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NPL Vacuum Guarded Hot-Plate for Measuring Thermal Conductivity and Total Hemispherical Emittance of Insulation Materials

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Abstract: The National Physical Laboratory has developed a Vacuum Guarded Hot-Plate (VGHP) for measurement of both the total hemispherical emittance and thermal conductivity of insulating materials in a vacuum or gas atmosphere. This paper describes the principles of operation of the VGHP and practical issues associated with the design and construction. Also described are features that make it a versatile and convenient device for measuring the thermal properties of a wide range of construction products.

Measurement results are presented on fumed silica powder of the type used in evacuated insulation panels, measured in a specially designed and instrumented container. Also presented are results of total hemispherical emittance measurements on reference materials of known emittance and on a low-emittance reflective insulation product. The VGHP emittance measurements are compared with the results by a spectrophotometric method, which is often not suitable for measuring insulation materials.

Keywords: thermal conductivity, total hemispherical emittance, evacuated insulation, reflective insulation, guarded hot-plate

Introduction

The need for efficient energy use for both commercial and environmental reasons has led to an increasing number of alternative insulation products, such as evacuated insulation panels and reflective foil products. Accurate thermophysical property data are needed for these new products, to facilitate fair competition between material manufacturers when quoting thermal performance.

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The most accurate and reliable apparatus for measuring thermal conductivity of insulation and poor thermal conductors is the guarded hot-plate. The National Physical Laboratory (NPL) has developed a Vacuum Guarded Hot-Plate (VGHP) that is an enhancement of this technique, intended to meet the growing requirement to characterize a wide range of insulation products in terms of total hemispherical emittance and thermal conductivity.

Details of the initial design and testing have been published in a previous paper [*1*]. However, it was found that the achieved vacuum of 10^{-2} mbar was insufficient to allow measurements on low emittance surfaces. Since that publication the vacuum capability has been improved to 9×10^{-5} mbar and the measurement of emittance has been validated using reference materials of known emittance. Many additional features have been added and the measurement of thermal conductivity has also been improved.

The measurement of thermal conductivity has been validated using the European reference material IRMM-440 [*2*] (resin-bonded glass fiber board, -10 °C to 50 °C) and with polymethylmethacrylate (Perspex), NPL Batch 7/81 (0 °C to 60 °C). The VGHP now conforms to the European standard ISO 8302:1991 “Thermal insulation – Determination of steady-state thermal resistance and related properties – Guarded hot plate apparatus”.

Apparatus Design

The VGHP is a 305 mm square, single specimen, guarded hot-plate apparatus incorporating a linear temperature gradient edge-guard, all mounted in a vacuum chamber.

