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Measurements of Thermal Insulation Performance: The Challenge of the Next Decade[1]

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The past two decades have stimulated significant growth both in thermal insulation materials and product development and in their use for new and different applications. These activities have had a resultant impact both on existing methods of measurement of relevant thermal properties and on the development of new or modified measurement techniques. Various examples of present measurement technologies applicable to the new materials and applications are discussed in relation to the current state of the art. These include (1) measurements on very high-thermal resistance per unit thickness insulation systems for appliances and buildings, (2) improvements in current standard methods of test, particularly in speed of operation and relevance to application, and (3) *in situ* and field measurements. The discussion includes examples of current limitations. These relate particularly to accuracy, especially at elevated temperatures, product variability, a need for relevant transient techniques, and very urgent requirements for reference materials and transfer standards. As a result, recommendations are proposed in the hope that they will stimulate necessary research and development work in the next decade.

KEY WORDS: ASTM C16 Committee; insulation (thermal); laboratory and field measurements; quality assurance; reference materials; standards; steady-state methods; transient methods.

1. INTRODUCTION

While thermal insulation has been used, particularly, in and on buildings for centuries, initial interest in measurement of its thermal performance can be traced to the early nineteen hundreds. At this time, the first guarded and unguarded plate and disk methods were developed for measuring the thermal conductivity of solids. During the next three decades, thermal

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insulation became much more widely used, especially for industrial applications at high and low temperatures, but developments of and improvements in measurement techniques followed much more slowly.

In the USA, ASTM Committee C-16 on Thermal Insulation was formed in 1938. However, it took 7 years to develop the first measurement standard, based on the guarded hot-plate technique C177. Other standards based on the heat flow meter C518, the pipe test C335, and the guarded hot box C236 took a further 15 to 20 years to be promulgated. A similar pattern of development can be seen in other countries during the same time frame.

In the first 30 years of its existence, the C16.30 Thermal Measurements Subcommittee of the C16 Committee held four short symposia devoted to thermal performance measurements [1–4]. These were, in general, devoted to improvements in techniques and methodology leading to the ultimate goal of better accuracy. Apart from the pipe test method, most of the early analytical and experimental work described related to the use of methods at or near room temperature. Furthermore, theory and analysis were applied to most materials, assuming phenomenological processes in homogeneous isotropic media. Results on insulation materials and products were presented as a solid thermal conductivity irrespective of the fact that other heat transmission mechanisms including radiation, gas conduction, and mass transfer could also occur. Apart from a limited number of very special applications, very few measurement approaches were driven by materials and applications issues.

However, the subject changed drastically during the next 15 years. As a result of the first energy crisis in 1973–1974 and similar crises later, energy conservation, particularly by the use of additional insulation, stimulated the international thermal insulation community to a multifold increase in activity. This became the driving force which affected the subject of thermal properties and performance measurements significantly as manifested in the greatly increased number of publications devoted to the topic.

During this time, for example, the ASTM C16 Committee and its Subcommittees have organized nine symposia related to this subject [5–13]. These have been supplemented with a number of similar meetings organized by related groups, e.g., ASHRAE, the International Thermal Conductivity Conference, and the European Thermophysical Properties Symposium, all of which contained major sessions devoted to measurement issues related to the thermal performance of insulations. Furthermore, the *Journal of Thermal Insulation* was started during this time period and each issue always contain a significant number of papers devoted to thermal measurement issues.

The results of all of these efforts have not only increased our knowledge in measurement and analysis techniques but also improved our understanding of materials behavior. However, we find that there are still many unanswered questions together with significant gaps in our knowledge.

This brief history is related here as a background to the present discussion to provide a focus for the subject of thermal performance needs. These are many, and the present paper discusses only a few. They are somewhat personal selection due to the direct or indirect involvement of the author in some of the subjects being discussed.

2. DEVELOPMENT AND IMPROVEMENT OF LABORATORY METHODS

As mentioned in Section 1, until the sixties and seventies measurement techniques were, in general, materials-oriented, with few being applications-driven. Now that the general understanding of a thermal insulation is that it is a system and the performance must be treated as such, much more effort has been and needs to be devoted to this issue, particularly as so many advances have been made in the development of insulations of all types.

