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Measurement of heat transfer coefficients for polymer processing simulation

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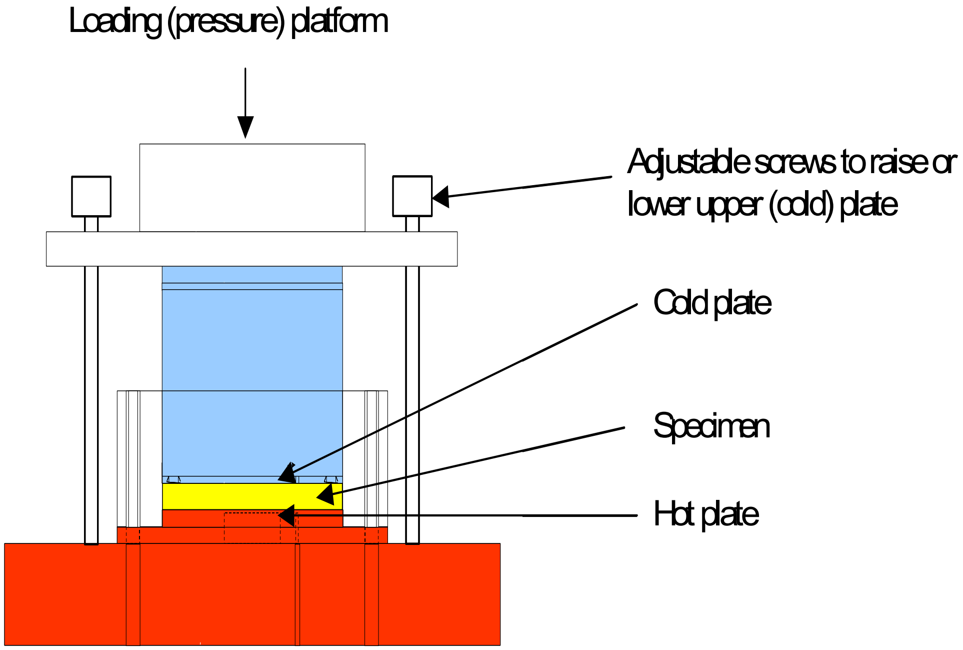
Heat transfer apparatus (HTC)



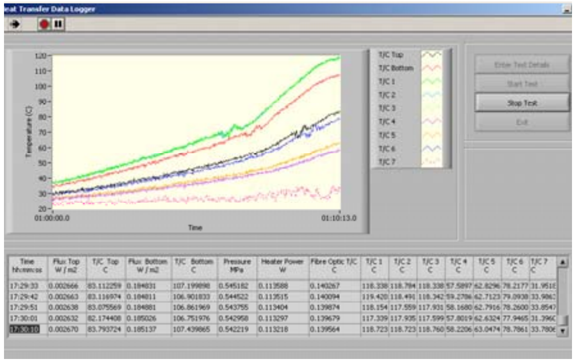
Loading (pressure) platform

Adjustable screws to raise or lower upper (cold) plate

Cold plate

Specimen

Hot plate



Time hh:mm:ss	Flux Top W / m2	T/C Top C	Flux Bottom W / m2	T/C Bottom C	Pressure MPa	Heater Power W	Fibre Optic T/C C	T/C 1 C	T/C 2 C	T/C 3 C	T/C 4 C	T/C 5 C	T/C 6 C	T/C 7 C
17:29:33	0.002666	83.112259	0.184831	107.199898	0.545182	0.113588	0.140267	118.338	118.784	118.338	57.5897	62.8296	78.2177	31.951
17:29:42	0.002663	83.116974	0.184811	106.901833	0.544522	0.113515	0.140094	119.420	118.491	118.342	59.2786	62.7123	79.0938	33.986
17:29:51	0.002638	83.075569	0.184881	106.861969	0.543755	0.113404	0.139874	118.154	117.559	117.931	58.1680	62.7916	78.2600	33.854
17:30:01	0.002632	82.174408	0.185026	106.751976	0.542958	0.113297	0.139679	117.339	117.935	117.599	57.8019	62.6324	77.9465	31.396
17:30:10	0.002670	83.793724	0.185137	107.439865	0.542219	0.113218	0.139564	118.723	118.723	118.760	58.2206	63.0474	78.7861	33.780

Heat transfer coefficient calculation

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

Heat transfer coefficient (h) across an interface is the heat flux per unit area (q) across an interface from one material of temperature T_1 to another material of temperature T_2:

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

Heat transfer coefficient

- Heat transfer coefficient is boundary condition for process simulation

- In injection moulding & compression moulding
  - Polymer to metal
  - Polymer-air-metal (GASM, shrinkage)

- In extrusion & film blowing
  - Polymer to fluid (eg air or water)

- Apparatus built to measure heat transfer coefficient at mould/polymer interface and mould polymer/air interface in order to investigate the significance of different interfaces to commercial processing

Thermal conductivity calculation

$$\boxed{\lambda = \frac{q\ x}{T_B - T_T}}$$

The thermal conductivity (λ) of a layer can be calculated from the thickness of the layer (*x*) multiplied by the heat flux per unit area (*q*) across the layer divided by the temperature difference between the hotter surface of the layer T_B and the colder surface of the layer T_T :

λ = thermal conductivity of a layer (W/(m.K))
x = thickness of layer (m)
q = heat flux at 'hot' surface ($W.m^{-2}$)
T_B = temperature on 'hot' side of interface (K)
T_T = temperature on 'cold' side of interface (K)

Thermal resistance across interface

$$\boxed{R = \frac{1}{h}}$$

$$\boxed{R = \frac{T_1 - T_2}{q}}$$

Thermal resistance across interface:

λ = thermal conductivity of a layer (W/(m.K))
x = thickness of layer (m)
h = heat transfer coefficient (Wm^{-2}K^{-1})
R = thermal resistance (m$^{2\cdot}$K.W^{-1})
T_1 = temperature on ‘hot’ side of interface (K)
T_2 = temperature on ‘cold’ side of interface (K)
q = heat flux at ‘hot’ surface (W.m^{-2})

Thermal resistance of layer

$$\boxed{R = \frac{x}{\lambda}}$$

$$\boxed{R = \frac{T_B - T_T}{q}}$$

Thermal resistance:

λ = thermal conductivity of a layer (W/(m.K))
x = thickness of layer (m)
h = heat transfer coefficient ($Wm^{-2}K^{-1}$)
R = thermal resistance ($m^{2}\cdot K.W^{-1}$)
T_B = temperature on 'hot' side of interface (K)
T_T = temperature on 'cold' side of interface (K)
q = heat flux at 'hot' surface ($W.m^{-2}$)

