GUARDED HOT PLATE AND HEAT FLOW METER METHODOLOGY

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Foreword

The papers in this publication, *Guarded Hot Plate and Heat Flow Meter Methodology*, were presented at a symposium held in Quebec, Canada, 8, 9 October 1982. The symposium was sponsored by ASTM Committee C-16 on Thermal Insulation and the National Research Council of Canada. C. J. Shirtliffe, National Research Council of Canada, and R. P. Tye, Dynatech R/D Company, are editors of this publication.

Related ASTM Publications

Thermal Insulation, Materials, and Systems for Energy Conservation in the '80s, STP 789 (1983), 04-789000-10

Thermal Insulation Performance, STP 718 (1980), 04-718000-10

Thermal Transmission Measurements of Insulation, STP 660 (1979), 04-660000-10

Thermal Insulations in the Petrochemical Industry, STP 581 (1975), 04-581000-10

Heat Transmission Measurements in Thermal Insulations, STP 544 (1974), 04-544000-10

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

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Introduction

ASTM Committee C16 on Thermal Insulations will be celebrating its golden anniversary in 1988. During the early days of its establishment over forty years ago the membership realized the significance and importance of the need to develop a reliable test method to measure the thermal performance of the materials and systems for which they were responsible. Much attention was paid to this subject, and, as a result of their early efforts, ASTM C 177 describing and utilizing the guarded hot plate method was published in 1945. This quickly became recognized and accepted as the fundamental absolute technique for measuring the thermal conductivity of thermal insulations and materials of low thermal conductivity. Many countries subsequently produced similar types of test method documents based on the technique.

During the following two decades there were significant developments of newer types of thermal insulations including fibrous glass and cellular plastics. In addition, new applications and uses of thermal insulation combined with increased use, particularly in buildings, produced a significant growth in the volume of insulation being manufactured and used. There was corresponding increase in the need for the measurements of properties of these materials and especially the thermal performance.

It became obvious however, that there was now a requirement for a method of measurement of thermal conductivity which was both more rapid and less complex than that utilizing the guarded hot plate, particularly for use during the manufacturing process. During this era several organizations had started working with a heat flux transducer calibrated within a hot and cold plate system with a reference material of known thermal properties. Their experience resulted first in a tentative test method in 1962 and ultimately in 1964 with ASTM C 518 the Heat Flow Meter Method. This again became accepted worldwide as the prime secondary method for measuring thermal conductivity of thermal insulations.

The first documents were, in general, directed towards evaluation of such materials at or near room temperature. Their contents were based totally on the expertise and experience of those few careful and dedicated experimental workers who had the foresight to become members of the T-6 Subcommittee of C16. This was the forerunner of the present C16.30 Subcommittee on Thermal Measurements, the body which organized the present meeting. However, as time progressed, the requirements for measurements at both elevated and cryogenic temperatures became more necessary. Thus, in 1963 the first major revision of C 177 was undertaken to reflect this need with a further more detailed revision taking place in 1971. In 1970, the C 518 method was also revised to reflect the additional knowledge gained in using the technique since it was first adopted. As a result of these revisions it was believed then that both methods reflected the state of the art and provided the means to obtain reliable results on the materials for which they were suitable.

However, as we are all aware, the world energy crisis of the early seventies provided a significant stimulus to the concept of energy conservations both for building and industrial applications. As a result, more insulation was prescribed, thicknesses of use increased, many more people became involved in measurement both in the laboratory and production areas, more and larger equipment, including commercial models, were being developed and used, and regulatory bodies became involved to mandate and regulate performance requirements. Each of these factors imposed new burdens on the measurement community.

It quickly became apparent that heat transmission characteristics particularly radiation and to a lesser extent convection imposed a need for more stringent test criteria. Heat transfer phenomena were complex through a media where solid conduction was not the prime mode of heat transmission. The old simple definition of thermal insulation having a thermal conductivity was abandoned in favor of the more correct individually measured thermal resistance or thermal conductance concept. In 1976, both C 177 and C 518 documents were revised radically in their philosophy to reflect the true requirements of the thermal insulation community.

