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Review

# Reflective multi-foil insulations for buildings: A review

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ABSTRACT

Slightly more than a decade ago, reflective multi-foil insulations were introduced onto the building market as a highly promising new type of thermal insulation material. These materials consist of several layers of thin metallic foil or metallised polymer film with a low emission coefficient combined with spacer materials in-between. Because of the low emission coefficient of the foils, radiation through the insulation material is significantly reduced as a result of which these materials are claimed to have very high thermal resistance, even up to 5 or 6 $m^2$ K/W. However, debate is still ongoing into whether these claims are correct. In contrast to some in situ measurements, hot box and hot plate measurements performed in laboratories result in much lower thermal resistance values. Based on a review of research reports and journal papers, this paper identifies the causes for the different results among different research institutes. From this analysis, conclusions are drawn about the thermal performance that can likely be expected from reflective multi-foil insulations.

**Contents**

## 1. Introduction

The attention for energy use reduction as an economic necessity and as a way of mitigating climate change has resulted in new building products. Somewhat more than a decade ago, reflective multi-foil insulations were introduced onto the building market as a highly promising new type of thermal insulation material. Although these materials are relatively new for buildings, they already have a longer history in the field of cryogenic engineering where they have been applied at atmospheric pressure [1,2] and at very low pressure [3–6]. Particularly these evacuated multi-foil insulations can achieve very low effective thermal conductivity even down to $1 \times 10^{-5}$ W/(m K) [3]. New developments for this type of evacuated reflective multi-foil insulations deal with the internal structure of these insulation materials so that an additional spacer material is no longer required [7]. Moreover, interest has arisen for high temperature applications [8,9]. This article will, however, deal with non-evacuated reflective multi-foil insulation for buildings (Fig. 1).

These reflective multi-foil insulations consist of several layers of thin metallic foil or metallised polymer film with a low emission coefficient for long-wave radiation. The foils are separated from each other by a spacer material which creates a distance between the foils in the order of 2–8 mm. Typically these spacer materials are made of closed-cell polymer foam, polyester wool or bubble foil (Table 1). Thin layers of polyethylene film or polyester fleece are

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**Table 1**
Overview of different types of reflective insulations.

| Type | Name | Characteristics |
|---|---|---|
| 1 | Thermal insulation board with reflective exterior | Insulation material of polymer foam (like PIR or EPS), glass wool (MWG) or rock wool (MWR) with on one or two sides a low-emissivity foil or coating. |
| 2A and 2B | Reflective multi-foil insulation | Multi-foil consisting of layers of metal foil or metallised polymer film, spacer material (for instance PE film of polyester fleece) and closed-cell polymer foam or polyester wool. In practice the number of layers varies between 5 and 20. The first and last layers consist of a (reinforced) coated aluminium foil. |
| 3 | Thin reflective (bubble) foil | This product has a thickness of less than 2 mm and consist typically of a bubble foil with on one or sometimes two sides a metal foil or metallised polymer film with low emissivity, as a result increasing the thermal resistance of the adjoining air spaces; The product itself hardly has any thermal resistance. |
| 4 | Reflective foils and thermos cushions | Reflective foils and thermos cushions consist of air cushions of metallised polymer film; thermos cushions are a foldable insulation material in which one or two air layers are trapped. |

Adapted from [14].

**Fig. 1.** Example of a reflective multi-foil insulation material.

sometimes added between the reflective foils and spacer materials as well [10–14]. The total thickness of such a package of multiple foils typically is in the range of 10–30 mm. Because of the low emission coefficients of the foils, radiation through the insulation material is significantly reduced, because of which some manufacturers claim very high thermal performance for these reflective multi-foil insulation materials. Examples of how this type of insulation material is used in buildings are shown in Figs. 2 and 3. Other ways of using reflective 'insulation' materials, is to equip one or two sides of a conventional insulation material with a highly reflective coating [15,16] or to use single-layer radiant barriers as part of a roof construction mainly to reduce solar heat gains [16–19].

