BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 66 (70), Numărul 2, 2020
Secţia
CONSTRUCŢII. ARHITECTURĂ

THE STUDY OF METHODS FOR DETERMINING THERMAL CONDUCTIVITY OF BUILDING MATERIALS

BY

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Received: April 8, 2020
Accepted for publication: April 29, 2020

Abstract. Although the level at which individuals are affected by global warming today varies according to where they live in the world, this is a current problem of society of particular importance for each individual. Thus, each of the fields of activity, with the passage of time and the awareness of the situation, they have started to develop solutions that will help reduce global warming.

The fact that the highest share of total energy is consumed by the building sector has led to an exceptional development of the energy performance of buildings. Thus, there is a constant interest in developing new high-performance thermal insulation materials, in building thermal protection systems or in developing building designs suitable for energy performance. A key factor in contributing to reducing global warming is the determination of the actual energy consumption generated by the use of buildings.

The article presents the main methods for determining the thermal conductivity of thermal insulation materials and extensions of the conventional methods presented in the literature. The advantages and disadvantages of methods will also be presented.

Keywords: building energy performance; heat flow meter; guarded hot plate; hot box; hot wire.

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1. Introduction

According to Eurostat, the buildings sector is the only major energy consumer in the European Union, covering around 40% of total energy consumed in Europe. This high share shows the huge importance of developing the energy efficiency of buildings in the global effort to reduce global warming. Energy Performance of Buildings Directive is the legislative framework in the European Union, which regulates this sector and has as one of the main objectives the reduction of total energy consumption generated by the use of buildings.

An important factor in achieving this is the development of high-performance thermal insulation materials which can be part of the building envelope. In general, the development of new thermal insulation materials is aimed at reducing thermal conductivity to obtain building elements with high thermal resistance for reduced thermal insulation thicknesses. Thermal conductivity is the main characteristic of such materials and thus its correct determination is a starting point in increasing the energy performance of buildings.

Also, an important factor in reducing energy consumption is the determination of the actual consumption of buildings. In situ, thermal conductivity and thermal resistance determinations can be made which sometimes give information about actual consumption that is different from theoretical consumption. Sometimes energy efficient buildings have a higher actual energy consumption than theoretical and energy inefficient buildings have lower actual energy consumption than calculated (Majcen *et al*., 2013). In situ measurements can help establish actual energy consumption and thus provide a better picture of expectations in reducing total consumption.

The paper presents the main methods for determining thermal conductivity in both laboratory conditions and in-situ, extensions of the conventional methods presented in the literature and a comparative analysis of their advantages and disadvantages.

2. Methods of Determination

2.1. Conventional Methods

Two basic methods are distinguished from the point of view of the thermal balance of the sample analysed for the measurement of thermal conductivity (Latif *et al*., 2011). The steady-state method records a measurement when the temperature is constant at each point of the material and the temperature does not change with time (Yüksel, 2016). The transient method is the second method and this technique involves a measurement during the heating process (Yüksel, 2016).

Methods for determining the thermal conductivity of construction materials, specific to both cases, are given below.

2.1.1. Steady-State Methods

2.1.1.1. Hot Box

The hot box is a steady-state conditions method used to determine the thermal resistance of a specimen. The basis of the method is the measurement of the heat flux through the material and the corresponding temperature differences across it (Soares *et al*., 2019). There are two varieties of this method: Calibrated Hot Box and Guarded Hot Box.

Apparatus used in first method is made of a metering box and cold box which are separated by the material analysed. A scheme of the Calibrated Hot Box method is presented in Fig. 1. The thermal flow value is obtained by subtracting from the total power input, the heat lost through the metering box insulation and the flanking loss.