Thermal resistance calculation

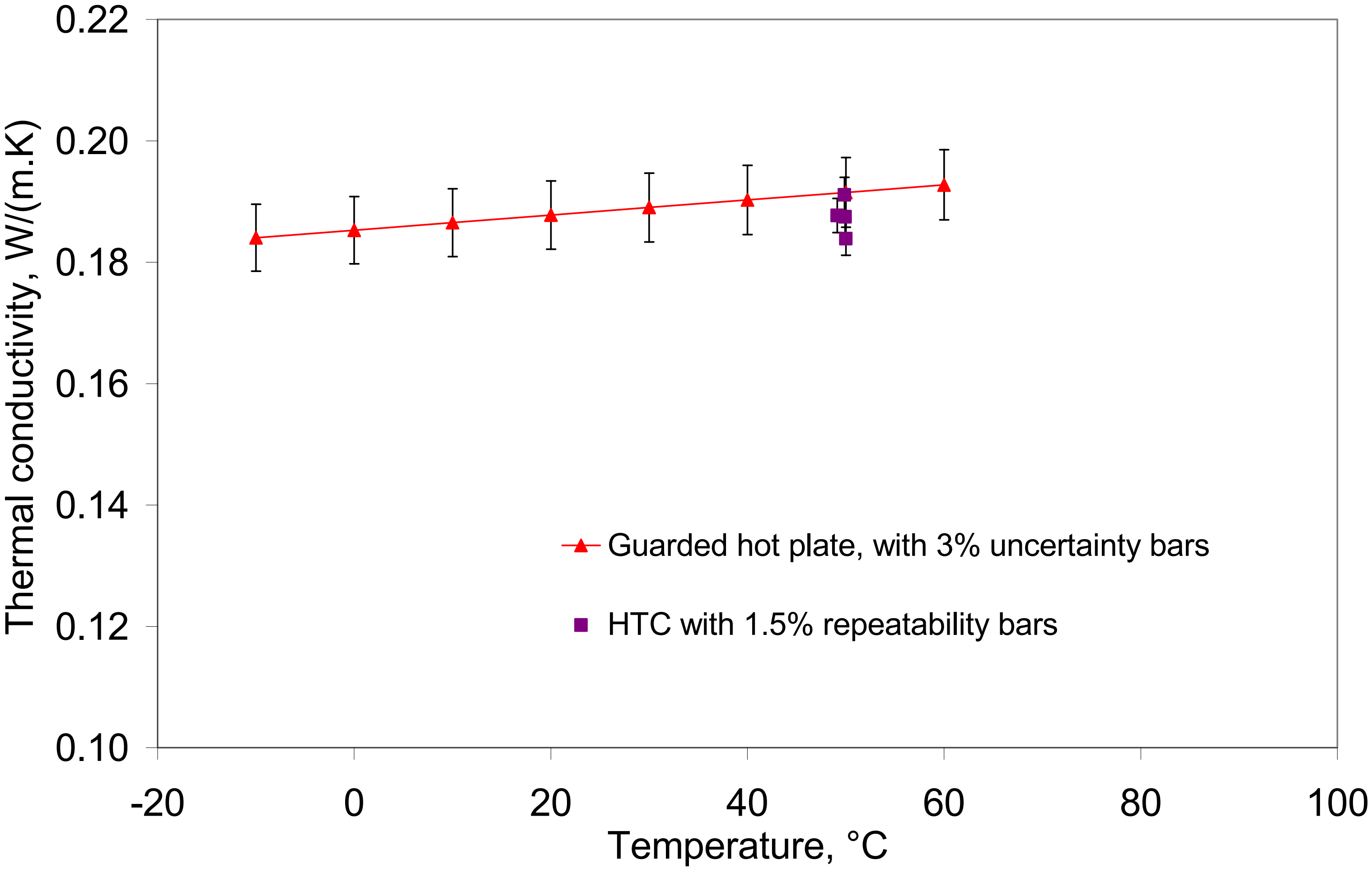
$$R = \frac{\delta T}{Q} = \sum r_i = \sum_i \frac{1}{h_i} + \sum_l \frac{x_l}{\lambda_l}$$

For a multi-layer system with heat flow in the through-thickness direction:

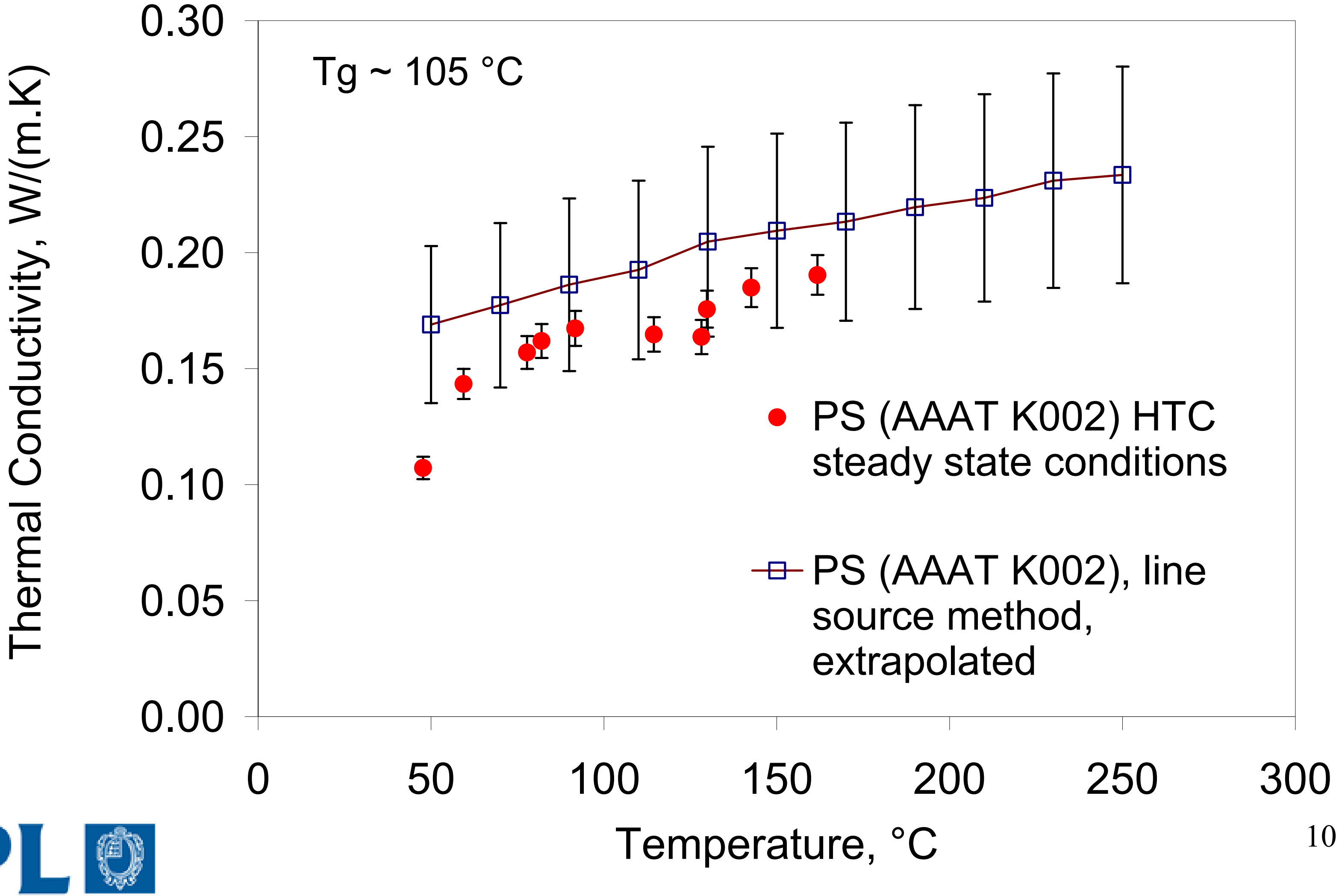
Total thermal resistance *R* (m².K.W^{-1}) = sum of thermal resistances of the individual layers r_l

Where: h_i is heat transfer coefficient at interfaces
x_l is thickness of layer
λ_l is thermal conductivity of layer