An early example of a new measurement technique was stimulated by the space program in the sixties. This related to the need for reliable thermal performance measurement of multilayer reflective insulation systems utilized for thermal protection of space vehicles, astronauts suits, etc. These systems performing in high vacuum have extremely low thermal conductance values and are highly anisotropic in nature. A special form of large hot-plate apparatus was developed using boil-off of cryogenic fluid having known properties as the means to measure heat flow. It is essentially a single-sided form of the guarded hot-plate method [14] where the boil-off from liquid cryogen of known properties such as helium, hydrogen, or nitrogen, is used both to measure heat flux and to control the cold face temperature for a given hot face, thus simulating particular outer space conditions. This form of apparatus was used extensively [15] to study the performance of such systems and, particularly, the effects of dominant parameters such as number of layers, applied load, effect of separators, effects of joints and other thermal bridges, etc.

In the early seventies, the space program was deemphasized and little work has been carried out in recent years using the technique. However, the impetus of the proposed space station and other exotic space-oriented projects has stimulated the use of new and improved multilayer and other evacuated insulation systems, and the basic method will again have to be utilized. Furthermore, the technique could be modified using different fluids for other temperatures and applications where high thermal resistance per unit thickness evacuated insulations are being considered.

In the latter context, considerable attention has been paid to improved insulation systems to reduce energy consumption in appliances, especially refrigerators and freezers. Most recently, this problem has been compounded by the fact that the currently used closed-cell cellular plastics containing fluorocarbon blowing agents are being restricted due to the deleterious effects of these gases on the environment. Although new blowing agents are being investigated and, no doubt, will be available in the future, serious consideration is being given to evacuated systems as a viable alternative.

Basically, these systems are composite panels consisting of evacuated submicron diameter particles either separately or as a package and surrounded by a closed-cell cellular plastic encased within a sealed metal/plastic unit. Evacuated window glass units are a similar high-thermal resistance composite system under consideration for buildings. Very high thermal resistances per unit thickness values of up to $6\ m^2 \cdot K \cdot W^{-1}$ can be obtained with such systems.

Measurements on such systems are somewhat difficult due not only to the overall high thermal resistance of the panel, but also to its inhomogeneity and lateral conduction along the metal and plastic skins. One good technique appears to be the use of a large thin-screen heater self-guarded hot plate [16] as developed by McElroy and co-workers at Oak Ridge National Laboratory. This type of large plate has been proven both analytically and experimentally (around 293 K) to be capable of providing results of high accuracy. Its size makes it suitable for evaluating complete panels such as refrigerator doors and wall panels. However, it should be pointed out that the method has been verified using only the very limited reference materials or transfer standards currently available. Such materials are of a much lower thermal resistance and their degree of anisotropy is of the order of only 30% or less, whereas that of the panels can be an order of magnitude or greater.

As mentioned earlier, the energy crisis in the seventies stimulated the use of much greater thicknesses of insulation materials and products for all applications, but especially in buildings. The use of thick insulations, especially (but not restricted to) low-density forms for the building envelope, showed that existing methods and apparatus were not suitable, particularly for the quality control/quality assurance role. Furthermore, a better understanding of heat transmission modes in such materials and products using new and improved methods was necessary both to understand and control their performance and to ensure that they were being utilized correctly at various temperatures.

A special requirement was related to the need for reliable thermal performance measurements on low-density fibrous and cellular insulations, which were becoming utilized in thicknesses well in excess of 25 mm. This had been a thickness widely used for previous measurements of thermal "conductivity" by the hot-plate method. It soon became apparent that such materials, due to inhomogeneity, variability, and the "thickness" effect due to radiative heat transmission [17], needed to be evaluated using a larger apparatus on a full or a "representative" thickness. Furthermore, the thermal resistance of the product was now being used directly as a quality control tool [18].

