Thermal Transmittance Property Evaluation of Insulation Systems

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ABSTRACT

The various methods used for evaluating the thermal transmittance of insulation systems are described. These include the guarded hot plate method, the heat flow meter method, the pipe insulation test method, and the methods for testing cold air duct sections and wall panels. In addition to the above steady-state methods, the operation of the transient thermal probe is discussed. The general literature on these measurement techniques is reviewed to identify sources which provide useful design and operating guidelines on such equipment. Some results obtained by the authors for dry and wet insulation slabs are also included. These have been measured using the heat flow meter method and the thermal probe.

INTRODUCTION

Since the oil price increase of 1973, there has been a growing interest in energy conservation, both in the domestic and the commercial areas of energy use. One of the most direct forms of energy conservation is the application of efficient thermal insulation. Good thermal insulants are relatively expensive and, therefore, careful sizing of the insulation and proper installation are of utmost importance. Poor installation usually leads to rapid degradation of the insulation and complete replacement is often warranted. Much work has been done on the design of insulation systems for application in temperate climates. The indoor temperatures in this case are maintained at comfort levels by heating, and insulation is used to prevent undue heat leaks to the outside ambience. In the case of tropical climates, indoor comfort is achieved by air-conditioning, and this is becoming increasingly common in large commercial buildings. The insulation materials used in chilled water pipes, cold air ducts and the walls of the building play an important part in the efficient use of air-conditioning in the building. The insulation in these situations operates under conditions which are different from those in temperate climates. In the case of cold air ducts and chilled water pipes, the outside of the insulation is subject to high ambient temperatures and high ambient relative humidities, which is common in the tropics. Also during heavy rain, the insulation may experience very moist conditions outside. The building materials are also subject to these changes in temperature and humidity. In cases where locally produced materials are used as insulations and building materials, there is a need for a careful assessment of the properties of these materials under changing weather conditions.

Most materials have some resistance to heat flow, but to be considered a thermal insulant, they must have a thermal conductivity which is less than about 1 W/m^2K [1]. Insulation materials usually have a porous structure which is produced by having either open air spaces, as in fiber glass, or closed air pockets, as in polystcrene and polyurethene. A detailed review of insulants and their properties is available in Probert and Giani [1]. The most important property of an insulant is its thermal conductivity, or the thermal resistance. However, several other properties which include mechanical strength, resistance to moisture absorption and transmission, thermal capacitance and density, resistance to fire and behaviour during a fire, health hazards posed by the material, and the cost are important in selecting a material as an effective thermal insulant. Because of their importance, the standards institutions, like the American Society for Testing and Materials (ASTM), have produced test standards for evaluating most of the foregoing aspects of the insulating material. Most manufacturers of insulations use these standards for quality control purposes.

The present paper is concerned mainly with standard testing and evaluation methods for the thermal conductivity and the thermal transmittance of the insulation system. The thermal conductivity is required by designers for the economic sizing of the insulations for various operating conditions [2, 3]. In the case of air-conditioning applications, this data is useful in designing the system to avoid condensation of vapour on the warm side of the insulation [4]. The evaluation of the thermal properties of insulations require some understanding of the heat transmission in fibrous and porous materials. Pelanne [5] uses experimental data to discuss the effectiveness of the various modes of heat flow in a fibrous medium. The main resistance to heat flow is by the open air spaces in the fibrous materials while the conduction paths along the fibers contribute very little. Thermal radiation transfer is important, and this is particularly so for low density porous materials. An understanding of the various components of heat flow in porous material is important in appreciating the various test standards for evaluating the thermal resistance of insulations. The conditions stipulated for determining the specimen thickness, the nature of the hot and cold surfaces, the preconditioning of the specimen and others are dictated by the nature of the heat transfer processes in the materials.

The measurement of the thermal resistance of an insulating material is straight forward in principle. However, accurate and reliable results can be obtained only if great care is taken during the design of the apparatus, and in calibrating the various measurement systems used. Due to these reasons, commercially available equipment for the measurement of thermal properties tends to be expensive. During the past several years, the authors have been developing equipment for the measurement of the thermal properties of insulations both in the laboratory, and under field conditions. Similarly, work is being done by other workers in laboratories in the ASEAN region [6]. The aim of the present report is to review the literature on the various aspects of the evaluation of the thermal properties of insulations. The experience of the authors in designing some of the equipment used for this purpose is also included. The general method adopted by the authors was to obtain the important transducers and measurement systems from manufacturers and to develop the complete apparatus by fabricating some of the hardware, like heaters, heat sinks and others, where it is possible to achieve the desired manufacturing precision.

The various test methods for different insulation arrangements will be discussed in turn, and this will be followed by a review of the relevant literature on each of the test methods. The paper is a summary of a more detailed report [7], which includes the literature on heat and moisture transfer in thermal insulation systems, in addition to the measurement and evaluation methods.