Thermal conductivity of PMMA by HTC



Thermal conductivity of PS:
HTC c.f. extrapolated line source data

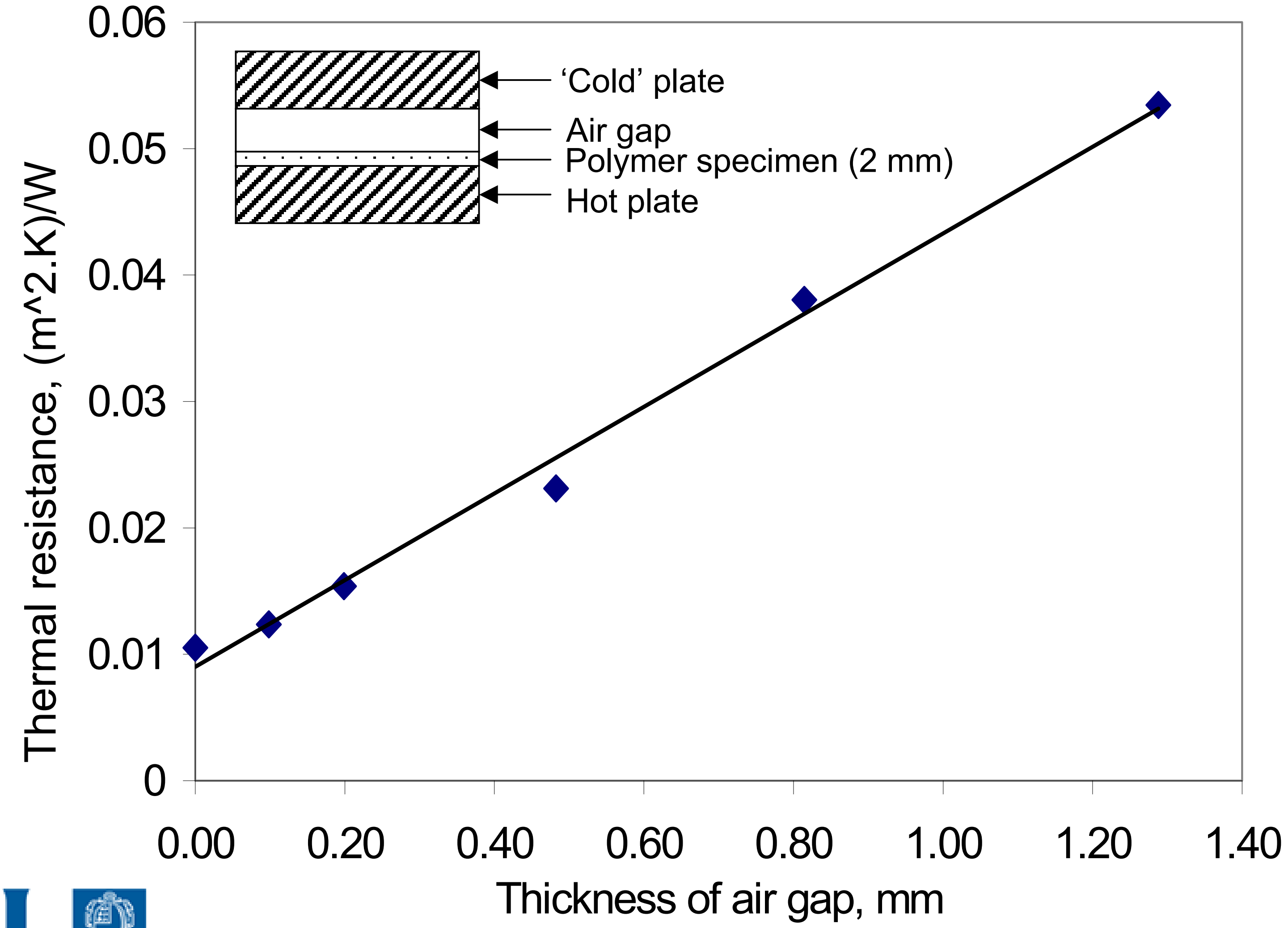


Thermal conductivity benchmarking of HTC instrument

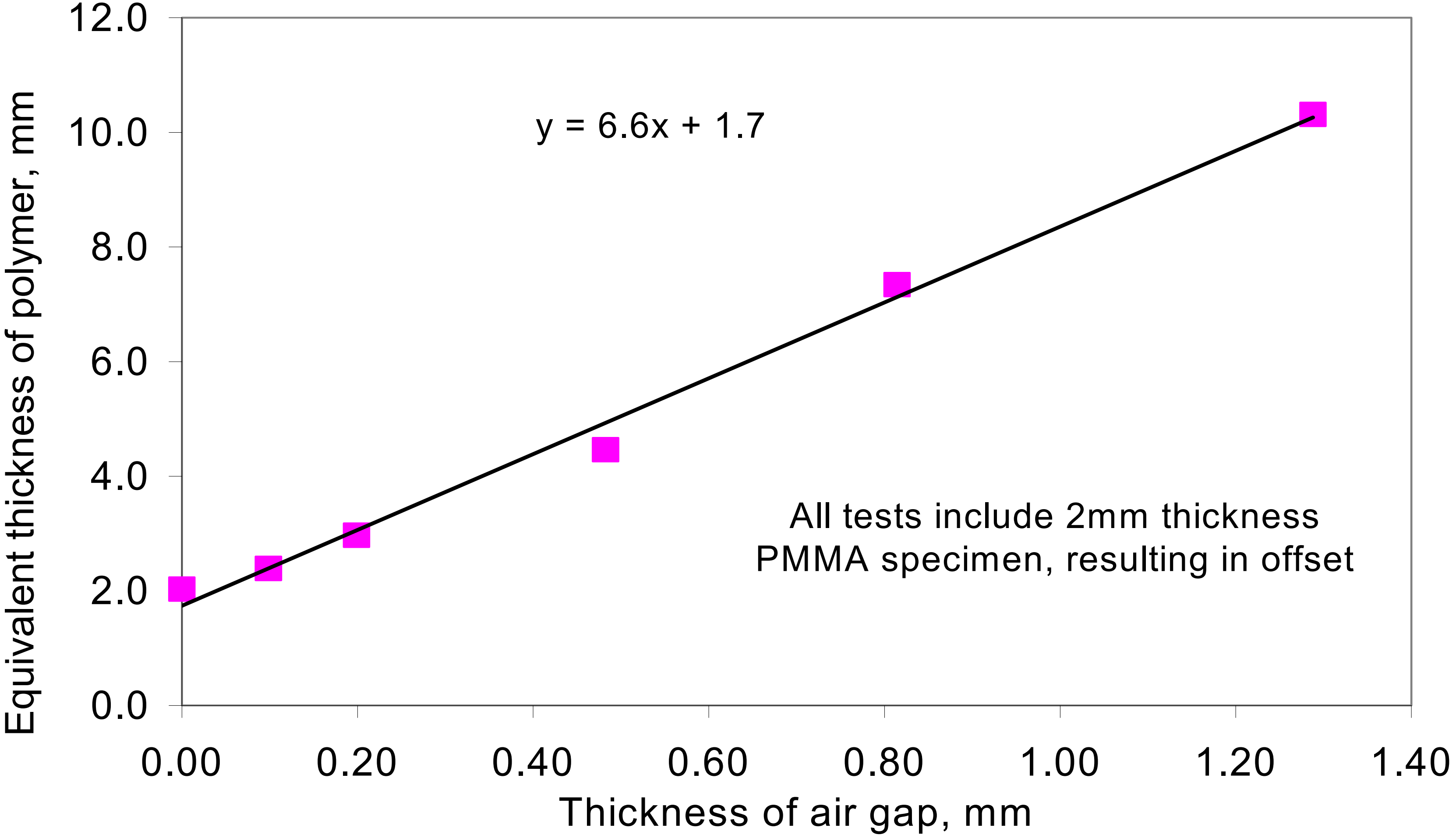
- Repeatability of heat transfer coefficient apparatus calculated as 1.5%

- Line source probe and heat transfer coefficient tests for PS show increase in thermal conductivity with temperature and consistent values of thermal conductivity within repeatability limits

Thermal resistance of PMMA specimen (2 mm) without and with air gaps of varying thickness

