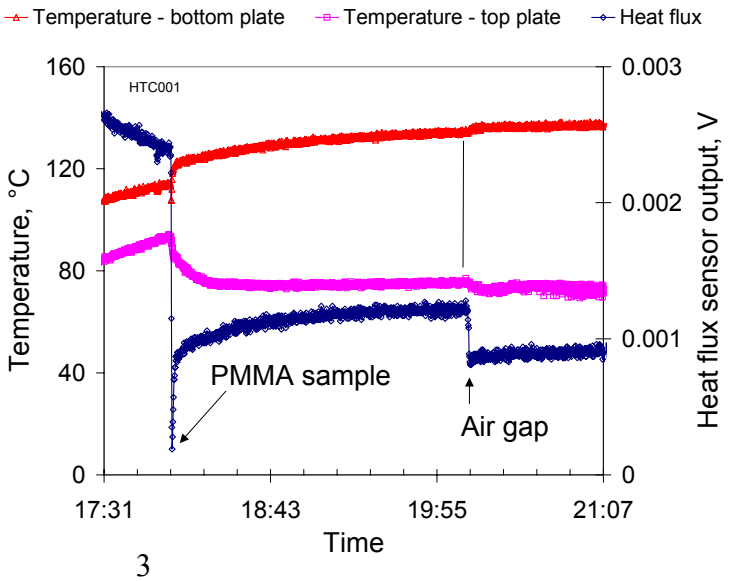

Figure 2: Experimental results showing effect of introducing a PMMA sample and subsequently an air gap between the polymer and the mould wall on heat transfer behaviour

CONCLUSIONS

The heat transfer apparatus has been successfully used to measure thermal conductivity of polymers at elevated temperatures and to quantify the thermal resistance of air gaps. The thermal resistance of an air gap was found to be equivalent to that of a polymer layer approximately ten times thicker.

The results clearly indicate the importance of maintaining contact of the polymer with the mould surface in order to obtain good heat transfer and thus short cooling times. The use of novel processing technologies such as gas-assisted moulding will ensure that contact is maintained between the polymer and the mould surface throughout the cooling phase thereby maintaining efficient moulding cooling. Furthermore, the implications of these results for process modelling are significant: shrinkage of the polymer away from the mould surface will potentially result in inaccurate predictions and localised hot spots.

REFERENCES

[1] Thermal conductivity of polymer melts and implications of uncertainties in data for process simulation, A Dawson, M Rides, J Urquhart and C S Brown, ECTP, Bratislava, September 2005.
[2] D.W. Van Krevelen, Properties of Polymers, Elsevier, 2000.

ACKNOWLEDGEMENTS

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