MEASUREMENT OF THERMAL PROPERTIES

Types of Measurements

The measurement of the thermal transmittance is one of the most important areas of activity in the field of thermal insulation. These measurements belong to different categories, and are performed in different organizations. The main types are: (a) quality control measurements, which are usually performed in a routine manner in manufacturing concerns; (b) highly accurate measurements, done by standards institutions like the National Bureau of Standards in the United States, for producing standard specimen; and (c) research and development related property evaluations, which are done either on new materials, or new operating conditions, to obtain a better understanding of the performance of the insulation system. The methods used for these measurements can be considered as absolute measurements when they are not based on comparisons with the thermal resistance of standard samples. Apparatuses for such measurements have to be designed according to strict guidelines to achieve satisfactory performance. The method of measurement also depends on the geometrical shape of the insulation system being evaluated. Flat slabs, which have either a square cross-section or a circular cross-section, are the most widely used shapes for thermal resistance measurements. When cylindrical pipe insulation sections are tested, a specially designed apparatus has to be used. The same is true for testing rectangular duct insulations, like those used in cold air ducts for air-conditioning. Building panels which are used in practice usually consist of composite walls, including the insulating layer. The thermal performance evaluation of such panels requires a special apparatus called the guarded hot box. Most of the test methods, which are recommended by organizations like the ASTM for insulation evaluation, rely on steady-state heat transfer across the specimen being tested. These methods are: (i) the guarded hot plate method, (ii) the heat flow meter method, (iii) the pipe insulations test method, (iv) the calibrated hot box for cooling-air duct sections, and (v) the guarded hot box for the performance of building assemblies. In addition to these steady-state apparatuses, a convenient transient technique can be used for local measurement of thermal conductivity. Thermal conductivity probes based on this concept are now available commercially.

In the following sections of the paper, each of the test methods mentioned previously will be described. The general literature on these methods, which is useful for designing such apparatuses and performing tests, will be reviewed.

The Guarded Hot Plate Method

The guarded hot plate method is a steady-state technique, which relies on Fourier's law of heat conduction, to deduce the thermal conductivity by observing the temperature gradient in a sample, when a known heat flux is applied. The apparatus is now available commercially, and samples of rectangular and cylindrical shapes can be tested. A schematic diagram of the guarded hot plate system is shown in Fig. 1. This equipment is similar to most of the other well designed equipment described in the literature. It consists essentially of a main heater which is surrounded by a guard heater. A small air gap, which is of the order of a few millimetres, is left between the two heaters. The most desirable sizes for these heaters and the gap are recommended in the various standards like the ASTM Standard C177 [30, 38]. The purpose of the guard heater is to ensure that the energy produced in the main heater is conducted in a direction normal to its surface. This is achieved by maintaining the mean temperature difference across the air gap at zero. The temperature difference is usually measured with a multi-junction thermopile. The energy supply to the main heater is determined by the operator and is maintained at a fixed value by a stable power supply. The electrical energy input to the guard heater is controlled either manually or in more recent equipment, automatically, using a controller whose output is based on the temperature difference across the gap. Two samples are placed between the main heater and the two heat sinks located above and below it. The heat sinks are usually liquid cooled, and are supplied with liquid from constant temperature baths. For low temperature measurements, these baths have to supply refrigerated liquid which is either brine or glycol. The heat sinks are constructed as tube-plate heat exchangers. For precise control of the temperature of the heat sink surfaces two additional electrical heaters may be located adjacent to the heat sink surfaces with a thin insulating

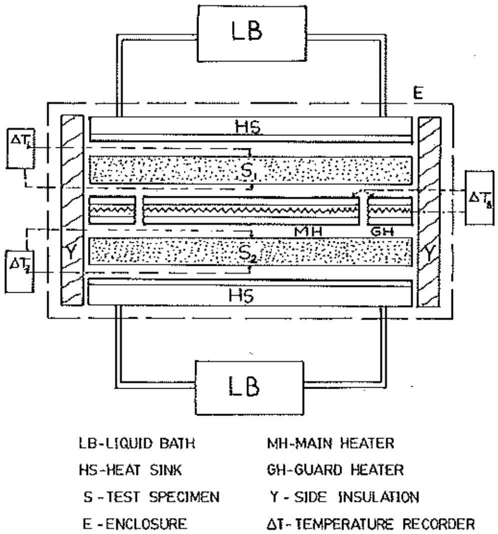


Fig. 1 Schematic diagram of the guarded hot plate apparatus.

layer separating it from the heat sink surface. This layer of insulation has a tendency to dampen temperature fluctuations, thus making the control of the surface temperatures much easier. Thermocouples are located in grooves made on the main heater surface and the heat sink heater surfaces. The grooves are filled with conducting cement and a smooth bearing surface is maintained. The thickness of the upper and lower insulation test samples are measured after they are positioned in the equipment. The various components are usually located by the holes in them which pass through a set of vertical threaded rods. Care has to be exercised when soft samples like fibre glass are tested to ensure that the correct pressure is applied on the samples, and the thickness of the sample is not altered by the load applied on it. The voltage and current supply to the main heater are measured carefully to obtain the heat input to the samples. The following equation, which is the steady-state solution to Fourier's equations, gives the thermal conductivity as

$$K_{eff} = \frac{VI}{A} \left[\frac{1}{\left(\frac{\Delta T}{d}\right)_1 + \left(\frac{\Delta T}{d}\right)_2} \right] \quad (1)$$

where VI = main heater power input
A = area of the main heater surface
ΔT = temperature difference across the sample
d = sample thickness
1,2 = represent the two samples

Several measuring instruments based on the guarded hot plate principle have been described in the literature [10, 11, 14, 21, 22, 23, 24, 25]. Although the principle of operation of this equipment is simple, its design, construction and operation require considerable experience as evident from the above references.