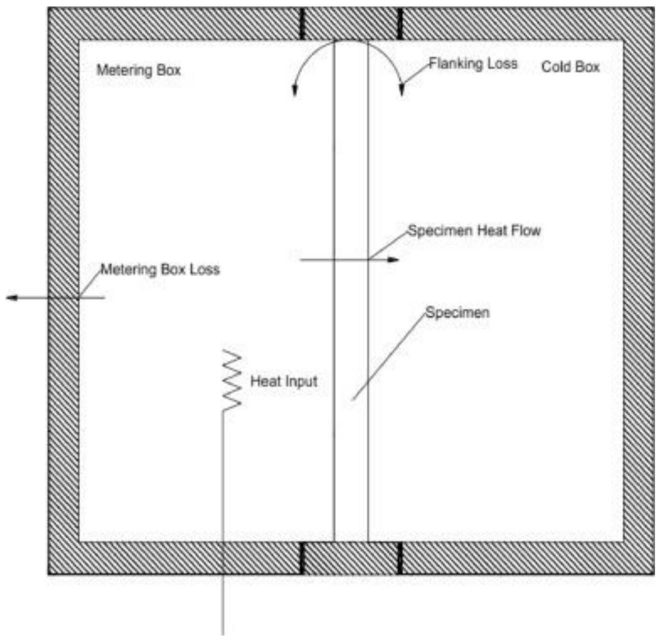

Fig. 1 – Calibrated Hot Box (Soares *et al*., 2019).

Different from the first method a Guarded Hot Box apparatus is made of a guard box, a cold box and a metering box. In this case the metering chamber is surrounded by a guard box. A scheme of Guarded Hot Box is presented in Fig. 2. Same as in the first method, the thermal flow value is obtained by subtracting from the total power input, the heat lost through the metering box insulation and the flanking loss.

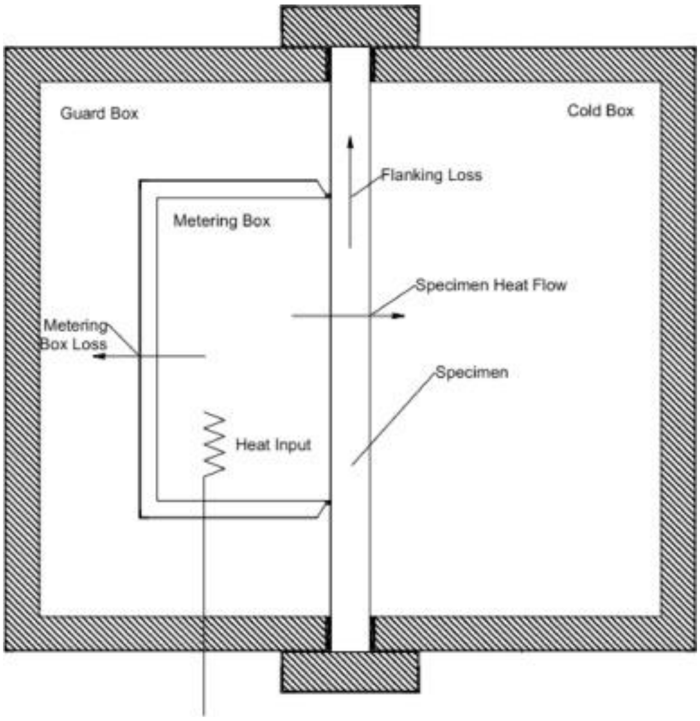

Fig. 2 – Guarded Hot Box (Soares *et al*., 2019).

The hot box method is standardized by American Society for Testing and Materials and by International Organization for Standardization. The standards are ASTM C1363-11 (2011) “Standard test method for thermal performance of building materials and envelope assemblies by means of a hot box apparatus” and ISO 8990:1994 “Thermal insulation – determination of steady-state thermal transmission properties – calibrated and guarded hot box”.