Thermal properties measurement was thus transferred from controlled laboratory conditions onto the factory floor. Rapid measurements were required utilizing more simple direct reading instrumentation used by less qualified staff. To meet this need, significant improvement took place in the development of the heat flow meter method, especially for thick specimens [19]. This technique is based upon the use of *in situ* heat flux transducers with calibrated transfer standards having different thermal resistance values, preferably of different types of insulation and thickness.

One type of such apparatus, using one heat flux transducer, has reduced measurement times on 150 mm of low-density fibrous and cellular insulations from the 6 to 8 h normally required by guarded hot-plate methods to less than 1 h while providing results having an accuracy of better than $\pm 3\%$ [20].

More recent studies in France [21], using two heat flux transducers, one mounted on each of the hot and cold plates, indicate that these measurement times can be further reduced significantly. The apparatus is very similar to a standard type of ASTM C518 instrument mentioned above, modified only with an additional heat flux transducer and a separate heater circuit to heat the hot plate during the specimen change-over period. It has been verified analytically and also experimentally with several types of fibrous insulations that averaging of the outputs from the two transducers provides the same result as that for steady-state conditions using one transducer in one-third to one-quarter of the time. More work is required on other types of insulations and at other temperatures for a total validation. If shown to be applicable to these needs, the method would serve as an excellent means to improve products by reducing more immediately some of the variability due directly to processing.

The method can be described as a transient method, although it is not a truly classical experiment which involves monitoring of temperature rise with time due to a pulse-type heat input. The only additional requirement is that the hot face of the apparatus be heated for a short time (30 s to a few minutes depending on the properties and dimensions of the specimen) during the specimen changeover period. This technique lends itself to complete automation, since both the heating and the measuring times are known functions of thickness, density, and thermal conductivity and specific heat of test specimens.

The measurement techniques discussed so far have all been based on steady-state undirectional heat flow. While such methods are a necessity to the subject, it is only on very rare occasions that a thermal insulation operates under steady-state conditions. This is particularly true for insulations used in buildings where the effects of the diurnal cycle come into play. Ideally, therefore, there is a need for thermal diffusivity measurements, especially for insulation materials and systems, particularly to aid in verification both of performance models and of current field measurement methods which are in use or being developed.

Both the thin screen heater technique and the two-heat flux transducer heat meter method offer possibilities of measuring this performance characteristic. In the former, the heater has a very low mass and rapid response, and its effects can be neglected. Thus, it should be possible to analyse the temperature–time response for a given power input and obtain the diffusivity directly. In the other method, it appears conceivable that thermal diffusivity can be measured directly from an analysis of the average of the transducer outputs with time, providing that the temperature of the plates can be controlled within tight limits.

3. STATE-OF-THE-ART

Taking North America as the example, measurements of thermal performance of insulations and insulated systems have been undertaken by standard methods for some 20 to 40 years, depending on the method. Limited guarded hot-plate interlaboratory studies were carried out over 20 years ago on corkboard and fibrous glass board, respectively. The results indicated that for a very limited temperature range, 270 to 320 K, agreement was, in the majority of cases, well within $\pm 5\%$.

More recently, several comparison studies have been undertaken under the auspices of ASTM C16. These are as follows.

(a) Guarded hot-plate/heat flow meter studies around 297 K on various mineral and glass fiber blanket products, using specimens of different thicknesses [20]. Overall, some 20 organizations participated, depending on their apparatus size, in all or parts of the study. Results were rather encouraging in that they illustrated an agreement to better than $\pm 3\%$ with one exception only. Furthermore, there was no discernible difference between the results from the guarded hot-plate and those from the heat flow meter methods.

(b) A study using large heat flow meters on a thick fibrous glass blanket. This was in support of a round-robin on measurements of loose-fill insulation materials used for buildings [23]. The results of this study, undertaken by some 20 organizations, confirmed that the overall precision was inside $\pm 3\%$. However, when measurements were made on prepared specimens of various loose-fill materials, agreement was quite poor, due solely to specimen preparation. Furthermore, the agreement differed for the type of material being evaluated.