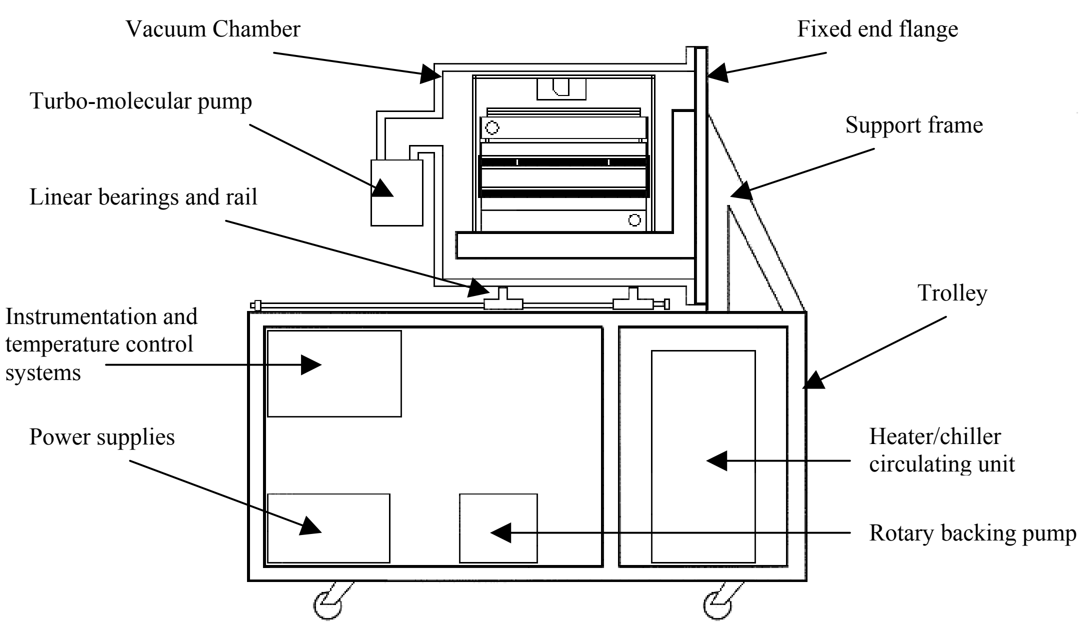

Figure 1 – *Vacuum Guarded Hot-Plate*

The VGHP can measure the thermal conductivity of a single 305 mm square specimen in air, other gases or at reduced pressure. Specimens are less than 65 mm thick having a conductivity of less than 2 W/(m•K) and thermal resistance greater than 0.025 (m²•K)/W. The apparatus can be operated with an evacuated gap between a specimen and the cold-plate of known emittance, thus allowing the total hemispherical emittance of a specimen surface to be measured.

The mean specimen temperature range of thermal conductivity measurement is -50 °C to 70 °C, typically with a 20 K temperature drop across the specimen. There is a reduced temperature range for measurement of emittance that is dependent on the type of specimen. The cold-plate temperature is controlled by a unit that is designed solely as a re-circulator, rather than a bath with an additional pump. This has the advantage that the silicone oil, which is used as the heat transfer medium, is not exposed to the air where it can adsorb moisture. It also offers a high flow-rate for increased stability and uniformity of the cold-plate temperature. The unit has a heat extraction capacity of 1 kW at -60 °C.

The vacuum system includes a rotary backing pump and a turbo-molecular pump. The achievable vacuum of 9×10^{-5} mbar is mainly limited by outgassing of the specimen and the materials in the heater stack. A separate valve is incorporated in the system to allow the chamber to be back-filled with gases other than air.