The most important aspect of the design and sizing of these apparatuses has been the various errors, which are likely to occur in the measurements, that make the applicability of equation (1) doubtful. These are: (a) the heat losses from the sides of the sample due to convection, (b) the error due to the temperature unbalance across the air gap, (c) the two-dimensional heat conduction effects in the sample, (d) errors due to the thermal contact resistance between the surfaces of the sample and the heaters, and (e) errors due to deviation from steady-state. Analyses of these errors in guarded hot plate systems have been made by Dusinberre [8], Somers and Cyphers [9], Woodside [12, 13], Donaldson [17, 18], Pratt [19] and Rennex [41].

Somers and Cyphers [9] derived an analytical solution based on the two-dimensional heat conduction equation which could be used to obtain correction factors for the edge heat loss error. More recently, Troussart [34] performed a finite element analysis of the heat transfer in the guarded hot plate apparatus to obtain the effects of end losses. Such heat conduction studies are useful in providing guidelines for the sizing of the various important components of the equipment. The time taken to reach steady-conditions in the guarded hot plate is also an important aspect of the design. This has been studied by Shirtliffe and Orr [20], and Shirtliffe [28]. The time constant of the system depends on several conditions which include the thermal capacitances of the heaters and the heat sinks and the thermal properties of the sample. The temperature stability of the immediate environment of the apparatus and the rates of stray heat losses will also affect the transient behaviour. For fibrous insulating materials in a guarded hot plate system, it may sometimes take up to ten hours for steady-conditions to be reached. Shirtliffe [28] obtained analytically the optimum operating conditions needed to achieve a short setting time. Analysis of the errors in a guarded hot plate is summarized in the recent papers by Rennex [40, 41].

The control of the guard heater to achieve a zero temperature drop across the air gap separating it from the main heater is an area of difficulty in the measurement. In the simpler equipment, this is done manually but in the more sophisticated commercial units [32], a proportional controller, with temperature error feed-back is used to control the guard heater. The errors in the results which may be caused by the temperature unbalance in the guarded hot plate is given in reference [12] and the automatic control of guarded hot plate apparatus is discussed by De Ponte and Frivik [24].

Efforts have been made to improve and simplify the design of guarded hot plate systems [27]. Some of these modifications are given by Zabrawski [14] and Gilbo [15]. Hager [16] considers a design where the heater is made of a very thin material which has a poor thermal conductivity, and whose lateral dimensions are large compared to the thickness. Such a heater was thought to have a short heating time and was expected to produce a nearly one-dimensional heat flux without the help of a guard heater. This was not completely successful but it did simplify the design of equipment considerably. A steady-state thermal conductivity measuring technique based on a line-heat source is reported in reference [29]. For testing samples which are cylindrical in shape, like pipe insulation sections, the guarded hot plate concept is used with the guarded main heater in a cylindrical form. Equipment of this type whose design and construction conform with standards recommended by ASTM are now available commercially. However, in general, they tend to be expensive and usually they incorporate features which are required only for special measurements. The design consideration for such apparatus will be given later in the paper. An apparatus of this type is currently being built at the Department of Mechanical Engineering of the National University of Singapore.

Heat Flow Meter Method

A thermal conductivity measuring technique which was accepted by standards institutions much later than the guarded hot plate, is the heat flow meter method [37]. Several instruments based on this principle are now available commercially [26, 31] and guidelines for their design and sizing are given in reference [37]. The apparatus developed by the present authors at the Mechanical Engineering Department is shown schematicallly in Fig. 2a. The heat flux transducer replaces the guarded hot plate, as the heat flow meter. A typical heat flow meter consists of a thermopile formed with the junctions located on either side of a thin layer of material of low thermal conductivity. The heat flow meter measures the temperature difference across this thermopile and it may be calibrated to read the heat flux, when the material conductivity and thickness are assumed constant.

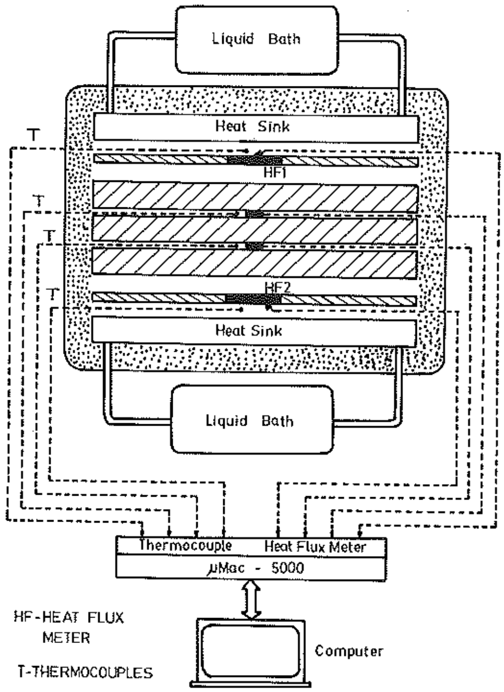


Fig. 2a Schematic diagram of the heat flow meter apparatus.

The design of the experimental apparatus developed by the present authors for the measurement of the thermal properties of insulations followed the guidelines in the ASTM standard [37]. Several modifications were made to the basic heat flow meter apparatus to obtain detailed information concerning the moisture migration processs in wet insulations. The test insulation slab is placed between the smooth faces of the hot and cold plates. These plates are essentially fin-tube heat exchangers built within thick brass plates. The heat exchangers are supplied with hot and cold fluid from two constant temperature water baths, whose temperatures are controlled automatically with an accuracy of 0.1 °C.