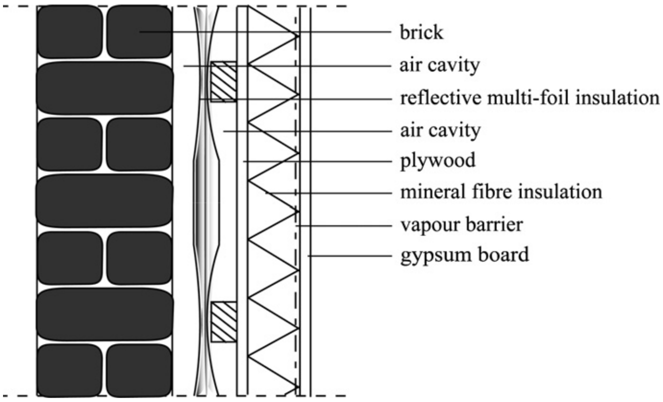

**Fig. 2.** Example of a timber frame wall with both reflective multi-foil insulation and 60 mm mineral fibre insulation. *R*-value of this total wall construction including standard boundary resistances is likely to be between 3.7 and 4.1 $m^2$ K/W.

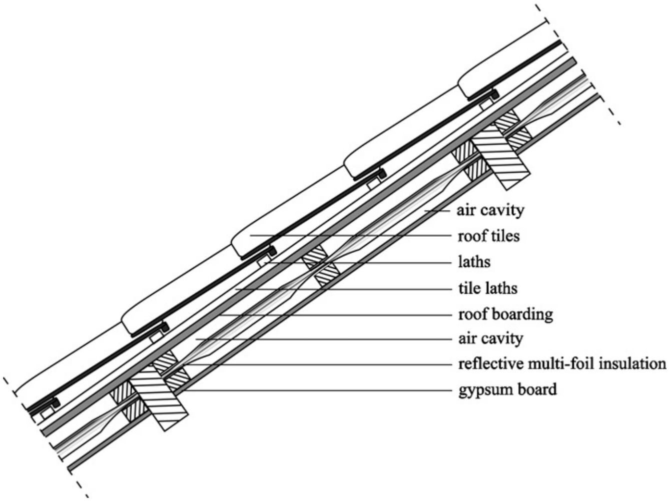

**Fig. 3.** Example of a roof construction with reflective multi-foil insulation. *R*-value of this total roof construction including standard boundary resistances is likely to be between 1.7 and 2.1 $m^2$ K/W.

Medina [17], for instance, showed that for the subtropical climate of Austin, Texas, with hot summers and mild winters radiant barriers combined with fibreglass insulation with $R = 1.94\ m^2$ K/W in the attic could reduce the heat load from the roof with 44% over a whole year. Combined with fibreglass insulation with $R = 3.35\ m^2$ K/W this reduction was 28%. This shows the potential of radiant barriers and similarly of other reflective insulation materials. Radiant barriers will, however, not be discussed in this article.

Several research institutes have tested different types of reflective multi-foil insulations using different test set-ups and equipment. On the one hand you have the measurements performed in a laboratory under strict testing conditions. FIW München, NPL, WTCB, Fraunhofer IBP and Dublin Institute of Technology for instance subjected multi-foil insulations to laboratory measurements using a guarded or calibrated hot box apparatus [20–25]. WTCB and Fraunhofer IBP also used a guarded hot plate apparatus to determine the equivalent thermal conductivity of this type of insulation material [21,24]. NPL also performed lab measurements with a heat flow metre apparatus [22]. On the other hand you have measurements performed in practice under real life conditions. BRE and Alba Building Sciences Ltd and the University of Reunion for example used a heat flow metre apparatus and thermocouples to determine the thermal resistance of built walls, roofs or floors insulated with reflective multi-foil insulations [26–29]. From these thermal resistance values they were able to deduce the thermal resistance of the insulation material (including air gaps). Sheffield Hallam University, Trada UK, WTCB, Fraunhofer

IBP, SFRIMM, CSTB and TNO Quality Services finally developed a set of test houses, one insulated with common mineral fibre insulation and the other with reflective multi-foil insulation to do a comparative study between the performance of mineral fibre insulation and reflective multi-foil insulation [21,24,25,30–35]. They compared the energy use of both houses to each other to draw conclusions on the thermal performance of reflective multi-foil insulation materials.