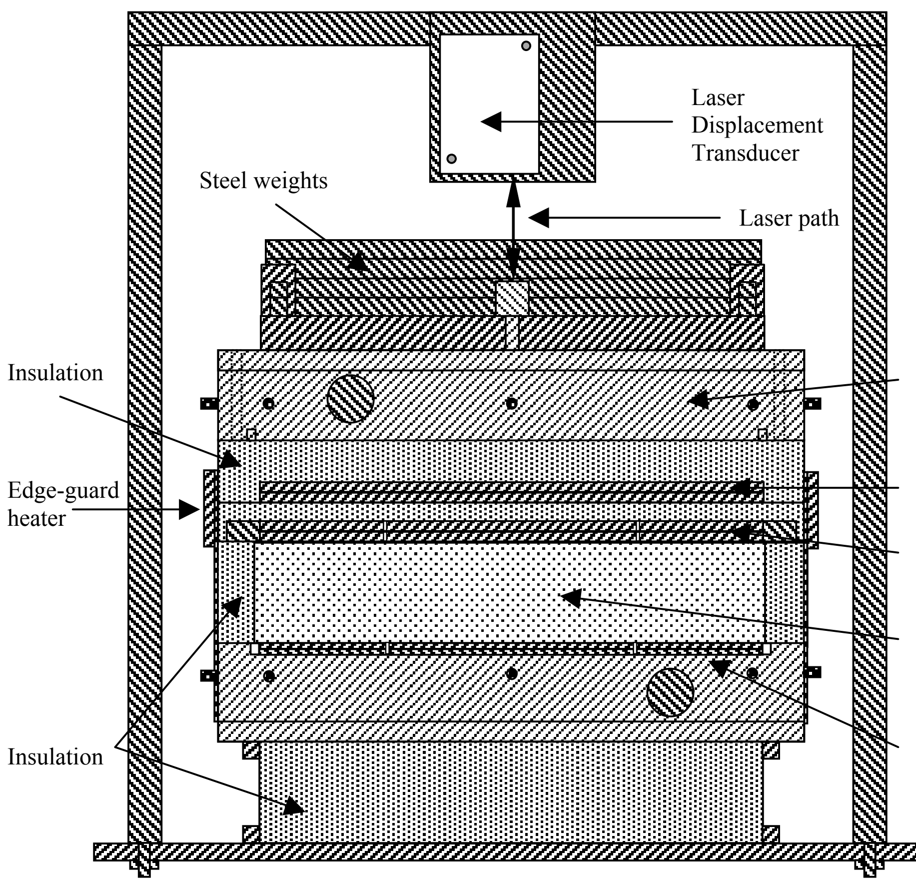

Figure 2 – *Guarded Hot-Plate Stack*

Single Specimen, Reversible Heat-Flux Configuration

The VGHP is a single-specimen design with an auxiliary heater plate behind the guarded heater plate, and maintained at the same temperature (normally within ± 0.01 °C when measuring insulations) as the guarded heater plate to prevent any net heat flow from its back surface. The auxiliary plate temperature is controlled by a differential thermocouple mounted on the adjacent surfaces of each plate. A layer of rigid closed cell foam insulation is placed between the plates to reduce the net heat flow for a given temperature difference, and thereby increase the effectiveness of the control.

The guarded plate, auxiliary plate and surrounding insulation can be removed from the apparatus as a single unit for reinsertion in the apparatus the other way up. This allows the specimen to be mounted either above or below the heater-plate and is useful in assessing the effect of convection within very low density specimens.

E-type thermocouples are mounted on the specimen surface to ensure accurate temperature measurement for specimens that have a thermal resistance less than 0.33 (m^2•K)/W, as recommended in ISO 8302:1991. Thermal contact sheets (foamed silicone rubber) are used to ensure even thermal contact with specimens by eliminating air gaps caused by either thermocouples or bowing of the specimen arising from differential expansion.

Guarded Heater-Plate

The design of the guarded heater plate is based on the recommendations of the European standards EN 12667 “Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance” and ISO 8302:1991. The plate is 305 mm x 305 mm with a central metering area of 152.5 mm x 152.5 mm.

The heater-plate is constructed from two 5 mm thick plates of an aluminum alloy tooling plate chosen for its stability when subject to repeated temperature cycling.

Sandwiched between the aluminum plates is a custom-designed, printed circuit board (pcb) heater. The heater has two circuits of copper track on each side, which can be used to provide up to 90 W in the central region and 240 W in the outer guard region. The potential drop across the circuit in the central metering area, on each side of the pcb, is measured and used in the heat-flux calculation. The heater is electrically isolated from the aluminum plates by thin laminate sheets of cloth impregnated with resin (Tufnol) and the whole heater plate is held together with an adhesive suitable for the temperature range -60 °C to 120 °C.

The heater-plate has five E-type thermocouples mounted in grooves, in the central metering area, and their temperature values are used in the calculation of thermal conductivity. There are two thermocouples in the lateral guard area, and the thermocouples in the underside of the heater-plate are used to form a differential with those in the adjacent surface of the auxiliary plate.

Across the 2 mm wide guard-center gap is a 64-junction differential thermocouple, which has 32 junctions on each side of the plate. The junctions are positioned in a groove, at a depth of 2.5 mm below the plate surface. The legs of the junction remain parallel to the gap for 15 mm before crossing it. The plate surfaces were machined flat to better than 0.05 mm and sprayed with a black paint having a total hemispherical emittance of 0.90.

Edge-Guard System

An edge-guard system is used because the sides of the specimen cannot be adequately insulated within the confines of the chamber and because the air cannot easily be controlled at the mean specimen temperature. The edge-guards can be attached to either of the cold-plates, depending on the specimen/heater orientation. They consist of four copper plates (1 mm thick) that are clamped to the edges of the cold-plate. At the other end of the copper plates is a strip-heater whose width matches the combined width of the main heater, the auxiliary heater and the insulation between them. This edge heater is controlled to match the temperature of the heater-plates to minimize heat losses from the main heater and auxiliary guard.