2.1.1.2. Guarded Hot Plate

The Guarded Hot Plate apparatus is usually composed of two cold plates, a hot plate with a measuring unit and a system of guarded heaters. A scheme of Guarded Hot Plate is presented in Fig. 3. The method consists in the measurement of the heat flux applied from the hot plate to the cold plates through the specimens. The thermal conductivity value is determined considering the heat flow rate, the temperature difference across the specimen and the heat transfer area.

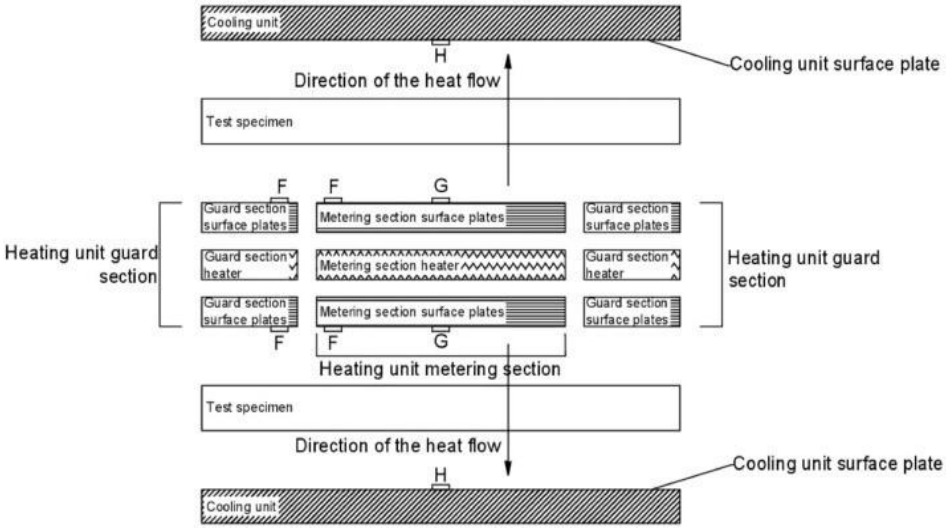

Fig. 3 – Guarded Hot Plate (Soares *et al*., 2019).

This method is presented by the following standards: ASTM C177-13 (2013) "Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus" and ISO 8302:1991 "Thermal insulation – determination of steady-state thermal resistance and related properties – guarded hot plate apparatus".

2.1.1.3. Heat Flow Meter

The method consists is the measurement of the heat flux through the specimen, at a different temperature at the two surfaces, using heat flux meters. To perform a measuring R-value, are necessary heat flux meters, thermocouples and a data acquisition system which should record data continuously or at fixed intervals between the measurements.

The main standards that present the method are: ASTM C1155-95 (2013), "Standard practice for determining thermal resistance of building envelope components from the in-situ data", ASTM C518-17 (2017), "Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus", ISO 9869-1:2014, "Thermal insulation – building elements – in-situ measurement of thermal resistance and thermal transmittance – part 1: heat flow meter method" and ISO 8301:1991, "Thermal insulation – determination of steady-state thermal resistance and related properties – heat flow meter apparatus".

2.1.2. Transient Methods

2.1.2.1. Hot Wire

The basis of the method is the measurement of the rise in temperature at a defined distance from a linear heat source. A schematic principle of the method is presented in Fig. 4.

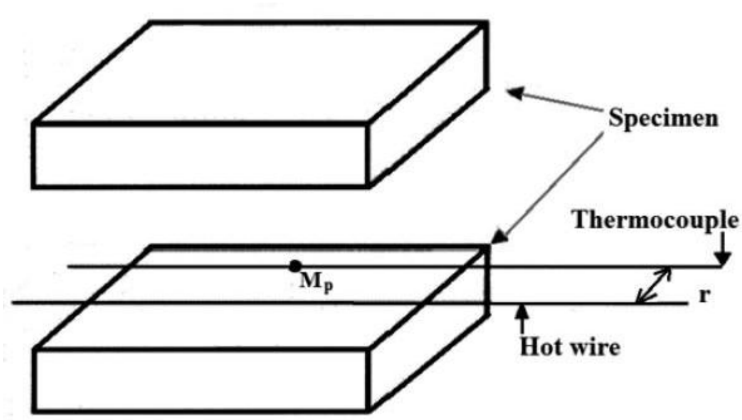

Fig. 4 – Parallel Hot Wire (Yüksel, 2016).