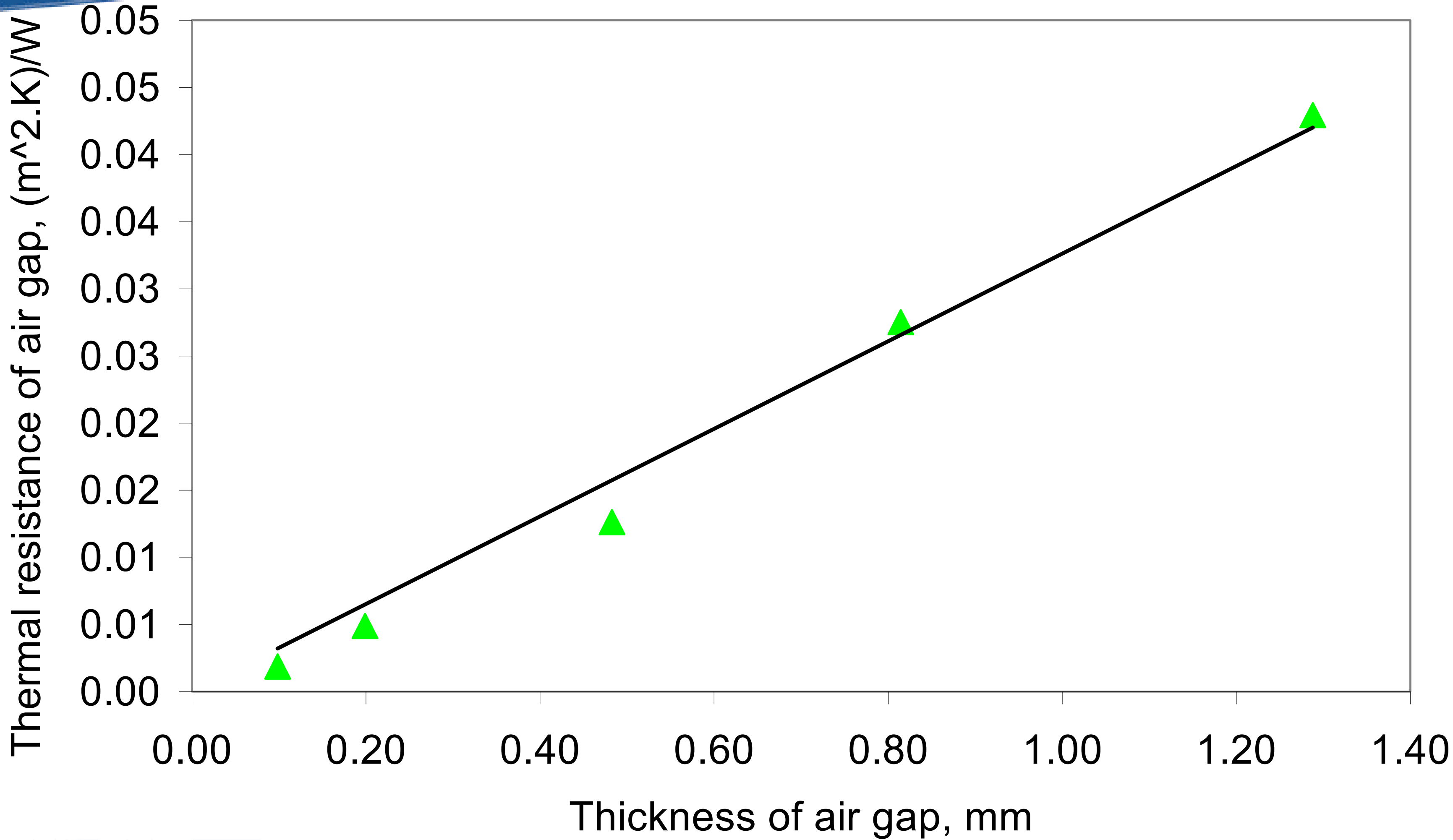


Equivalent thickness of polymer vs. thickness of air gap

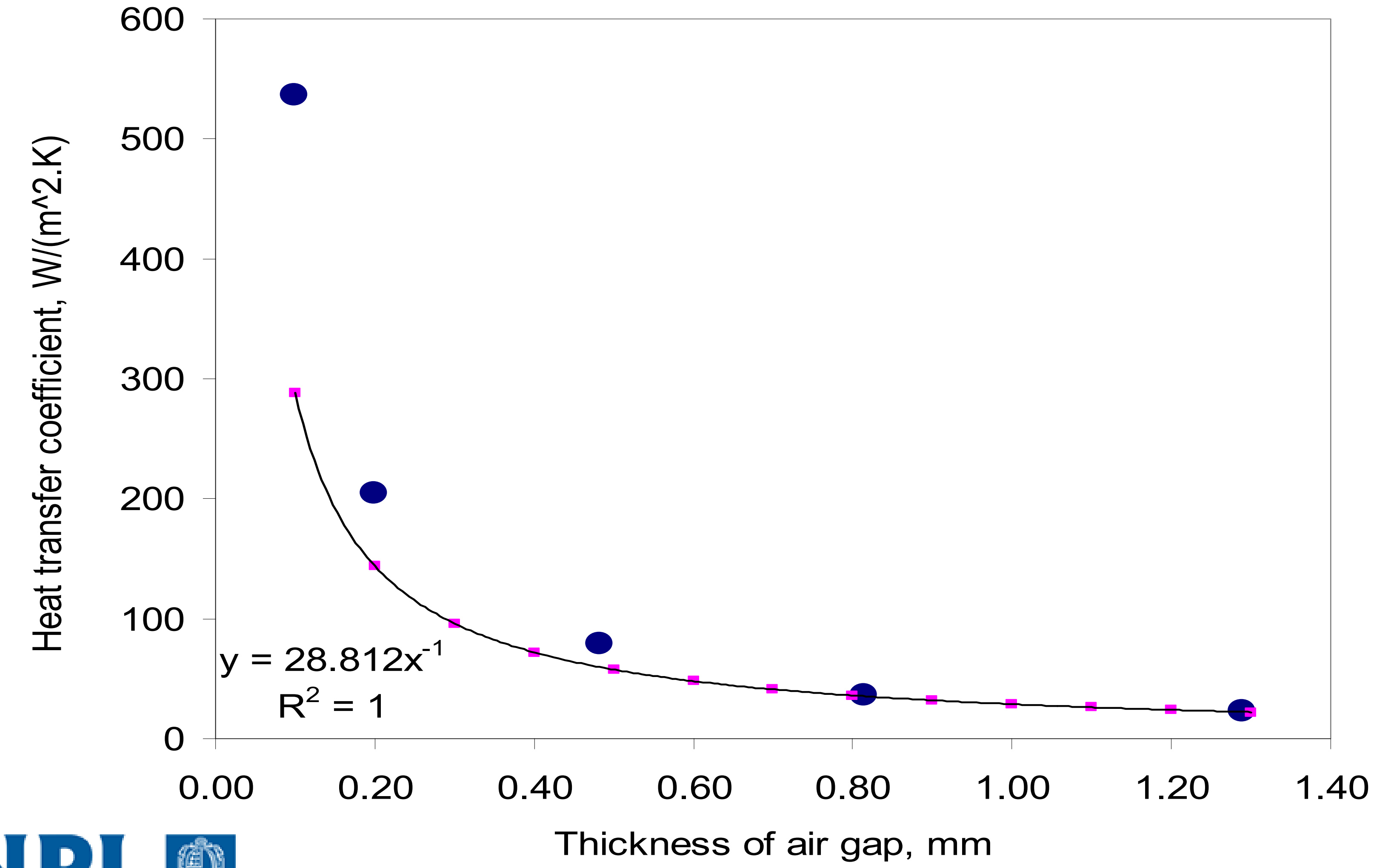


All tests include 2mm thickness PMMA specimen, resulting in offset

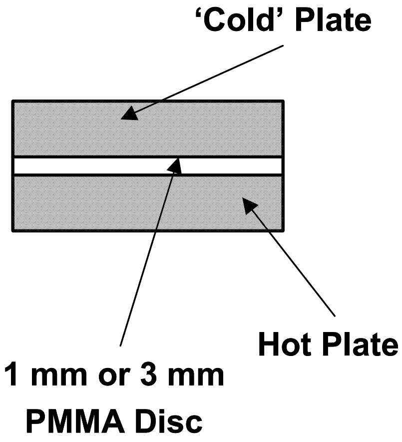
Thermal resistance of air gap vs. thickness of air gap



Comparison of measured HTC coefficient across air gap with HTC predicted by λ air model



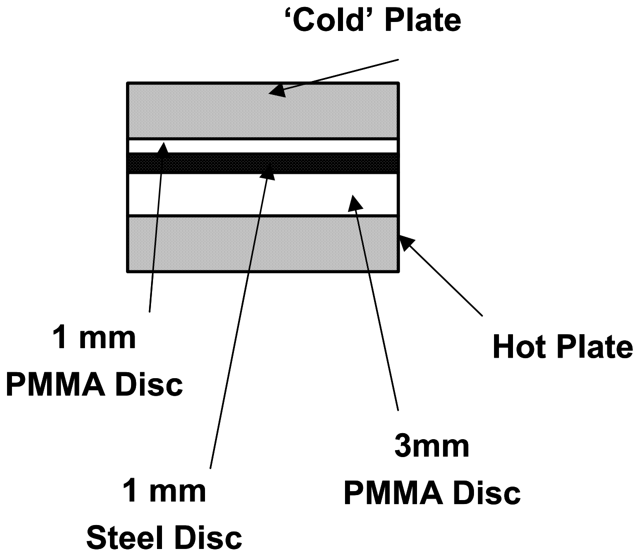
Comparison of measured HTC coefficient across air gap with HTC predicted by λ air model