The section of the edge guard adjacent to the specimen will have a similar temperature gradient and will therefore minimize net heat flow from the edge of the specimen. Compressible insulation of 25 mm thickness is placed between the specimen edge and the edge-guard to stop convection currents from forming in the gap. When the apparatus is running in vacuum, the edge-guard's outer surfaces are covered with a thermally reflecting foil, to minimize heat transfer by radiation with the inside of the chamber walls. When running in air, insulating blanket is wrapped around the stack and 25 mm of flexible foam insulation covers the outside of the chamber.

This system allows thermal conductivity measurements in air, over the whole temperature range, without the need for controlling the air temperature within the chamber, as the specimen and heater edges are thermally isolated from the external environment.

Cold-Plate Heat-Flux Transducer

A heat-flux transducer is incorporated into the lower cold-plate to allow the heat flux on the cold side of the specimen to be measured. This will allow rapid measurements (2-3 hours) of specimens with conductivities greater than about 0.2 W/(m•K).

The transducer was custom made by Isover Saint Gobain in France and is a 0.6 mm thick glass-reinforced plastic substrate with 900 thermocouple junctions covering an area matching the central metering area of the VGHP heater plate. It is mounted in a recess in the cold-plate, with a 4 mm thick high-pressure laminate sheet of cloth impregnated with resin (Tufnol) between the heat-flux transducer and the cold-plate, to damp out small rapid temperature fluctuations caused by the liquid passing through the plate. On the other side of the transducer is an aluminum alloy cold surface which is in contact with the specimen, and in which the cold-plate thermocouples are mounted in 1.5 mm grooves. This surface plate has a 2 mm gap similar to the heater-plate, to reduce lateral heat flow between the edges and the central region.

This unit is calibrated by placing a thin thermal contact sheet between the lower cold surface and the heater plate. When the apparatus is in thermal equilibrium, it can be assumed that there is the same heat-flux in the transducer as leaving the heater. Thus by applying different heat fluxes at different temperatures, a calibration can be made between transducer output and heat flux, at different temperatures.

Thickness Measurement (Displacement Transducer)

Specimens with a high coefficient of thermal expansion may change thickness over the full temperature range of the apparatus. Also, the thickness of semi-compressible insulations may vary with time as they settle under the load, applied by means of calibrated weights on the upper cold-plate. To enable the thickness of the specimen to be accurately monitored during a series of measurements, a laser displacement transducer is mounted above the upper cold-plate. The transducer operates by measuring the angle of scattered light from a white surface mounted on the cold-plate, and gives a signal that is proportional of the displacement.

The transducer output is calibrated against the specimen thickness by setting up the guarded hot-plate stack with sets of calibrated gauge blocks, of different thickness, in place of the specimen. The calibration is also carried out at several temperatures to take account of expansion or contraction of the plates and insulation in the rest of the stack. The transducer output is monitored during thermal conductivity measurements to give the specimen thickness value used in calculating the thermal conductivity.

Validation of Thermal Conductivity Measurements

The VGHP measurement of thermal conductivity in air has been evaluated according to the performance checks specified in ISO 8302:1991. They have also been validated using the European reference material IRMM-440 [*2*] (Table 1) and with NPL reference material Perspex Batch 7/81 (Table 2).

The IRMM-440 is a resin-bonded glass fiber board, certified over the temperature range -10 °C to 50 °C, and with a quoted uncertainty of ± 1 %. In addition to their measurements that contributed to the certified reference values, the Istituto di Fisica Tecnica in Italy also made measurements down to -170 °C.