Sandwiched between the faces of the test insulation specimen and the heat sink surfaces are two heat flux measuring pads. These include two heat flow meters which are located within a square cut out in a sheet of rubber with nominally the same thickness as the heat flow meter. The rubber sheet acts as a "side guard" to reduce the lateral heat flow into the heat flow meter. A thin sheet of rubber is placed on either side of the heat flow meter to obtain good thermal contact with the heat sink surfaces and the insulation specimen. This helps to reduce fluctuations in the heat flow meter output voltage which is sensitive to the thermal contact resistance on its surfaces. The use of two "measuring pads" helps to determine the magnitude of the side heat losses and also the dynamic changes in the heat flow resulting from vapour migration and condensation when wet insulation specimens are tested. Thermocouples are located on each face of the measuring pads. The apparatus in this form is used to measure the thermal resistance and the thermal conductivity of dry insulations. The two hot and cold plates are carried on cross bars. These have holes guided through four vertical threaded rods. This arrangement enables the adjustment to accomodate slabs of different thickness and also control the pressure applied to the insulation specimen. The entire assembly is surrounded with thick blocks of insulation which helps to achieve stable conditions rapidly.

When wet insulation specimens are tested, they are cut into three thin layers and two small heat flow meters are placed within the slab to obtain details of the heat flux variation through the slab. Thermocouples are also placed close to the heat flow meters to determine the variation of the temperature distribution within the insulation slab.

The various important dimensions of the apparatus, the properties of the surface, and the accuracy and size of thermocouples are based on the guidelines provided in ASTM Standard, C518, for the design of the steady-state heat flow meter apparatus. The output voltages from the four heat flow meters and the various thermocouples are recorded through the appropriate interfaces in the μ-mac 5000 data acquisition and control system from Analog Devices Corporation. The experimental data is processed in an IBM PC/AT computer which is interfaced to the μ-mac system. This automatic data acquisition arrangement is particularly useful in dynamic measurements which usually take experimental times of the order of days. Coupled to the necessary software, the system produces as output, the various plots of the variation of the heat flux, the temperature and the effective thermal conductivity of the test insulation specimen.

The test procedure involved three important phases. These are: (a) calibration of the apparatus, (b) measurement of the thermal conductivity of dry specimen and (c) the measurement of the dynamic variation of the thermal properties in moist insulation specimen. In the calibration experiments the thermocouples were separately calibrated using a temperature calibration set-up. The regression curve obtained was incorporated into the data analysis software used subsequently. The μ-mac system was calibrated to operate at the point which gives the best linearity between the transducer input voltage and the μ-mac output voltage. The temperature correction curves of the heat flow meters which were supplied by the manufacturer were also included in the data analysis software. The complete apparatus including the data acquisition system was calibrated using a standard insulation test specimen from the National Bureau of Standards [35, 39], of USA. The thermal resistance measured in these tests were useful in establishing the accuracy of the calibration curve for the heat flow meters.

The thermal conductivity, k, is calculated using Fourier's Law in the one-dimensional form:

$$k = E.f. \left(\frac{d}{\Delta T}\right) \qquad (2)$$

where E = the steady output of the heat flow meter
f = the calibration factor of the heat flow meter
d = the thickness of sample
ΔT = the temperature difference.

The installation of the heat flow transducer on a surface and its proper calibration are very important aspects in obtaining accurate and reliable values for the thermal conductivity. Some of these aspects are discussed in references [33, 36, 37, 42]. General guidelines on the design of heat flow meter based equipment are given by Bomberg and Solvason [43]. Larson and Corneliussen [44], and Larson

[45] used the heat flow meter method for the field testing of roof systems using spray-applied insulation.

Test methods based on the heat flow have a shorter response time compared to the guarded hot plate method. They are less expensive to implement than the guarded hot plate but the analysis of the errors involved [42], and the effect of the changes in the calibration of the sensor [43] must be given due consideration, when interpreting the results obtained with the heat flow meter method. Larson [45] shows that the calibration constant of a sensor increases with the thickness of the standard sample used and also the mean temperature of the sample.

Some Test Results

A series of tests were undertaken to measure the thermal conductivity and the thermal resistance of fibreglass slabs. The slabs were subsequently used to study the effect of water vapour migration and condensation on the thermal properties of insulation. In wet tests, water is sprayed on to one of surface of the test specimen which is assembled in three layers with heat flow meters and thermocouples sandwiched in interfaces between the layers. The weight of water added is determined by measuring the increase in weight of the test specimen. The water is sprayed with the help of an atomizer which ensures a reasonably uniform spread of the water on the surface of the insulation. The wet specimen is then placed in a plastic bag and it is sealed to prevent the leakage of moisture to the surroundings. The preparation of this wet specimen required considerable care. Experience of the method of preparation was gained by performing a series of exploratory tests until consistent results were obtained. The heat flow meter apparatus is allowed to reach steady conditions at the pre-set hot and cold bath temperatures, with a "dummy" specimen in position. At the start of the proper wet sample test, the dummy specimen is replaced with the wet test specimen. The output of the heat flow meters and thermocouples are continuously monitored until steady conditions are attained in the test specimen.