‘Cold’ Plate

Hot Plate

1 mm or 3 mm
PMMA Disc



‘Cold’ Plate

1 mm
PMMA Disc

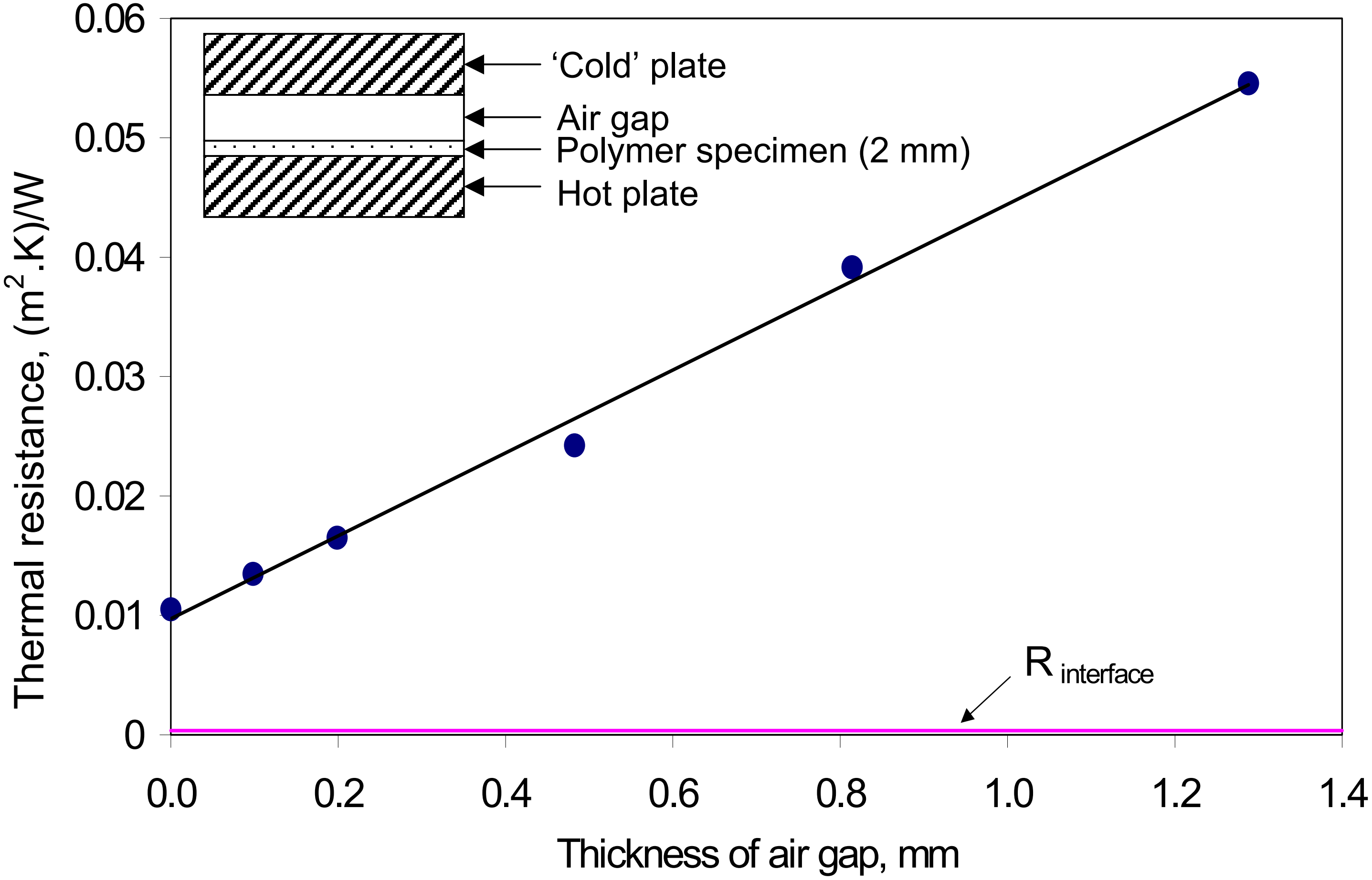
Hot Plate

3mm
PMMA Disc

1 mm
Steel Disc

HTC polymer-metal ≈7000

Thermal resistance of PMMA specimen (2 mm) without and with air gaps of varying thickness



Effect of an air gap on HTC measurements and repeatability of HTC measurement across a steel/air Interface

- Effect of air gap on thermal resistance quantified: air gap equivalent to polymer of 6.6 x thickness

- Experimental data shows a rapid decrease in heat transfer coefficient across the air gap is observed as thickness of the air gap increases.

- Good correlation with heat transfer coefficient values obtained from calculations based on the thermal conductivity of air.

- Heat transfer coefficient data could be used to provide more accurate modelling data for polymer processing and product design

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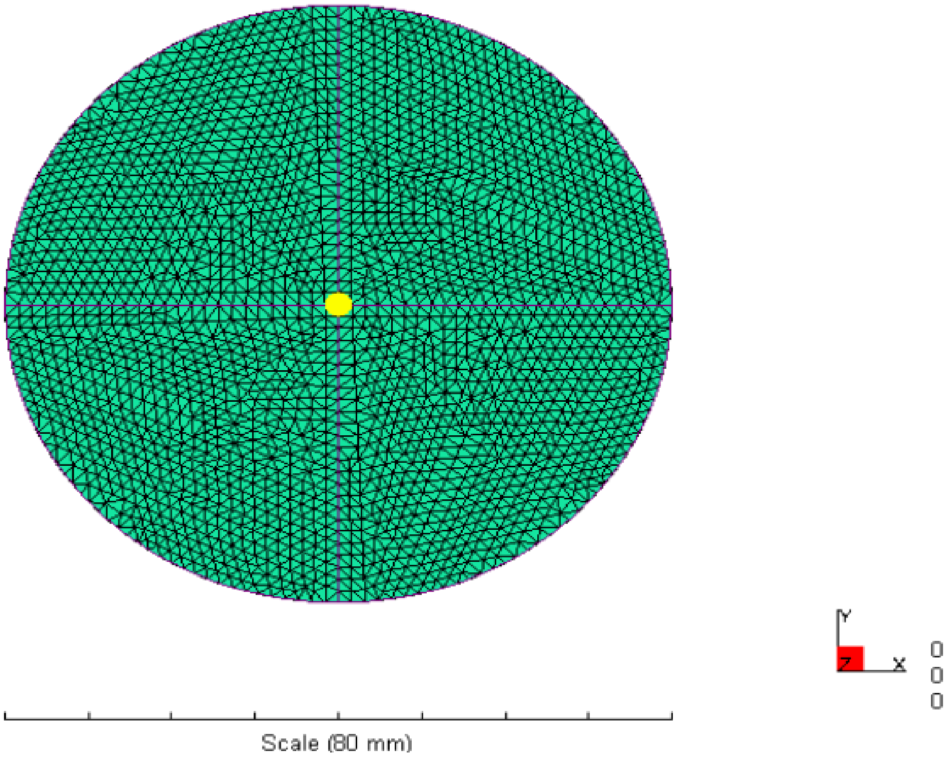
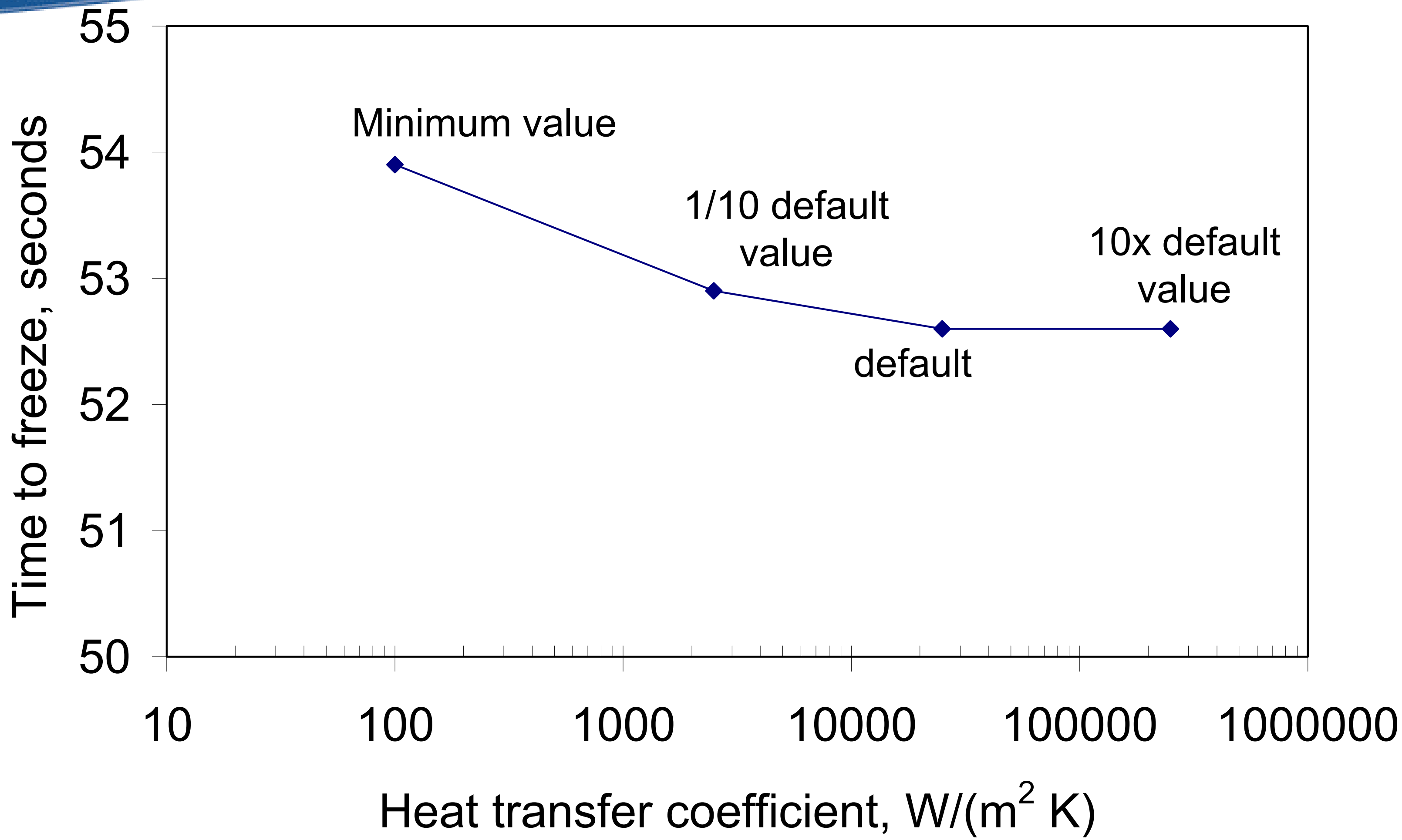
Finite element analysis of 80 mm diameter HDPE disc