Table 1 – *Measured Thermal Conductivity of IRMM-440 Reference Material*

Mean Specimen Temperature, °C	VGHP Measured Thermal Conductivity	IRMM Thermal Conductivity Reference	Difference (Measured - Reference)
-50.0	0.0248	0.0244 [1]	1.6 %
-30.9	0.0266	0.0264 [1]	0.8 %
-10.9	0.0286	0.0283	1.0 %
9.3	0.0305	0.0304	0.3 %
29.7	0.0329	0.0327	0.6 %
50.0	0.0357	0.0352	1.4 %

[1] These values are not part of the official material certification.

The VGHP values for the IRMM-440 glass fiber board have an estimated uncertainty of ± 1.5 % and are in agreement with the IRMM-440 reference values within the combined measurement uncertainty.

The NPL Perspex Batch 7/81 reference material is polymethylmethacrylate, certified over the temperature range 0 °C to 60 °C, with an uncertainty of ± 3 %.

Table 2 – *Measured Thermal Conductivity of NPL Perspex (7/81)*

Mean Specimen Temperature, °C	VGHP Measured Thermal Conductivity	Perspex Thermal Conductivity Reference	Difference (Measured - Reference)
-0.8	0.1860	0.1877	-0.9 %
19.6	0.1878	0.1904	-1.4 %
39.6	0.1904	0.1931	-1.4 %
59.5	0.1937	0.1958	-1.1 %

The VGHP values for the Perspex (7/81) have an estimated uncertainty of ± 3 % and are in agreement with the NPL reference values within the combined measurement uncertainty.

Measurements on Powder in Vacuum

Evacuated Insulation Panels

With the increasing use of evacuated insulation in refrigeration and also in specialized applications, there is a growing need to evaluate these products. The panels consist of filler material, generally fumed silica or aerogels, which are evacuated and surrounded by a laminated gas barrier of different plastics and an aluminum foil. They can have a thermal resistance that is ten times greater than a conventional insulation of the same thickness. Better characterization of the filler material will allow further development and comparison of various panel designs.

Evacuated-Powder Container

To measure powders in vacuum, an instrumented container was constructed to hold the powder in the form of a 305 mm square specimen. The container is placed as a specimen in the VGHP and its contents are evacuated along with the vacuum chamber.

The container is made of a 4 mm thick high-pressure laminate sheet of cloth impregnated with resin (Tufnol), so as to provide a rigid reusable box. The laminate sheet has a thermal conductivity of about 0.3 W/(m•K), which minimizes lateral heat-flow through the base, lid, and vertically through the sides. The 25 mm high sides consist of two layers, the inner bolted and glued to the base, while the outer is bolted to the inner. A layer of "vacuum cleaner bag" paper is sandwiched between the inner and outer layers, both of which have large cutouts in them. These cutouts and the paper form windows, allowing the inside of the container to be evacuated, while keeping the powder contained.

The temperatures on either side of the powder are measured with five thermocouples mounted on the inner surface of the base and lid. They are made from E-type wire of 0.2 mm diameter, which have been rolled flat to less than 0.1 mm (the calibration is not significantly altered by this process). The inner surface of the container is sprayed with a black paint with a total hemispherical emittance of 0.90.

Evacuated-Powered Measurements

Trial measurements (Table 3) were carried out on typical fumed silica used in evacuated panel insulations. The absolute pressure inside the chamber was less than 10^{-3} mbar.

Table 3 - *Measured Thermal Conductivity of Fumed Silica (69 kg/m^3)*

Mean Specimen Temperature, °C	Thermal Conductivity, W/(m•K)
49.5	0.0067
19.2	0.0044
-17.1	0.0026

There is very little data on this fumed silica product, but the values obtained by NPL are similar to those published by the manufacturer. The NPL measurements are also in good agreement with measurements carried out at the Oak Ridge National Laboratory on similar types of fumed silica [*3*], using a radial heat-flow apparatus with vacuum capability. The Oak Ridge measurements show similar temperature dependencies as those in the VGHP. They were in the range 0.003 W/(m•K) to 0.008 W/(m•K) at temperatures between 27 °C and 57 °C, at pressures of 2 x 10^{-2} mbar to 4 x 10^{-2} mbar.