In a series of separate tests, the rate of condensation of moisture on the cold side of the specimen was measured by removing the test sample from the apparatus at different times. After the measurement of the weight of the test specimen, that particular test was terminated and a new test was started with the same quantity of water on the wet face. This test was similarly terminated at a later time. By this procedure it was possible to obtain the history of the vapour condensation process for a given set of conditions at the hot and cold plates and for a given initial moisture content at the hot face. Attempts to remove the test sample from the apparatus and thus measure the condensation rate continuously did not prove satisfactory due to changes which occur during the measurement process.

The heat flow meter apparatus was first calibrated using a standard insulation sample from the National Bureau of Standards. The thermal conductivity of the sample was measured over a range of temperatures using the manufacturer's calibration curve of the heat flow meter to convert its output to units of heat flux.

The results of these tests are shown in Fig. 2b. It is seen that the thermal conductivity of the sample as supplied by the NBS is about 6 per cent higher than the measured thermal conductivity. This data was then used to recalibrate the heat flow meters to obtain agreement with the standard thermal conductivity of the sample. The same procedure was used to check the validity of the manufacturer's calibration curve for all the heat flow meters used in the present experimental set-up.

The condensation of moisture in insulation systems and its effect on the thermal properties is an important problem, as mentioned previously. A comprehensive test programme to study vapour diffusion, the subsequent condensation and its effect on the heat flow and the thermal conductivity was, therefore, undertaken. The results of these tests are summarized in Tables 1 and 2. A complete

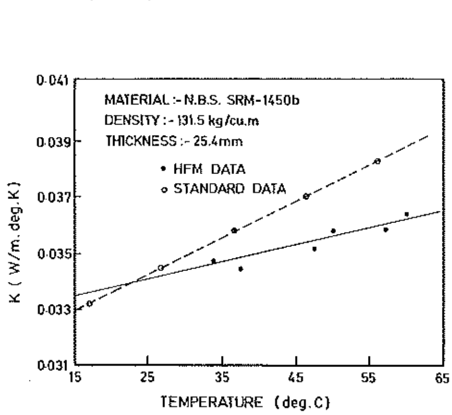


Fig. 2b Calibration curve for fibreglass.

Table 1 Effective thermal conductivity of fibreglass by the heat flow meter method.

Hot plate temp °C	Cold plate temp °C	Moisture content per cent by volume	Effective thermal conductivity W/m°C
42.8	26.5	dry	0.0328
39.2	21.3	dry	0.033
32.7	22.5	1.766	0.123
33.5	22.5	0.707	0.124
35.6	22.8	1.573	0.122

Table 2 Comparison of measured and estimated heat flux for wet specimen.

Moisture per cent by volume	Insulation Surface temp. °C		Conduction heat flux	Latent heat flux	Total flux	Measured heat flux
	hot	cold	q_D, $\frac{W}{m^2}$	q_L, $\frac{W}{m^2}$	$q_t = q_D + q_L$	q_m, $\frac{W}{m^2}$
0.707	31.8	20.8	9.74	23.85	33.59	33.69
0.500	31.8	20.8	9.74	23.85	33.59	33.67
0.250	31.9	20.8	9.82	23.85	33.67	33.42
0.707	39.5	13.1	23.01	57.76	80.77	79.80
0.707	47.4	5.0	37.52	106.51	144.03	140.26

discussion of the results is beyond the scope of the present review paper and these are available in reference [85].

The Transient Probe Method

The guarded hot plate apparatus and the heat flow meter method are steady-state techniques for the measurement of thermal conductivity. The transient hot wire or the transient probe method, as it is often called commercially, is an unsteady-state method which requires a much shorter time to perform a measurement. The transient hot wire consists of a thin heating wire which is stretched between two supports as shown in Fig. 3. A thermocouple is attached to the mid-point of the wire and

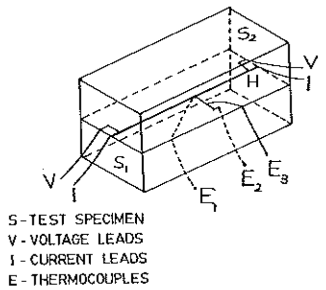


Fig. 3 Schematic diagram of the transient hot wire apparatus.

current and potential leads are placed at the two-ends of the wire. The material of the wire can be nichrome or constantan but usually a material of low thermal conductivity is preferred. The heating wire is placed between two layers of the insulating material whose thermal conductivity is to be measured. The entire set-up is placed in a chamber whose temperature is controlled to the value needed in the test sample for the particular measurement. When conditions are steady, and electric current, which is sufficient to raise the temperature of the surface of the wire by about 5 to 10°C when the system has reached a steady-state, is passed through the wire. The transient variation of the temperature of wire surface, as indicated by the thermocouple, is recorded continuously. The shape of this temperature history can be used to deduce the thermal conductivity of the medium surrounding the wire.

The thermal probe is made of a thin wire with high thermal conductivity while the thermal conductivity of the test medium, which is an insulator in the present case, is very low. This justifies the application of the lump capacitance approximation to the probe region. Also, the test sample can be treated as an infinite medium. With these assumptions, the solution to the wire surface temperature is obtained in terms of the various material properties and dimensions. The general form of this solution is shown in Fig. 4. It can be shown that for larger values of time, the solution takes the asymptotic form given by

$$T(t) - T_o = \frac{Q}{4\pi k}[\mathrm{Ln}\, t + B] \tag{3}$$

where T_o is the initial temperature, $T(t)$ is the temperature of probe surface at time t, Q is the rate of heat input per unit length and B is a constant.