During the seventies, the C16.30 Thermal Measurements Subcommittee took the world lead in this area by organizing three symposia. These were directed towards general and specific understanding of heat transmission phenomena in insulations and their measurement. Position Papers were developed by the Subcommittee to address the specific areas of measurement philosophy and the need for reference materials and transfer standards for ensuring good measurements. International participation was sought and encouraged. This stimulated significant cooperative efforts between North America and European workers, and overseas membership of the subcommittee grew. Members of the Subcommittee actively participated in the formation in 1976 of the ISO TC163 Committee on Thermal Insulations and in its subsequent work, particularly on the Subcommittee SCI Test Method Group. As a result of these cooperative efforts truly satisfactory comprehensive guarded hot plate and heat flow meter test method documents have been developed and are in the promulgation stage.

During the past decade or so there has been considerable additional worldwide efforts expended in the area of measurement of thermal performance of insulations by these two recognized methods. Efforts have been directed toward better analysis of the methods in order to devise improved means of attainment of one-dimensional heat flow or to obtain more precise corrections. In addition, great improvements have been made in apparatus design and operation while newer concepts have been also developed. There was a need to bring these experiences together especially as C16.30 in the process of undertaking further revisions of the documents to reflect the newer information.

The Symposium was organized, therefore, to provide a forum for an exchange of these ideas and experiences by the group of international workers and to document the current state of the art specifically involved with these two methods. The ultimate goal being to enable better measurements to be made on all types of insulations at all temperatures and conditions with comparable reliability whoever is involved and whichever of these two techniques are utilized.

The international group of papers covers a wide variety of subjects from basic analyses, apparatus design and development, and instrumentation details to applications and use. These papers should provide the required stimulus to achieve the desired goal.

The Chairmen wish to thank all of the authors, session chairmen, and many reviewers for their efforts in making the Symposium a success. Due to illness our good friend and colleague Dr. Karl Heinz Bode was unable to present his paper but with the approval of Pergammon Press we have included an important contribution of his which is directly relevant to this subject. Finally, we wish to thank The National Research Council of Canada for its financial support and particularly Ben Stafford of the Division of Building Research for his stalwart local organizational efforts.

C. J. Shirtliffe

Division of Building Research, National Research Council, Canada K1A 0R6; editor.

R. P. Tye

Thermatest Department, Dynatech R/D Company, Cambridge, MA 02139; editor.

Apparatus Analyses and Error Analyses

Louis R. Troussart[1]

Analysis of Errors in Guarded Hot Plate Measurements as Compiled by the Finite Element Method

REFERENCE: Troussart, L. R., **"Analysis of Errors in Guarded Hot Plate Measurements as Compiled by the Finite Element Method,"** *Guarded Hot Plate and Heat Flow Meter Methodology, ASTM STP 879,* C. J. Shirtliffe and R. P. Tye, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 7-28.

ABSTRACT: The object of this research was to study the effect of various design parameters of a guarded hot plate (GHP) on the error of measurement due to gap unbalance without having to resort to simplifying assumptions as has been the case in existing analytical studies. A better knowledge of this effect could lead to better national standards. It could explain some of the discrepancies often found between the results of round-robin tests. The method used is the finite element (FE) method applied to an axisymmetric GHP. The latter choice is justified by the fine discretization of the domain which is achievable without requiring a huge computer memory. This feature allows us to study the influence of thermopile wires crossing the gap.

The results show that for a given gap unbalance, one is not free to arbitrarily choose the thermopile wire diameter, nor the temperature drop across a given specimen thickness, if one seeks accurate measurements. One cannot achieve precise measurements with one apparatus and only one set of operating conditions that would apply to a broad range of thermal conductivities.

The value of the FE method to solve the differential equation of heat conduction while satisfying the operating boundary conditions of the GHP apparatus is also demonstrated.