Discussion

The uncertainty for measurements on evacuated specimens will be higher than the ± 1.5 % for measurements on conventional insulations in air. This is due to the power required to create the desired temperature drop through the specimen (20 K) being much smaller (100-200 mW), so that the uncertainty on the power could be up to ten times greater. The guard-center balance will also be far more critical and any heat gain or loss from the edges of the specimen will have a greater effect. Although further performance evaluation is required before a detailed uncertainty budget can be produced, the uncertainty is estimated to be about ± 10 %.

Due to the extremely low thermal conductivity of the evacuated specimens, the VGHP took much longer than normal to reach thermal equilibrium. The measurements given above were taken after the test had been running for 48 hours. The long drift-time and small heat-fluxes involved suggest that some fine-tuning is required to determine the optimal tuning of temperature controllers and the equilibrium criteria. Variations due to guard/center off-balance and the optimum temperature drop also need to be investigated.

Measurements of Total Hemispherical Emittance

Conventional apparatus that measure near-normal total emittance are generally not suitable for the dusty, inhomogeneous materials commonly used in building construction and it is necessary to obtain these values using a different technique. The method chosen was to measure the total hemispherical emittance by measuring the net radiation interchange between the specimen surface and a colder surface of known emittance. Total hemispherical emittance relates to the integration of the radiation over all angles and all wavelengths that the surface is radiating. This is often more directly applicable than normal total emittance, which must be corrected before it can be used in heat transfer calculations of building elements.

This technique has previously been used with an air-filled gap [*4*, *5*]. It is generally carried out with the air gap under the heater to reduce convection. It is also often used to measure the emittance of heater-plates that have a high emittance, as described in ISO 8302:1991, using a varying gap thickness to avoid significant corrections for air conduction. However, when this technique is used for surfaces with a low emittance, the radiative flux is small compared with that conducted through air, which is the reason that an evacuated gap is used in the VGHP. For rough, inhomogeneous materials this method also has the advantage of using a more representative area than is possible using the small samples required for a spectrophotometric apparatus.

Configuration for Emittance Measurements

The effective emittance of a specimen surface is determined by measuring the radiant heat transfer across a gap between the heated specimen and the cold plate. The surface of the cold plate has been sprayed with the same black paint as the heater-plate, whose emittance, 0.90 at 20 °C, has been measured at NPL using a spectrophotometric apparatus [*6, 7*].

To suppress heat transferred across the gap by air conduction and convection, the apparatus has been mounted in a vacuum chamber. For gaseous conduction to become negligible with a 3 mm gap requires a pressure of the order of 10^{-4} mbar. Once this level of vacuum is achieved, the radiative heat transfer across the gap is assumed to be equal to the electrical power into the central heater, as the lateral and edge guarding minimize net lateral heat transfer.

Small Tufnol spacers at each corner of the lateral guard area maintain the gap between the specimen surface and the top cold plate. The spacers are 3 mm long tubes of 5 mm diameter and 2 mm wall thickness. By keeping this gap small and by covering the edge guards with a reflective aluminum foil, the net radiant heat emitted by the central metering area to the edge guard is reduced to a negligible level.

The surface temperature of the cold plate is measured by thermocouples embedded in grooves in the surface of the plate before it was sprayed. The specimen's surface temperature is measured by a thermocouple of 0.2 mm diameter wire, rolled flat to 0.1 mm and taped to the specimen surface. A tape is selected with similar emittance to the specimen and just enough is used to ensure good thermal contact between the thermocouple and specimen.