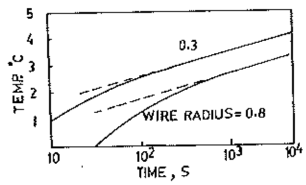
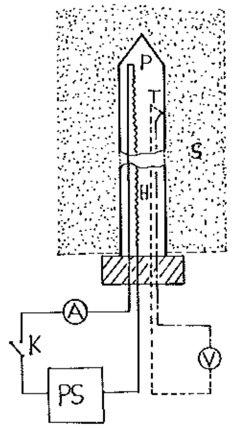


Fig. 4 Temperature variation of wire surface.

This shows a linear variation between the temperature rise and Ln(t). In most probe applications, equation (3) is used to obtain the thermal conductivity, k of the test medium from the measured surface temperature variation. However, it is seen that it requires an accurate knowledge of the heat input Q per metre length of the probe. The thermal probe version of the equipment is shown in Fig. 5.

The basic heat transfer analysis of the probe is available in Craslaw and Jaeger [47] and this has



P - BODY OF PROBE | T - TEMPERATURE SENSOR
H - HEATING WIRE | S - TEST SPECIMEN
PS - POWER SUPPLY | K - SWITCH
A - AMMETER | V - TEMPERATURE RECORDER

Fig. 5 Thermal conductivity probe.

been the starting point for the derivation of several important extensions and corrections for the thermal probe analysis. This method was applied to liquids by Van der Held and Van Drunen [48], and the former author later studied the effects of radiation and boundary conditions [53, 56]. Further extensions of the measurements are given in reference [57]. The use of the transient method for thermal conductivity measurements is reported by Hooper and Lepper [49, 50], and also by D'Eustachio and Schreiner [51]. DeVries [52] applied the same technique for measurements related to the thermal properties of soils. Further development and application of the thermal probe are reported in references [54, 55, 60]. Blackwell [58, 59, 61] published a series of papers on the application of the transient method to thermal insulations and considered improvements for the analysis of the heat transfer in the probe. Joy [62] obtained the thermal conductivity of moist materials using the transient method. Further work relating to measurements in soils is given in references [63, 64] and [67]. Woodside [65, 66] reports data obtained with the thermal probe applied to wet and dry materials. The use of the transient method has found application in several fields and many practical measurement considerations have lead to further developments [68, 69, 70, 73]. A detailed theoretical study of the heat transfer problem in the transient hot wire was presented by Healy, de Groot and Kestin [71]. Several correction terms accounting for the various assumptions made are also given in the paper by Kestin and Wakeham [74]. Measurements under high pressure are reported in reference [72] and the application of the probe to high temperature measurements in ceramics is presented by Morrow [75]. Kay et al. [76] report measurements in frozen soils while Batty et al. [80] have applied the hot wire techniques for measurements in moist materials. A detailed numerical study, with experimental results, is presented in a recent paper by Masaaki and Manabu [78]. A full-cycle probe method using both the temperature variation during the heating and the subsequent cooling period are considered by Mcgraw [79]. An assessment of the thermal probe method for measurements in wet and dry insulation materials was made in the studies reported by Batty et al. [77] and Wijeysundera et al. [81]. From these papers, it is evident that the transient hot wire method has proved to be a reliable and useful technique in the measurement of thermal conductivity. However, it has still not been accepted as a standardized method by standards institutions, such as the ASTM, for the measurement of the thermal conductivity of insulation systems.

The probe version of the apparatus (Fig. 5), which is now available commercially, has the shape of a needle and it can be introduced into a large insulation layer to obtain local values of the thermal conductivity. A comparison of the use of the heat flow meter apparatus and the thermal conductivity probe for wet and dry fiberglass was made by Wijeysundera et al. [81]. For dry materials, the thermal conductivity given by the two systems agree closely. However, for wet specimens of insulations, the probe gives only a local value which depends on the distribution of the moisture in the specimen, while the heat flow meter apparatus gives the overall average value of the thermal conductivity. The results by the present authors using the thermal probe are summarized in Table 3.

Table 3 Effective thermal conductivity of fiberglass by the thermal probe.

Moisture content per cent by volume	Mean temp, °C	Heating Current, amp	Effective Thermal conductivity, W/m°C
dry	31.5	0.0960	0.0310
dry	31.3	0.1000	0.0313
0.540	29.5	0.1084	0.0557
1.763	28.7	0.1151	0.0739
2.188	30.0	0.1139	0.0870
3.957	29.0	0.1249	0.0843
6.330	29.0	0.1269	0.9880

Horizontal Pipe Insulation Tester

The horizontal pipe insulation tester is a steady-state apparatus for evaluating the thermal resistance of insulations applied to pipe sections. It is based on the same principle as the guarded hot plate method, except that the hot and cold surfaces are now cylindrical in shape. The use of this apparatus is less widespread than the flat slab thermal conductivity apparatus. A schematic diagram illustrating the general principle of operation is shown in Fig. 6a. The cylindrical test insulation specimen is applied to the test pipe which is heated by a coaxial heater pipe. The outer surface of the