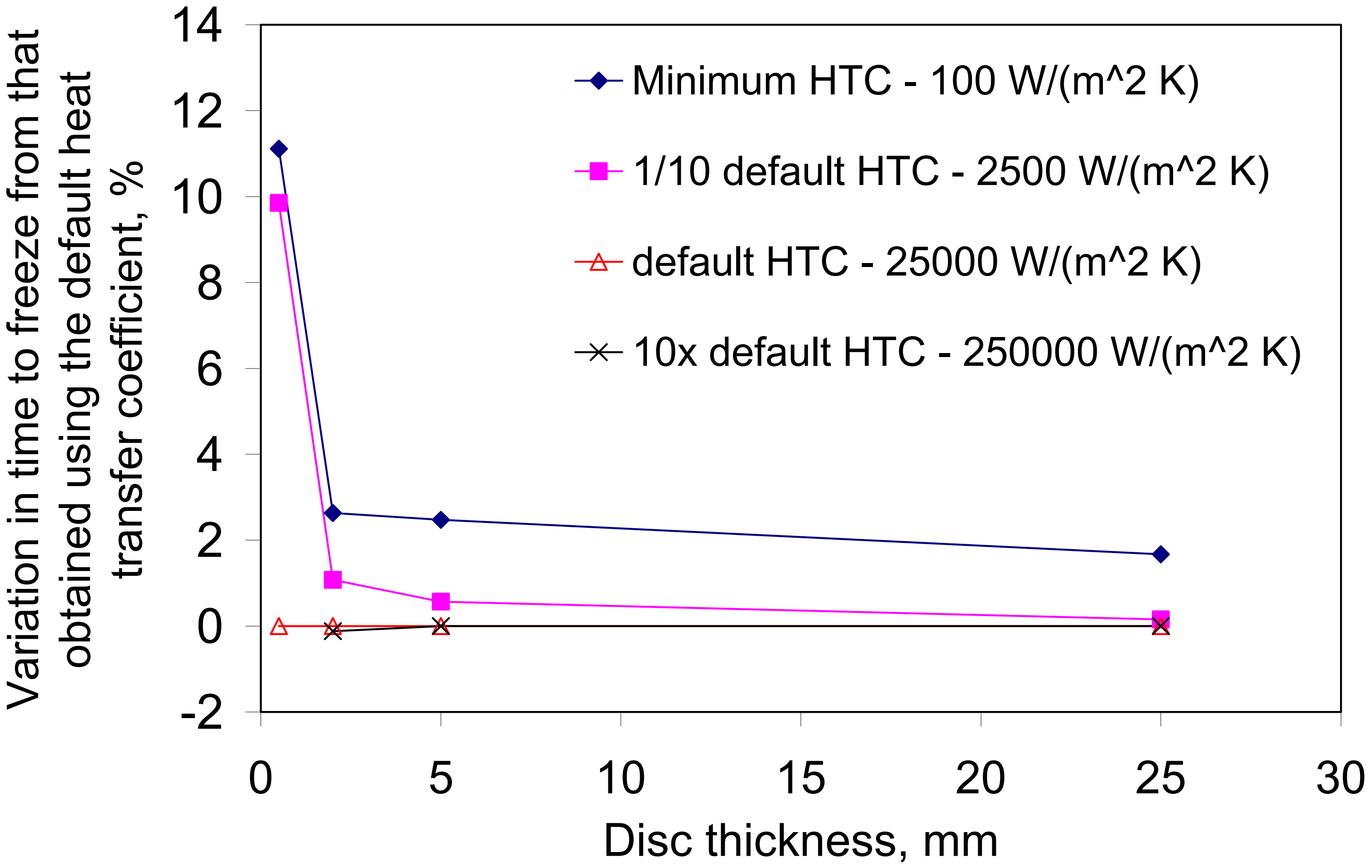


Model used to simulate effect of 0.4 mm air gap on 'time to freeze' of part using HTC value of 100 W/(m^2.K)

Effect of heat transfer coefficient on t_f of 80 mm disc of 5mm thickness



Effect of HTC on t_f for moulded discs of different thicknesses



Effect of variations in polymer-mould HTC on T_f for HDPE discs of different thickness

- For all disc thicknesses of 2 mm and greater, the effect of varying the heat transfer coefficient on the time to freeze was similar to that observed for the 5 mm thick moulded disc.

- For these thicknesses, the simulation of a 0.4 mm air gap, modelled by reducing the heat transfer coefficient to 100 W/(m^2 K), increased the time to freeze by 2.5%.

- For mouldings of 0.5 mm thickness variations in heat transfer coefficient had a more significant effect. The introduction of the simulated 0.4 mm air gap, modelled by reducing the heat transfer coefficient to 100 W/(m^2K), resulted in a 11% increase in time to freeze of the HDPE moulded disc.

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Summary

- The need for reliable data for heat transfer coefficients, between the mould surface and the polymer or an air gap, is greatest for thin mouldings – an area in which there is growing interest.

- Reliable heat transfer data are also likely to result in improved predictions of distortion and warpage of mouldings with consequent benefits in product performance.

- Significant differences in predictions can be achieved depending on the heat transfer coefficient values used.