Principle of Emittance Measurements

The specimen and top cold plate surfaces are assumed to be diffuse reflectors and emitters, and have thermal radiative properties that do not vary with wavelength, i.e. they are gray. The expression for the net radiative heat exchange *Q* between two infinite parallel flat plates in terms temperatures T_{hot} and T_{cold}, emittance ε_{hot} and ε_{cold}, area *A*, and Stefan Boltzmann constant σ, 5.67 x 10^{-8} W/($m^2 \cdot K^4$), is then given by [*8*]

$$Q = \frac{A\sigma(T_{hot}^4 - T_{cold}^4)}{\frac{1}{\varepsilon_{hot}} + \frac{1}{\varepsilon_{cold}} - 1} \qquad (1)$$

Rearranging equation (1) we obtain an equation for the specimen emittance ε_{hot}.

$$\varepsilon_{hot} = \frac{1}{\frac{A\sigma(T_{hot}^4 - T_{cold}^4)}{Q} - \frac{1}{\varepsilon_{cold}} + 1} \qquad (2)$$

Hence, measuring the net radiant heat transfer *Q* from the metering area *A*, measuring the surface temperatures and knowing ε_{cold}, the specimen emittance ε_{hot} can be calculated.

Comparison with NPL Spectrophotometric Standard

In order to validate the performance of the new VGHP apparatus, the emittance of polymethylmethacrylate (Perspex) and a coated glass were measured by the NPL Optical Radiation Measurement Group using a spectrophotometric apparatus. This apparatus can measure both diffuse and regular (spectral) components of reflectance and transmittance, from which the spectral emittance can be calculated. Knowledge of the spectral emittance over the thermal infrared spectrum enables near-normal total emittance to be calculated. This method requires small specimens and is generally not suitable for inhomogeneous materials or materials with a low heat capacity. This method also has large uncertainties for highly reflective materials.

To compare the near-normal total emittance values produced by the NPL spectrophotometric technique with measurements made in the VGHP, the near-normal values need to be converted into a total hemispherical emittance. This can only be achieved to high-accuracy if the emission and reflection properties of both surfaces are known, and it involves complex calculations. However, for the purposes of this comparison, tables of "corrected" emittance in the European standard EN 673:1998 "Glass in building – Determination of thermal transmittance (*U* value) – Calculation method", will provide sufficiently accurate conversion factors.

Emittance of Polymethylmethacrylate

The near-normal total emittance of a sample of polymethylmethacrylate thermal conductivity reference material (NPL batch 7/81) was measured using the NPL spectrophotometric technique, converted to total hemispherical emittance, and compared with measurements made in the VGHP (Table 4).

Table 4 – *Measured Thermal Emittance of Polymethylmethacrylate*

Specimen Surface Temperature, °C	VGHP Measured Emittance	Spectrophotometric Reference Emittance [9]	Difference (Measured - Reference)
-24.7	0.949	0.896	0.054
-6.7	0.917	0.897	0.021
12.6	0.939	0.898	0.041
22.3	0.951	0.898	0.052
32.8	0.974	0.899	0.075

The temperature difference between the specimen (hot) surface and the calibrated cold-plate surface was 12 K to 15 K.

Emittance of a Coated Glass

The near-normal total emittance of a sample of glass with a low emittance semi-conducting coating of tin oxide doped with fluorine atoms, was measured using the NPL spectrophotometric technique. These results were then converted to total hemispherical emittance, and compared with measurements made in the VGHP (Table 5).

Table 5 – *Measured Thermal Emittance of Coated Glass*

Specimen Surface Temperature, °C	VGHP Measured Emittance	Spectrophotometric Reference Emittance [10]	Difference (Measured - Reference)
-19.2	0.208	0.167	0.041
1.3	0.187	0.169	0.018
21.4	0.180	0.171	0.009
21.8	0.184	0.171	0.013
43.9	0.201	0.173	0.027
63.5	0.208	0.175	0.032

The temperature difference between the specimen (hot) surface and the calibrated cold-plate surface was 20 K to 25 K.

Emittance of a Reflective "Aluminized" Insulation

There has been a recent emergence in the UK construction industry of "reflective insulation" products being used inside cavity walling as an alternative to conventional insulations. The principle on which they are marketed is that they reduce heat transfer by radiation, which can be a significant component of the thermal transmittance of an un-insulated cavity wall. Products such as "aluminized bubble-wraps," consist of a layer of plastic and air cavities, of nominally 5 mm to 10 mm thickness, with reflective aluminum foil on one or both surfaces. The single foil products are nailed to the inner leaf of a cavity wall, while the double foil products are hung centrally within the cavity.