Thermal conductivity can be obtained as a function of temperature, time and heat flow with the assumption that the hot wire is a continuous line source which generates cylindrical coaxial isotherms in an infinite homogenous medium with initial equilibrium condition.

2.1.2.2. Portables Devices

To carry out in-situ thermal conductivity determinations in a short time frame, a number of portable devices have been developed to do so. These measuring devices function in a transient regime of thermal flux (Pruteanu *et al.*, 2020) and the thermal conductivity is measured directly by means of needle sensors or surface sensors. Considering the sensor types, measurements of thermal conductivity can be made on both rigid and less rigid insulation materials.

2.2. Extensions from Conventional Methods of Determination

Conventional methods of determining the thermal conductivity of building materials, are usually time expansive (Rasooli and Itard, 2019) and sometimes in practice, some of the methods, such as Heat Flow Meter method can generate precision problems (Rasooli and Itard, 2018). Also, for the Hot Box Method is necessarily a heavy and an expensive equipment (Meng *et al*., 2017). To avoid some of these problems, a number of authors propose improvements to conventional methods. Some of these will be presented below.

Sassine (2016) presented a practical and fast method for thermal conductivity in-situ determination which is based on the comparison of measured and theoretical heat fluxes. At regular time intervals of 20 min, the temperatures on the inside and the outside of the wall and also the outside heat flux are measured and recorded. Using the measured temperatures and the designation of random values for thermal conductivity and thermal capacity, a theoretical flow of heat is determined and compared to the measured flow. The optimization gives the values of thermal capacity and thermal conductivity. Although in the case studied the monitoring duration was five days, this method is presented like a practical method considering the lack of particular boundary conditions and the accuracy of the results.

Another method of reducing the time taken to make measurements is given by Rasooli *et al*. (2016). Excitation Pulse Method is a transient in-situ measurement method of thermal resistance based on theory of response factors. This method can also provide the thermal conductivity and the volumetric heat capacity. A schematic principle of the method is presented in Fig. 5.

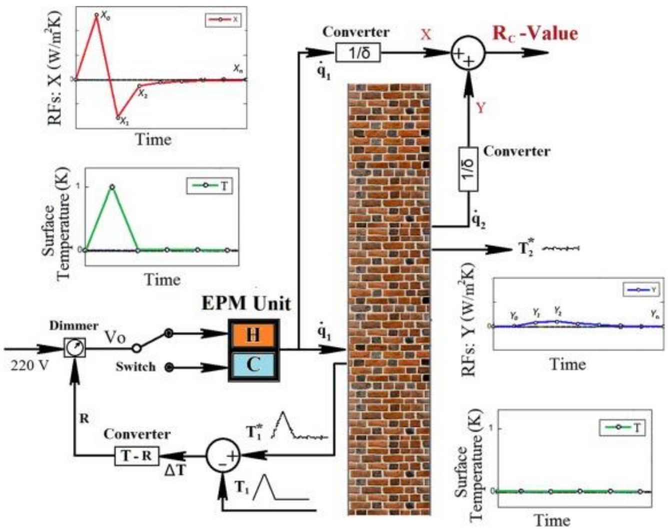

Fig. 5 – Excitation Pulse Method (Rasooli *et al*., 2019).

The study by Rasooli *et al.* (2016) presents a comparison between the Excitation Pulse Method and the method based on the ISO 9869 which shows a difference less than 2% for the obtained values of thermal resistance. Total duration of measurements for the conventional method was more than two weeks and in the case of the Excitation Pulse Method was an hour and a half. In the same paper has shown a solution in improvement of the method presented by ISO 9869. The time and accuracy can be improved using two heat flow meters instead of one and by averaging the two sets of results.