However, big differences in thermal resistance of reflective multi-foil insulations are reported between the laboratory measurements on the one hand and the in situ measurements with the test houses on the other hand. This has led to a fierce debate particularly among different manufacturers of insulation materials and has resulted in the development of the European standard EN16012:2010 [36] and a Dutch publication with guidelines [14]. The standard specifies that manufacturers should present the thermal resistance of the multi-foil reflective insulation material's core material but also allows manufacturers to specify a so-called Manufacturers Declared Value which includes two 25 mm thick air cavities.

This paper presents a review of the literature on this type of thermal insulation material for application in buildings. Based upon this review and upon a description of the calculation procedure an expected thermal resistance value for this type of product is being suggested.

This paper starts with first describing the studies that have been done into non-evacuated multi-foil insulation materials per type of investigation: hot box measurements (Section 2), hot plate measurements (Section 3), in situ measurements with a heat flow metre apparatus (Section 4) and comparative in situ measurements using test houses (Section 5). In Section 6 differences among the results of these studies are explored. In Section 7 the standard calculation procedure of calculating the thermal resistance of reflective multi-foil insulation materials is presented. Opaque insulation in heated spaces is the reference situation, meaning that the focus is on preventing heat losses.

## 2. Hot box measurements

Hot box measurements on reflective multi-foil insulations have been performed at the Research Institute for Thermal Insulation München (FIW München), the National Physical Laboratory (NPL), the Belgian Building Research Institute (BBRI/WTCB), the Fraunhofer Institute for Building Physics (Fraunhofer IBP) and the Dublin Institute of Technology. The tests were performed according to international standard NEN-EN-ISO8990:2007 [37]. Fig. 4 presents a cross-section through a typical hot box apparatus. An overview of the results of these studies is presented in Table 2.

The studies that use a guarded or calibrated hot box apparatus in a laboratory setting generally find a thermal resistance from approximately 1.5 m$^2$ K/W to just above 2.0 m$^2$ K/W with a thickness of the multi-foil reflective insulation of around 20 mm [20–25]. The exact value depends on thickness of the insulation material, existence and thickness of air cavities on both sides of the insulation material, direction of the heat flow and emission coefficients of the foils. The results show that a multi-foil reflective insulation material has the best thermal performance if the heat flow is downwards or in other words if the insulation material is placed on top of or below a floor of a heated space. The worse thermal performance occurs for an upward heat flow, i.e. application in a roof. This can easily be explained by the influence of convection in the air cavities along the insulation material. The measurements conducted by the Fraunhofer IBP institute [23,24], two measurements by the Dublin Institute of Technology [25], and one measurement of the British Board of Agrément [39] show a somewhat lower thermal resistance of the insulation material. The main reason for this is that no air cavity exists on both sides of the insulation material while the hot box specimens used in other studies did have such air cavities. In case of the Fraunhofer IBP study, the insulation specimens directly bordered the air of the two rooms in the box, while in case of the Dublin Institute of Technology study the specimen on one side bordered an air cavity and on the other side the air of the room.

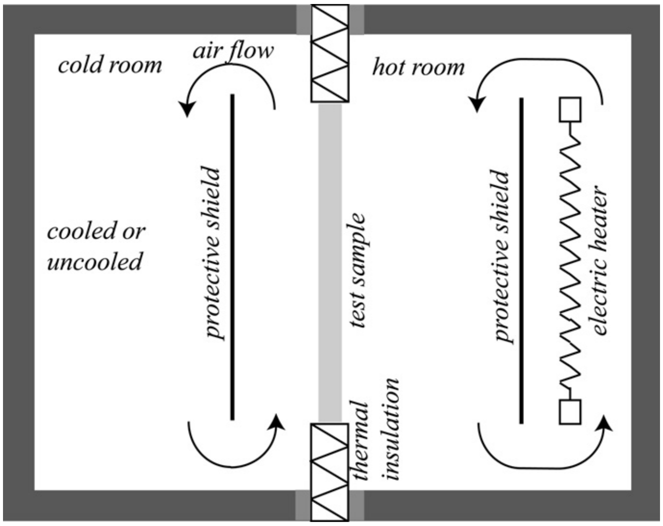

**Fig. 4.** Schematic section through a hot box apparatus. The hot (or cold) room can also be encased in a larger protective room.