The performance of these products are currently evaluated by NPL using thermal transmittance measurements made in a Hot Box, with the product mounted in a reference cavity. However, Hot Box tests are expensive and time consuming. The VGHP offers a more economic approach and can provide direct measurements of both emittance and resistance. This will enable investigation into some of the issues surrounding these products, which include the transparency of plastics used to coat the aluminum foil and the reduction of performance due to dirt, dust and tarnishing.

The near-normal total emittance of a sample of reflective "aluminized" insulation was measured using the NPL spectrophotometric technique, converted to total hemispherical emittance, and compared with measurements made in the VGHP (Table 6).

Table 6 – *Measured Thermal Emittance of Aluminized Insulation*

Specimen Surface Temperature, °C	VGHP Measured Emittance	Spectrophotometric Reference Emittance	Difference (Measured - Reference)
-1.0	0.040	0.073	-0.033
20.2	0.038	0.074	-0.036

The temperature difference between the specimen (hot) surface and the calibrated cold-plate surface was 20 K.

Discussion

The agreement between the VGHP total hemispherical emittance measurements and the spectrophotometric values are of accuracy acceptable for many construction industry applications. The VGHP measurement uncertainty is higher than the spectrophotometric method. However, further refinements should lead to improved accuracy and it is a good alternative for materials that are not suitable for the spectrophotometric method.

The uncertainties of the measured values for temperature difference and the heat-flux both have a significant effect on the overall uncertainty of the measured emittance.

The emittance of the cold-plate has far less effect as long as the painted surface is well maintained. Examples of the estimated effect of each of these measured parameters are given for high emittance specimens (Table 7) and low emittance specimens (Table 8).

Table 7 – *Estimated Effect of Measured Parameters on the Uncertainty in Emittance for a Specimen of High Emittance (0.95)*

Measured Parameter	Estimated Uncertainty	Effect on Emittance Value	Emittance Uncertainty, %
Temperature difference	0.5 K	0.047	4.9
Heat-flux	2 %	0.021	2.2
Cold-plate emittance	0.005	0.006	0.6

Table 8 – *Estimated Effect of Measured Parameters on the Uncertainty in Emittance for a Specimen of Low Emittance (0.18)*

Measured Parameter	Estimated Uncertainty	Effect on Emittance Value	Emittance Uncertainty, %
Temperature difference	0.5 K	0.004	2.2
Heat-flux	2 %	0.004	2.2
Cold-plate emittance	0.005	negligible	0.1

The temperature drop is measured by a thermocouple taped to the specimen surface, with heat sink compound used to aid thermal contact, and another in embedded in a groove on the cold-plate surface. Future improvement in the performance of the VGHP may be achieved by alternative approaches to mounting the specimen thermocouple.

While the electrical power into the central heater of the guarded heater plate can be measured to about 0.03 %, the resulting net radiative heat flux between the specimen surface and the cold-plate, will be affected by the amount of additional heat gained or lost to the environment. This heat gain or loss will depend on the effectiveness of the lateral, auxiliary and edge guards, and will have a greater influence the further the surface temperature is from ambient.

Summary and Planned Developments

The NPL VGHP provides a versatile measurement facility for characterizing a wide range of insulation products. The thermal conductivity of a filler material used in evacuated insulation panels has been measured under vacuum conditions in an instrumented container. The values are in good agreement with those from other sources with similar filler materials. Future enhancements may include some form of control over the pressure within the chamber to allow determination of a relationship between thermal conductivity and pressure. It is also intended that the VGHP will make measurements on insulations in gases other than air and at elevated pressures.

The total hemispherical emittances of polymethylmethacrylate, a coated glass and a reflective insulation product have been measured with accuracy acceptable for many construction industry applications. Further work on evaluating the performance of the apparatus will allow a detailed uncertainty budget to be produced. Practical problems still need to be overcome to allow measurement of low-density insulations, as temperature gradients within the evacuated insulation can be much greater than across the evacuated gap.

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