(c) Some 20 organizations participating in a round robin study using both guarded and calibrated hot boxes on specially prepared specimens of a well-characterized expanded polystyrene [23]. Results were somewhat disappointing in that they showed an approximately $\pm 7\%$ spread for this "homogeneous" material. In addition, there was a definite and, as yet, unexplained constant difference between the results of guarded and those of calibrated boxes. Since hot box methods are used primarily to evaluate more complex insulated building systems containing thermal bridges and other anomalies, it is likely that the above accuracy will not be attained for such systems. Much additional verification and validation is necessary for such types of systems.

(d) A pipe tester study undertaken, with some seven laboratories participating [24]. The specimen was a bonded mineral wool which, unfortunately, did have some material variability. The overall temperature range was approximately 300 to 700 K. The results, excluding allowance for material variability, agreed to better than $\pm 5\%$ and they confirmed the results of an earlier study [25] which covered a more limited temperature range.

(e) A study on several materials including three well-characterized insulations, Ottawa sand, and pariffin wax using the transient line-source method in various forms including the probe. The results of the study were not encouraging since they indicated standard deviations of some 20% for the different forms, differences of mean values of 15 to 35% between the different forms, and differences of results in excess of 10% from current accepted values obtaining with steady-state methods for the insulations.

The line-source technique has often been proposed as a possible method for use on insulation materials, particularly at high temperatures. The present results, especially when considered with respect to additional error source and practical issues of anisotropy, radiation heat transfer effects, and possible electrical conduction effects at very high temperatures, certainly indicate that considerable thought and effort must be expended before such a method can be utilized successfully with thermal insulations.

(f) A high-temperature guarded hot-plate study involving some seven organizations, carried out in 1987 on a high-density calcium silicate and a moderate density aluminosilicate fiber board up to approximately 770 K. This was undertaken both to evaluate the current state-of-the-art and to provide information to assist in the revision of the current C177 standard [27].

While each experienced participant carried out the measurements very carefully according to their interpretation of the standard, the results indicated a reproducibility of the order of 15 to 16%. This is considerably greater than the 2 to 5% which is claimed normally, albeit at lower temperatures. In this study, seven different specimens were used, and some variability was seen, although small corrections were made for this based on simple assumptions. Plans are under way for each organization to measure at least one different specimen of each material. In addition, the participants plan a workshop where techniques and procedures are to be discussed. It is hoped that this will result in a less ambiguous set of guidelines, an improved standard, and better measurements.

The latter study covered only moderate temperature, and the need is for higher-temperature measurements, particularly to 1000 K or higher. Materials such as aluminosilicates and carbon and graphite fibers are becoming more widely used for insulating industrial systems to 1600 K. Basically, the community has no reliable and validated measurement technique available. The ASTM C201 water flow calorimeter has been shown to have serious deficiencies [28], while the problems of the proposed line-source method have been discussed earlier.

Clearly, it can be seen that while there are reasons to believe that accurate measurement can be made to the order of 2 to 3%, this applies to a very limited number of cases only. Much work is necessary, for example, to develop new or improved techniques for measurements to high and low temperatures, regimes which are becoming more important for a number of important applications. In addition, accurate data are required to improve our understanding of heat transmission mechanisms for these temperature regimes and applications.

4. REFERENCE MATERIALS AND TRANSFER STANDARDS

The above discussion highlights a serious deficiency in the thermal measurements field. There is a distinct lack of reference materials and calibration specimens available for us to verify our primary and new methods and to calibrate the secondary techniques. In the latter category, the very widely used heat flow meter method is totally dependent on transfer standards. In particular, since the method is now being used or considered for use at higher temperatures, the need for calibration samples with known properties to at least 500 K is now urgent. Furthermore, higher-temperature stable heat flux transducers are now being developed such that the needs are being extended even further.

In 1986, the present author discussed the subject in detail [29] from an historical context and provided information on work currently under way internationally. In particular, in the United States the screening work started initially on the microporous fumed silica board ($\lambda \sim 0.0211\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$) has been completed [30]. By the end of 1989 it is expected that the material will be issued with a certificate as a Standard Reference Material at 297 K only, and some 70 to 80 specimens will be available for purchase. Currently, additional work is being carried out at NBS Boulder and elsewhere to extend the temperature range to above 600 K. Initial results are encouraging and it is hoped that within a year or so the certificate will be extended to cover the higher-temperature range.