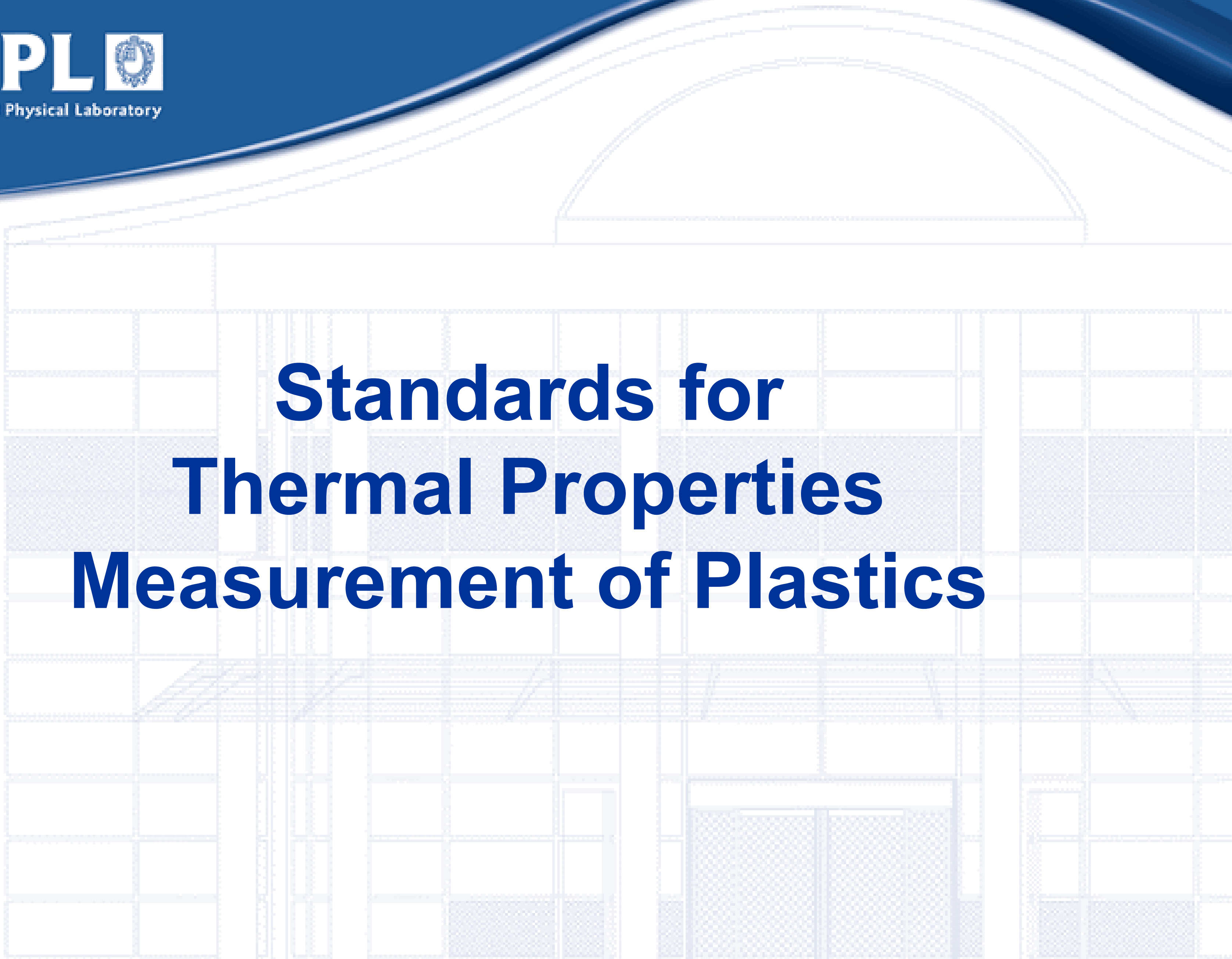
- Simulation of the injection moulding of thinner plastic parts could be improved by reducing the uncertainties in the measurement of heat transfer coefficients, leading to improvements in cycle time predictions and consequently to productivity.

Thermal Intercomparison in Support of Development of ISO 22007 Parts 1 to 4

Plastics - Determination of thermal conductivity and thermal diffusivity

Thermal Intercomparison Outline

- Thermal diffusivity and thermal conductivity
- Initial study involved project leaders
- Two grades of PMMA studied: one from Sumitomo Chemical (Sumiplex) and the other supplied through NPL
- Various measurement techniques used in round robin study including hot disk, line source, heat flow meter, laser flash, and temperature wave analysis techniques



Standards for Thermal Properties Measurement of Plastics

Plastics thermal conductivity standards

ISO TC61 SC5 WG8 Thermal Properties

ISO 22007 Plastics –
Determination of thermal conductivity and thermal diffusivity

ISO/CD 22007-1 Part 1: General principles

ISO/DIS 22007-2 Part 2: Transient plane source hot-disc method (Gustafsson method)

ISO/DIS 22007-3 Part 3: Temperature wave analysis method

ISO/DIS 22007-4 Part 4: Laser flash method

Plastics thermal conductivity standards

Possible proposal to develop
Line Source Method for Thermal Conductivity
as part of ISO 22007 series

Method currently standardized as:

- ASTM D 5930-01, Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique

However this does not make provision for:

- effect of applying pressure to minimize measurement scatter, and
- effect of pressure on thermal conductivity
- inadequate calibration procedure
- over-simple analysis of data

Your support?. Other methods?

Plastics thermal conductivity standards - intercomparison

Intercomparison of thermal conductivity methods

- Being carried out in support of standardisation activity
- Repeatability / reproducibility of methods is suspect
- To cover transient methods
  - but not excluding steady state methods
- Results to help prepare precision statement for ISO 22007 series

Led by NPL/Japan

Initial restricted intercomparison results received,
possibly to be followed by larger participation intercomparison

Plastics thermal conductivity standards - intercomparison

Intercomparison of thermal conductivity methods

Methods included:

- Transient plane source hot-disc method (Hot Disk AB)
- Temperature wave analysis method (Tokyo Inst. Tech.)
- Laser flash method (NMIJ, DataPoint Labs, NPL, LNE, OMTRI)
- Line source probe (DataPoint Labs, NPL, Moldflow, CEAST)
- Guarded Hot plate / heat flow meter (OMTRI, DataPoint Labs,)

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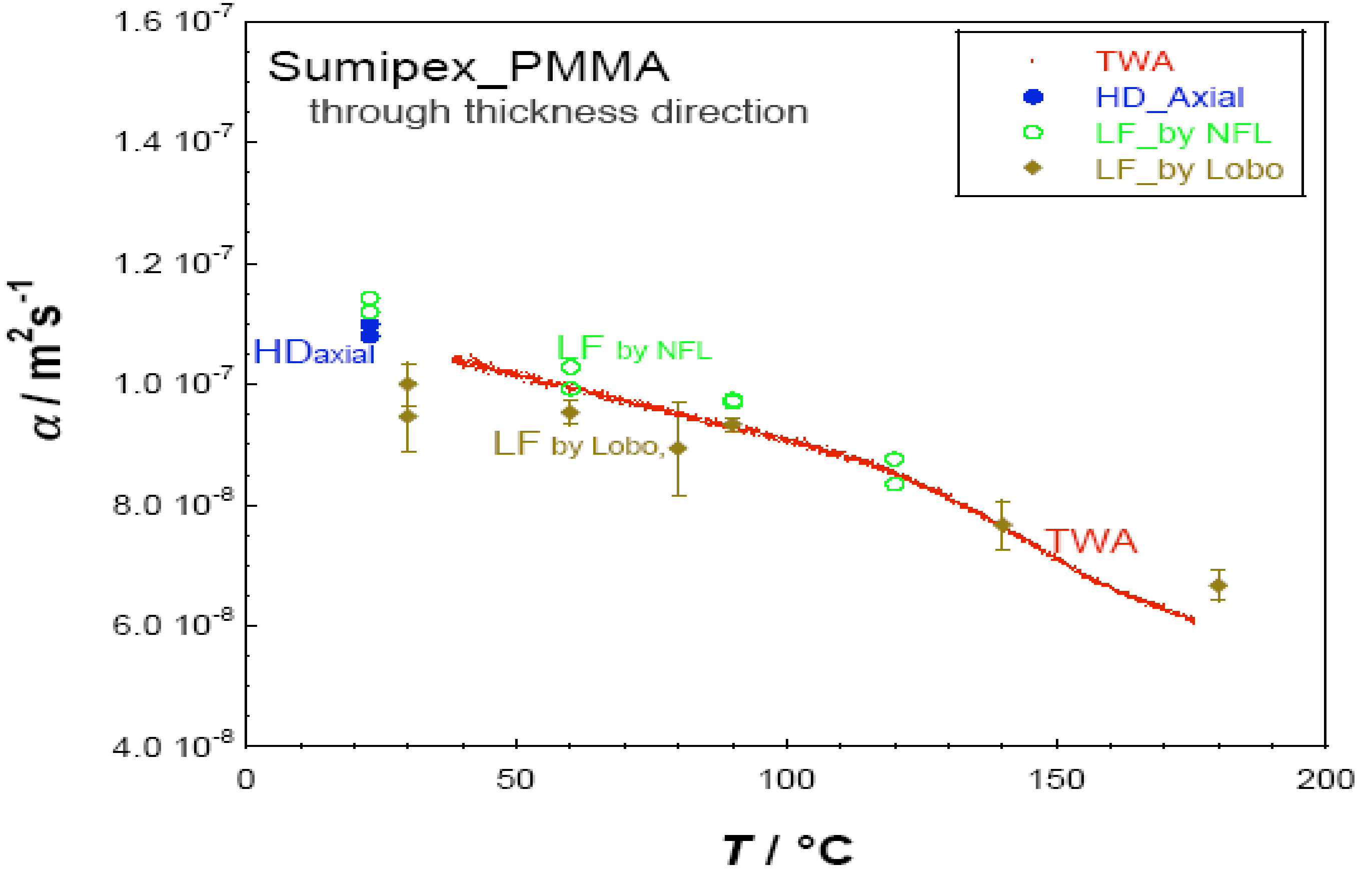
Thermal Diffusivity of Sumiplex_PMMA