Meng *et al*. (2015) proposes a Simple Hot Box – Heat Flow Meter Method to measure the thermal transmittance in situ. The method avoids the limitations of individual conventional methods such as thermal environment limitations of the Heat Flow Meter method or the heavy equipment of Hot Box Method. A schematic principle of the method is presented in Fig. 6.

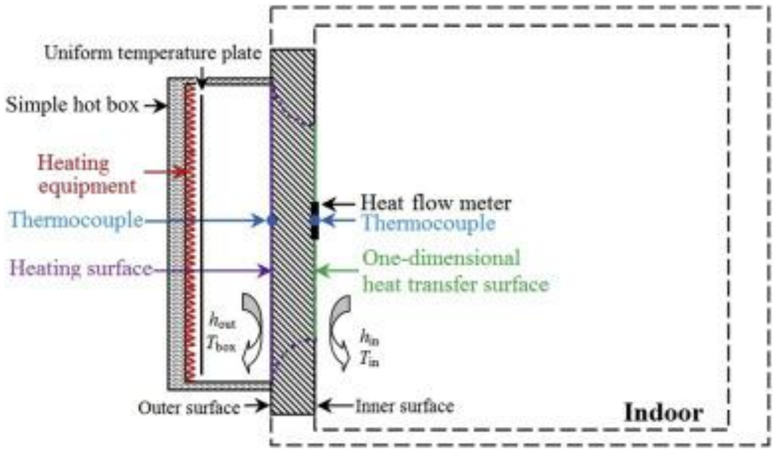

Fig. 6 – Simple Hot Box – Heat Flow Meter (Meng *et al*., 2015).

A similar method with the Simple Hot Box – Heat Flow Meter Method is presented by Scarpa *et al.* (2017). The method consists in the generation of a high, constant temperature by means of an electric heater on the inside surface of the building element. The temperature shall be maintained by means of a box made of insulation material. In this case stable boundary conditions are obtained and a significant temperature difference between internal and external environments is achieved, which can make measurement possible even in hot climates. It also shortens the time required to take measurements and increases the accuracy of the results.

Kobari *et al.* (2015) presented an improvement of the Guarded Hot Plate Method, which makes possible the determination of thermal conductivity of high-performance insulation materials such as vacuum insulated panels (VIP). A Peltier module is proposed as a unit of measurement that makes possible, considering the sensitivity to temperature differences, a better control of the hot plate which is leading to a high degree of thermal equilibrium. Thus, the method is suitable for insulating materials with a very low thermal conductivity.

A method of determining the thermal conductivity of granular materials was presented by Vasilache *et al*. (2010). The method consists in heating a granular material, placed in a PVC recipient, with an electrical wire. Other necessary equipment to perform the measurements are thermocouples, a microvolt meter, a recording apparatus and an infrared camera. The experimental apparatus is presented in the Fig. 7. In order to determine the thermal conductivity of the specimen a steady-state thermal regime should be achieved.

Fig. 7 – Measurement with IR camera (Vasilache *et al*., 2010).

3. Comparative Analysis of Advantages and Disadvantages

The main advantage of The Hot Box Method is the accuracy and reliability of obtaining thermal resistance. In particular The Calibrated Hot Box apparatus is simpler in design and operation than the Guarded Hot Box which does not need to have a calibration factor for flanking loss (Soares *et al*., 2019). Another advantage for Guarded Hot Box is the fact that can be used both in laboratory or in-situ measurements, differently of Calibrated Hot Box which can be used only in laboratory tests. The most important drawbacks are the long measuring time, the cost which is high, the difficulty of the operation and the heavy equipment necessary for measurements.