While this work is promising, and an additional SRM will be of great help, the material itself is not ideal. It is microporous and, thus, has a performance property which varies with atmospheric pressure. Although this variation is small, it is still present. Furthermore, although the material is a high-density product, it is somewhat friable and great care is required in its handling. Thus, more materials are required.

In this context, the aluminosilicate board measured in the previously mentioned high-temperature round-robin is a candidate. However, there were some definite inconsistencies associated with this material which came to light in the analysis of the results. Thus, it is likely that a more refined and homogeneous product may be required. The low-density blown stabilized aluminosilicate fiber (Nextel) blanket discussed in the 1986 survey would seem to offer significant potential in this respect. Finally, the development of the high-R systems discussed earlier would seem to present an additional need for a suitable reference system in order for the insulation community to have confidence in the many future measurements to be carried out on these anisotropic systems as the technology develops.

5. DEVELOPMENT AND IMPROVEMENT OF FIELD METHODS

The increased use of thermal insulations for the building envelope has stimulated a need for understanding thermal performance under live environmental conditions. Actual measurements either in the laboratory or *in situ* are time-consuming and expensive. Thus, a variety of analytical models has been developed to predict building performance. However, these models still need validation with accurate data obtained by appropriate field measurement techniques. This has to be supplemented with improved laboratory evaluation of insulated systems under specifically chosen transient conditions in addition to the current accepted steady-state methods.

A number of workers [31–35] have developed differing field measurement strategies together with estimates of their efficacy and accuracy. However, until the results of a recent study were made available [36], no direct comparisons of *in situ* data have been made. This 2-year study was undertaken at the Roof Thermal Research Apparatus (RTRA) at Oak Ridge. It involved two distinctly different experimental and analysis strategies using heat flux transducers on an insulated roof system. The strategies were developed by workers at Oak Ridge and by the author and co-workers, respectively.

The results were encouraging in that agreement of 4 to 8% was obtained for times of the year when weighted mean temperatures were outside the approximate range 20 to 35° C, i.e., when heat fluxes were very small. In the latter regime, differences of 10% and greater were experienced. However, the study illustrated that reliable, reproducible measurements can be undertaken providing great care is taken in the experimental strategy, particularly calibration of heat flux transducers, etc., and the way that the data are analyzed. However, one of the major issues addressed is that worthwhile results can be obtained only with integration of collected data over long time periods and where significant heat fluxes are involved.

In situ measurements are most time-consuming and very expensive, and thus, there is a need for the development of a methodology to measure dynamic thermal performance of insulated systems using laboratory hot box methods. In this context, the slow ramp test technique developed by Stephenson and colleagues at National Research Council in Canada for use with the guarded hot box appears highly promising [37]. Furthermore, Burch and his colleagues at NBS Gaithersburg have modified this in terms of a fast ramp technique for the calibrated hot box at that facility [38]. Thus, the means are available for studies to be made to verify the efficacy of the basic technique.

In these measurements, the insulated specimen is mounted between the two climatic chambers and allowed to equilibrate. It is then subjected to a ramp change of temperature on one side. For example, in the calibrated hot box technique, the specimen is sandwiched between the metering and the climatic chambers. The metering chamber is maintained at typical indoor conditions and is also being used as the calorimeter to determine the transient heat transfer rate. Once equilibrium has been attained, a dynamic excitation function, i.e., a fast ramp change from an initial to a final test temperature, is generated in the climatic chamber. The heat transfer response to this is analyzed to yield transfer functions coefficients which characterize the dynamic performance of the specimen. Initial results on simple systems appear very encouraging.

6. SUMMARY

The needs for reliable thermal performance data and some of the major activities relating to present and future requirements in the area of thermal performance measurements of thermal insulations and insulated systems have been discussed. While much work has been started, it serves only as a stimulus for further laboratory and field work. This is necessary to ensure that future steady-state and dynamic measurements in each area provide results which are both analytically and experimentally acceptable. Furthermore, there is an urgent need for sufficient appropriate reference materials and transfer standards to be made available in order to support these efforts.

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