KEY WORDS: guarded hot plate, errors, finite element, thermopile

Nomenclature

- h Convection heat transfer coefficient, W/m^2 K
- r, z Cylindrical coordinates, m
- q Boundary heat flux density, W/m^2
- t Sample thickness, m
- N_i Interpolation function pertaining to node i

[1]Director of Manufacturing and Process Development, Pittsburgh Corning Europe N. V., B-3980 Tessenderlo, Belgium.

S Area, m^2
T Temperature, K
λ Thermal conductivity, W/m K
θ Cylindrical coordinate, radians

Subscripts

b Denotes bottom
e Denotes element
t Denotes top
i Local node index
∞ Used with T to indicate convective-air temperature

In 1981, we had started a three-dimensional study of the guarded hot plate (GHP) by the finite element (FE) method [*1*]. In this early work we used a square GHP model because our laboratory apparatus consisted of square plates. With that model, it was not possible to examine the influence of thermopile wires crossing the gap because of the limitation in computer memory. Yet, we felt that these wires would have a great influence on the error of measurement as a function of the gap temperature unbalance. Therefore, we chose a circular GHP model because it could be generated by one 360° revolution of a half diametral section, and such a model enabled us to use a very fine grid that includes thermopiles. The study is not finished. To date, we have studied insulating specimens of 0.042 W/m K thermal conductivity. We plan to study specimens of various thermal conductivities including 0.21, 1.05, and 0.021 W/m K or so. We may use higher order elements in future work.

Governing Equations

Assuming the steady-state and constant-thermal properties in the domain, the differential equation of heat conduction in cylindrical coordinates for the axisymmetric case when there is no internal heat generation is given by

$$\lambda \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \lambda \frac{\partial T}{\partial r} + \lambda \frac{\partial^2 T}{\partial z^2} = 0 \tag{1}$$

A half diametral cross section representing the upper part of the apparatus is given Fig. 1 where

S_1 extends from the center of the plate to the outside of the ring and coincides with the cold plate; the latter is a cold sink.

S_2 extends from the center of the center plate to its heater edge. The FE method can account for a heater that does not extend exactly to the edge of the central plate; the heater does in this report.

S_3 designates the vertical cylindrical surface of a glass fiber insulation plus

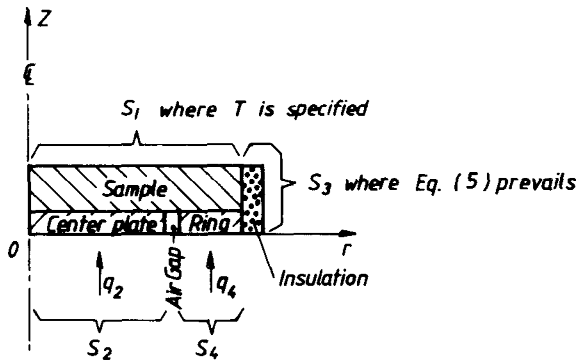

FIG. 1—*Half cross section of top half of circular GHP.*

its ringlike top surface, that is, the cold sink is not assumed to extend over the top of the insulation; a convection boundary condition reigns over S_3.

S_4 extends exactly over the guard ring heater, that is, its width need not be exactly that of the guard ring; it does in this report.

The boundary conditions used in this report are given by

$$T = T_0 \quad \text{on} \quad S_1 \tag{2}$$

$$-\lambda \frac{\partial T}{\partial z} = q_2 \quad \text{on} \quad S_2 \tag{3}$$

$$-\lambda \frac{\partial T}{\partial z} = q_4 \quad \text{on} \quad S_4 \tag{4}$$

where q_2 and q_4 are > 0.

$$\lambda \frac{\partial T}{\partial r} + h(T - T_\infty) = 0 \quad \text{on} \quad S_3 \quad \text{(convection)} \tag{5}$$

Though we assumed that T_0, q_2, and q_4 are radially uniform, it must be emphasized that the FE treatment does not require such an assumption. However, the use of the circular model assumes that these quantities are uniform along the θ-direction.

Finite Element Models

The meshes used in this report consisted of, respectively, 363 nodes with 640 elements and 585 nodes with 1064 linear triangular elements. The latter, used for plates with thermopiles, is shown Fig. 2. It shows that a finer mesh was used