Same as The Hot Box, the Guarded Hot Plate method is a highly accurate one, being the most accurate technique for determining the thermal conductivity (Soares *et al*., 2019). Other advantages are the reduced cost and the simplicity of the apparatus. The main disadvantage is the time needed to carry out the determination, which is a long one.

In the case of the heat flow measurement method, the main benefits are international recognition and the widespread use of the method for determining thermal conductivity (Meng *et al*., 2017). Other advantages are lightweight equipment and the fact that the method can be applied both in controlled laboratory conditions or in-situ measurements. Different from the Hot Box Method and the Guarded Hot Plate Method, the accuracy of the results of the measurements made in-situ can be hard to obtain considering different factors such as temperature gradient or the calibration and errors of the apparatus. Also, an important disadvantage is the long measuring time, which can be more than three days.

Conventional steady-state methods of determining the thermal conductivity have as their main advantage the standardization, international recognition and the widespread use. In contrast, extensions of conventional methods need to confirm the accuracy of results by considering more tests on several wall types and under different external measurement conditions.

The main disadvantage for the conventional methods and the main advantage of the extensions of the conventional methods is the time necessary for measurements. In the majority of the papers that presents improvements of the conventional methods, a key point is the reduction of the time of determination. Another advantage of extensions of conventional methods is the improvement of the accuracy of the results obtained under different environmental conditions for determining the thermal conductivity in situ.

4. Conclusions

The correct determination of thermal conductivity in laboratory conditions for newly developed materials or in situ for materials used in existing envelopes is essential in the analysis of the energy performance of buildings. The subject is of major importance where there is a wide variety of conventional methods, steady-state or transient, that are standardized and recognized by the international scientific community, but which are particularly difficult to use in situ determinations considering the time required for measurements and environmental conditions.

Challenged by difficulties in conventional methods a number of authors propose improvements to them such as reducing the time needed for measurements, increasing the accuracy of the results or reducing the equipment costs. There are also extensions to conventional methods that make it possible to determine thermal conductivity more accurately in the case of high-performance insulating materials.

Obtaining results with high accuracy depends on the correct choice of a determination method. Factors such as the possibility of laboratory conditions or in situ testing, environmental conditions or performance of the tested material should always be considered in the choice of method. When extensions of conventional methods are used, it is important to choose a method that confirmed the accuracy of the results for the conditions and the type of wall tested.

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*** *ASTM C1363-11 (2011), Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus.*

*** *ASTM C1155-95 (2013), Standard Practice for Determining Thermal Resistance of Building Envelope Components from the in-situ Data.*

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STUDIU PRIVIND METODELE DE DETERMINARE A COEFICIENTULUI DE CONDUCTIVITATE TERMICĂ AL MATERIALELOR DE CONSTRUCȚIE

(Rezumat)

Cu toate că nivelul în care oamenii sunt afectați de încălzirea globală în prezent este diferit în funcție de unde aceștia locuiesc pe glob, aceasta este o problemă actuală a societății cu o importanță deosebită, care privește fiecare persoană. Astfel, pentru fiecare din domeniile de activitate, cu trecerea timpului și conștientizarea situației, au început să se dezvolte soluții, care să contribuie la reducerea încălzirii globale.

Faptul că cea mai mare pondere din totalul de energie consumat este cea a sectorului construcțiilor, acesta a condus la o dezvoltare excepțională a domeniului performanței energetice a clădirilor. Astfel, există un interes constant în dezvoltarea de noi materiale termoizolatoare performante, în alcătuirea sistemelor de protecție termică sau în dezvoltarea conformărilor energetice. Un factor cheie în participarea la reducerea încălzirii globale îl reprezintă determinarea consumului real de energie generat de utilizarea clădirilor.

Articolul prezintă principalele metode de determinarea a coeficientului de conductivitate termică a materialelor termoizolatoare și extinderi ale metodelor convenționale prezentate în literatura de specialitate. De asemenea, se vor analiza comparativ avantajele și dezavantajele metodelor.