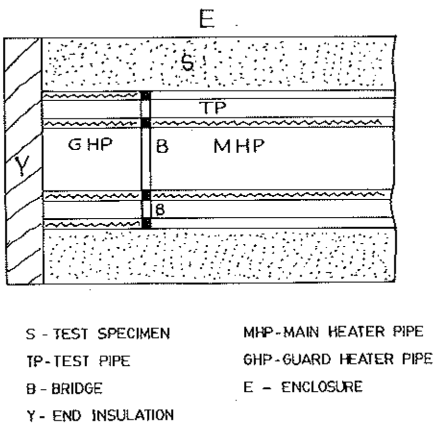
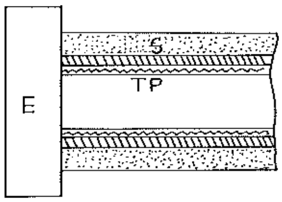


Fig. 6a Guarded-end pipe insulation test apparatus.

insulation is maintained at a constant temperature by locating the apparatus in a constant temperature chamber. It is also possible to have a sheath on the outer surface which is either heated or cooled to the desired temperature. Guidelines for the design of this apparatus are available in the ASTM standard C355 [82].

Two alternative arrangements are possible for reducing the heat losses from the two ends of the pipe. In the first method shown in Fig. 6a, a cylindrical guard heater is located on an extension of the heater pipe and the test pipe. The extensions are fixed to the main pipe through bridges placed across an air gap between the main heater and the guard heater. The mean temperature difference between the test section and the guard section is measured by means of a differential thermopile, with the alternate junctions located on the two sides of the separating air gap. Several alternative arrangements of the guard are described in reference [82], and some of these require the use of double guards or end correction factors to account for end heat losses.

The heat losses from the ends of the test pipe may also be accounted for by using a calibrated/calculated end arrangement, as shown in Fig. 6b. In the calculated end design, the two ends of the test pipe are insulated by materials of known thermal conductivity. Additional thermocouples are placed in the end insulation, which provide the data needed to compute the heat losses through the ends. These calculated quantities are used as correction factors when computing the heat input to the test pipe. Alternatively, the heat losses from the ends of the pipe are obtained by calibrating the end insulation in separate tests using a calibration heater. In this case, the two end insulations enclose the short calibration heater pipe completely and, therefore, the end losses are equal to the heat input to the calibration heater. This heater has the same design as the end heaters of the test pipe. The design and operating parameters of the test set-up which need attention are: the size and location of thermocouples on the test pipe and the outside surface of the insulation, the design of the calibrator heater pipe or the guard-ends, the accuracy of the temperature and power measuring systems, the temperature stability and well emissivity of the enclosure.



TP - TEST PIPE S - TEST SPECIMEN
E – END INSULATION

Fig. 6b Calculated/calibrated-end pipe insulation test apparatus.

The thermal resistance of the pipe insulation is obtained by applying Fourier's law of heat conduction in the cylindrical one-dimensional form:

$$R_p = \frac{L}{Q}(T_i - T_o) \tag{4}$$

where T_i = temperature of pipe surface
T_o = temperature of insulation outside surface
Q = rate of heat flow
L = length of the test section.

The heat input Q, is computed by applying the end loss correction factors to the electrical energy input to the test section heater.

Calibrated Hot Box for Cold Air Ducts

This test method is intended primarily for measuring the steady-state thermal transmittance of insulated cold air ducts. However, the principle of the method may be adopted for testing insulations applied to chilled water pipes. Fig. 7 shows a schematic diagram of the section of the test apparatus. The calibrated hot box is installed at a convenient section of a long cold air duct. The duct is connected to a cold air supply system which is equipped with controls to supply cold air at a steady rate under constant temperature conditions. The purpose of the test is to determine steady-state heat gain through the insulation applied to the duct when the outside ambience of the insulation is maintained at a constant higher temperature. The constant temperature is maintained by the calibrated box which is installed around the duct with air tight end surfaces to prevent air leakage into the box volume. An annular air duct supplies constant temperature air to the calibrated box. This duct is equipped with a heater and a fan and two air diffusers are located at the points where the warm air enters and leaves the calibrated hot box. The outside of the annular duct is surrounded by insulation and the whole system is located in a room, which acts as a guard to limit heat transfer through the walls of the box. The rate of heat transfer from the box to the room is obtained by separate calibration tests and corrections derived from such tests are applied to the main test data.

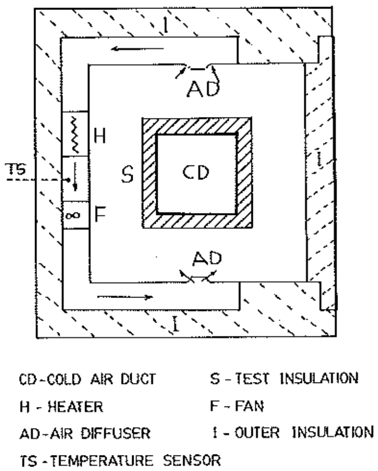


Fig. 7 Calibrated hot box for cold air duct insulation testing.