TWA – Temperature wave analysis
HD – Gustaffson Hot Disc probe
LF – Laser flash

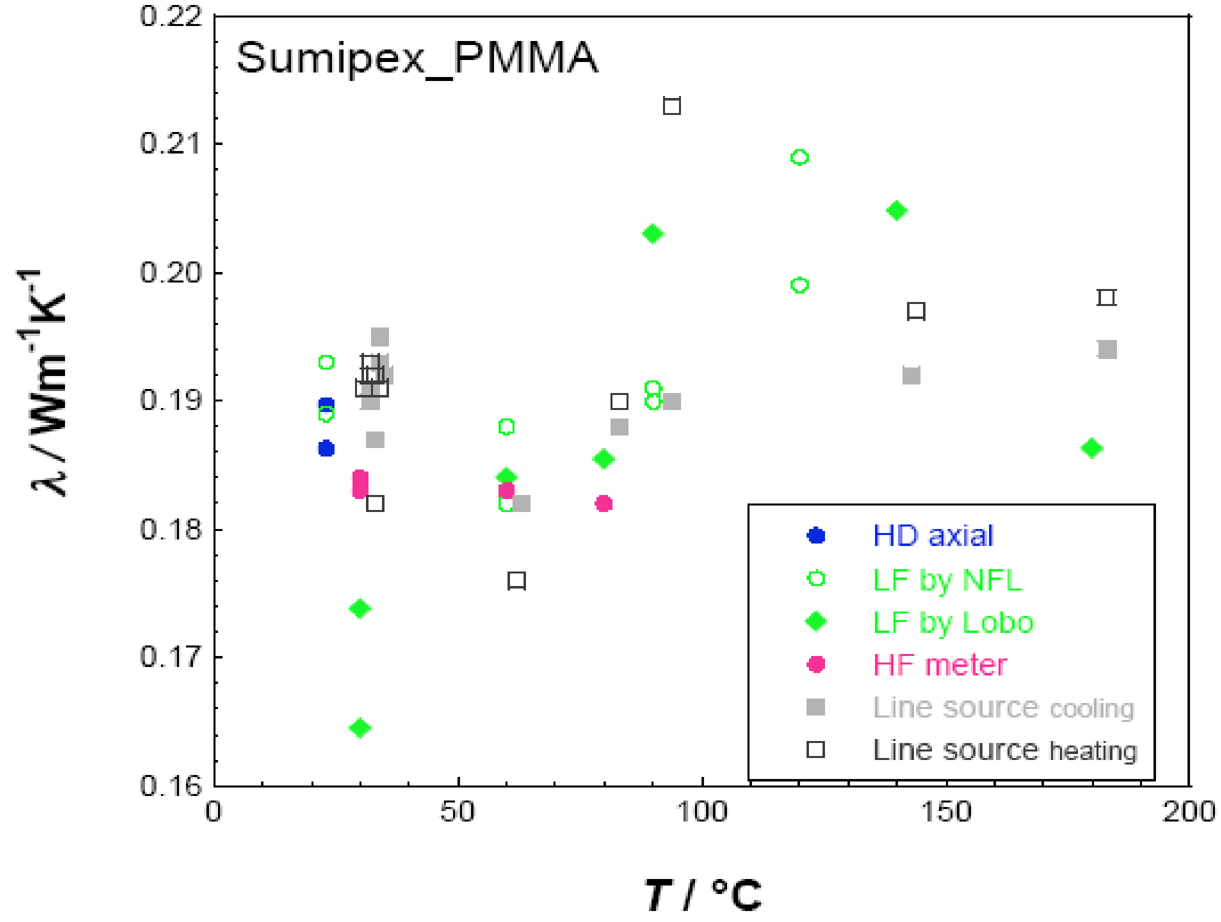


Thermal Conductivity Measurements of Sumiplex PMMA

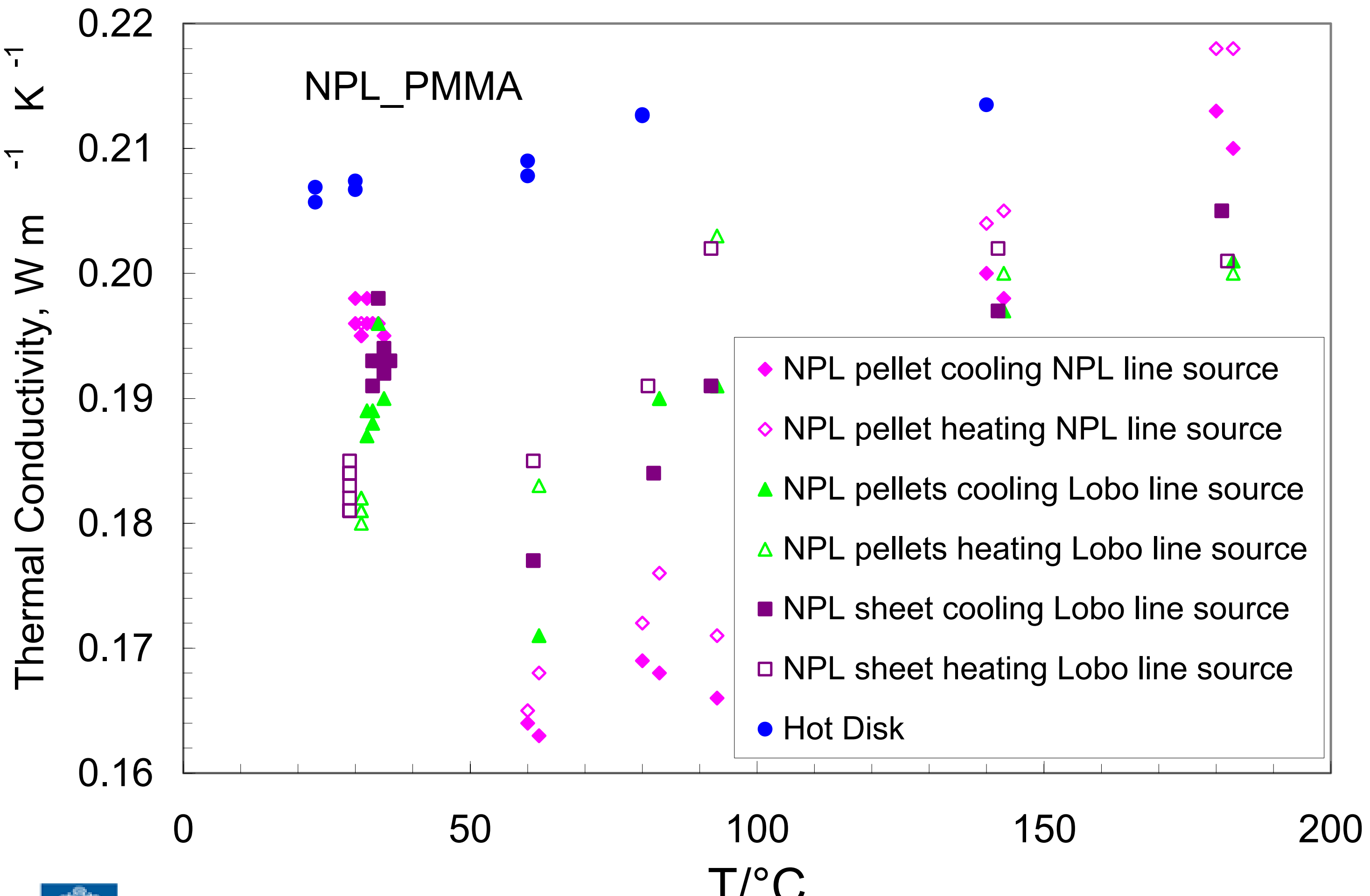
HD – Gustaffson Hot Disc probe

LF – Laser flash (calculated from diffusivity)

HF – Guarded heat flow meter



Thermal Conductivity Measurements of NPL PMMA (Both Sheet and Pellet)



Differential scanning calorimetry standards

ISO TC61 SC5 WG8 Thermal Properties

ISO 11357 Plastics - Differential scanning calorimetry (DSC)

- ISO 11357-1: 1997 Part 1: General principles (being revised)
- ISO 11357-2: 1999 Part 2: Determination of glass transition temperature
- ISO 11357-3: 1999 Part 3: Determination of temperature and enthalpy of melting and crystallization
- ISO 11357-4: 2005 Part 4: Determination of specific heat capacity
- ISO 11357-5: 1999 Part 5: Determination of characteristic reaction-curve temperatures and times, enthalpy of reaction and degree of conversion
- ISO 11357-6: 2002 Part 6: Determination of oxidation induction time
- ISO 11357-7: 2002 Part 7: Determination of crystallization kinetics

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- Acknowledgements

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