The general guidelines for designing the calibrated hot box apparatus are given in reference [83]. This ASTM standard gives important limits to the various parameters involved in the test and the accuracy of the instruments to be used. The thermal transmittance, U is obtained from the energy balance as

$$U = \frac{Q}{A\,(T_a - T_i)} \tag{5}$$

where Q = rate of heat flow into the cold air through the insulation
T_a = temperature of the air in the calibrated box
T_i = temperature of the cold ducted air
A = area of heat flow at the inside of the duct.

The rate of heat flow to the duct is obtained by subtracting the heat losses from the calibrated box to the room. Therefore

$$Q = Q_{input} - Q_{losses} \tag{6}$$

The details of the correction terms and the calibration procedure are given in reference [83]. The recommendations given in the ASTM standard are useful in designing test systems for research applications involving duct and pipe thermal insulations. The design and operating parameters of the test set-up which need careful consideration are: the size and shape of the metering box, the conductance and surface emissivity of the walls of the metering box, the accuracy of the temperature and power measuring equipment, size and location of the thermocouples, and the calibration procedure to obtain the box heat loss factor.

The Guarded Hot Box Method

The thermal transmittance and the thermal conductivity of flat slabs can be determined accurately by using methods such as the guarded hot plate method or the heat flow meter method, as described in the foregoing sections. However, some of the panels or walls used in buildings may consist of multiple layers of materials, whose thermal performance has to be determined under conditions close to those in real operation. The guarded hot box method [84] is used for testing flat panels and wall sections when the ambience on either side of the test specimen is maintained at steady conditions. Fig. 8 shows a schematic diagram of the guarded hot box through a vertical section. One surface of the test panel forms the side of the cold box while the other surface has a guard box bearing on it. Enclosed

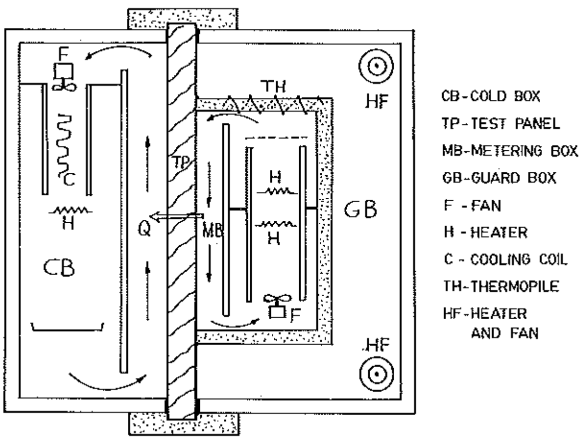


Fig. 8 Guarded hot box for testing insulation panels.

inside the guard box is the metering box, which provides the metered heat input to the system through a set of electrical resistance heaters. The fan in the metering box provides a uniform ambience on one face of the test panel by circulating the air. The guard box is equipped with a set of heaters and fans which maintain the annular space between the two boxes at a temperature which is close to the temperature of the air in the metering box. This would minimize the heat loss from the metering box to the guard box. The cold box, which is heavily insulated on the outside, has a refrigerating coil to control the temperature of the air inside it. The circulation of the cold air helps to maintain a constant temperature ambience on the other side of the test panel. When the temperatures of hot and cold boxes are adjusted, care should be taken to ensure that condensation does not occur on the warm surface because moisture ingress would affect the results obtained during a test. Ideally zero temperature difference should be maintained across the walls of the metering box. The temperature difference is monitored with a multi-junction thermopile, the junctions of which are applied to the inside and outside surfaces of the metering box walls. The thermopile and the walls function as a heat flow meter, which can be calibrated by using a test panel of known thermal transmittance. Thus,

$$Q + C\,\Delta E = AU\,(T_1 - T_2) \tag{7}$$

where
ΔE = the emf of the thermal
C = the thermopile constant
A = heat transfer area of the test panel
U = thermal transmittance of the test panel
T_1, T_2 = temperatures in the hot and cold boxes
Q = steady power input to the metering box.

The heat transfer across the wall between the metering and guard boxes must be less than one per cent of the energy input to the metering box according to reference [84]. When a panel is tested, equation (7) can be used to calculate the unknown U-value from the measured steady-state values of the other parameters.

CONCLUSION

Thermal insulation is an important aspect of energy conservation. A knowledge of the thermal transmittance is required for the economic sizing of insulations and as an input to energy analysis of buildings. Insulations operating in warm humid climates pose special problems when one of their surfaces is at a low temperature, as in the case of cold air ducts and chilled water pipes. There is the possibility of condensation of moisture on the warm surface, which must be avoided by correctly sizing the insulation. The methods used for the measurement of thermal transmittance depends on the shape of the specimen and its application in practice. The guarded hot plate apparatus and the heat flow meter apparatus are used with flat specimen. The guarded heater concept is also used for testing cylindrical pipe insulation sections. These are steady-state methods which involve long testing times. The transient thermal probe can be used for the rapid measurement of the thermal conductivity. For testing the thermal performance of cold air duct insulations, a calibrated hot box method can be used, while building panels require the use of the guarded hot box method. The ASTM Standards provide very useful guidelines based on experience for the design and operation of thermal property evaluation systems. Also useful for this purpose are the recommendations made in the literature on thermal insulation.

ACKNOWLEDGES

The authors acknowledge with gratitude a grant awarded under the ASEAN-Australian Economic Cooperation Programme in support of the work on thermal insulation. The interest of Dr. S.K. Chou is especially appreciated.

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