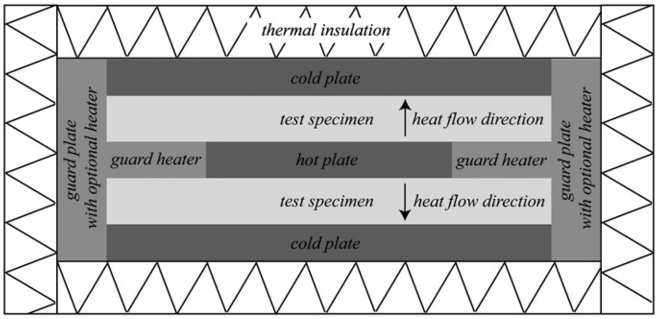

**Fig. 5.** Principal schematic section through a guarded hot plate apparatus.

## 3. Hot plate measurements

Only the Belgian Building Research Institute (BBRI/WTCB) and the Fraunhofer Institute for Building Physics (Fraunhofer IBP) performed guarded hot plate measurements on reflective multi-foil insulations in conjunction with hot box measurements. These tests were performed according to international standard ISO8302:1991 [40]. Fig. 5 presents a principal cross-section through a typical guarded hot plate apparatus. An overview of the results of these studies is presented in Table 3.

The measurements with a guarded hot plate apparatus show lower thermal resistance values than the measurements with the hot box [21,24]; thermal resistance values between 0.47 and 0.60 m$^2$ K/W are found. The reason for these lower values is that the hot box measurements typically include the thermal resistance of one or two air cavities along the insulation material. In case of hot plate measurements however such air cavities are not present; the reflective multi-foil insulation material typically borders a rubber mat that is placed between the specimen and the heated or cooled

**Table 2**
Overview of studies into the thermal performance of reflective multi-foil insulation materials using the hot box method.

| (Guarded of calibrated) hot box method | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Research institute | Year | Uncompressed thickness [mm] | Thickness of cavities aside the insulation material [mm] | $\varepsilon_{\text{folie}}$ | $\Delta T$ [K] | $T_{av}$ [°C] | $R_{\text{tot}}$ [m$^2$ K/W] | | | Sources |
| | | | | | | | Heat flow ↑ | Heat flow ↓ | Heat flow → | |
| FIW München | 2001 | 25 | n.a.[a] | n.a. | n.a. | n.a. | 1.21 | | | [20] ref. to [38] |
| NPL | 2004 | 7.49 | 2 × 20 | 0.06 ± 0.01 | n.a. | n.a. | – | 1.60 ± 0.06 | – | [20–22] |
| | | 25[b] | 1 × 90 | Not measured | n.a. | n.a. | ±1.40/±1.46[c] | – | 1.60 | |
| | | 25[b] | 2 × 45 | Not measured | n.a. | n.a. | 1.71/±1.80[c] | – | 1.89 | |
| WTCB | 2006 | 7.5 | 2 × 20 | 0.06 ± 0.01[d] | 10 | 10 | 1.05 ± 0.06 | 1.53 ± 0.09 | – | [21] |
| | | 18.8 | 2 × 20 | 0.18 ± 0.02[d] | 10 | 10 | 1.55 ± 0.09 | 1.61 ± 0.10 | – | |
| | | 19.2 | 2 × 20 | 0.19 ± 0.11/0.16 ± 0.13[d] | 10 | 10 | 1.26 ± 0.08 | 1.63 ± 0.10 | – | |
| NPL | 2007 | 23 (mean) | ±43 and ±83 | Not measured | 19 | 10 | 1.89 ± 0.08 | 2.88 ± 0.12 | 2.04 ± 0.08 | [22] |
| Fraunhofer IBP | 2007 | n.a. | None[a] | Not measured | 20.7 | 10.5 | – | – | 0.72 | |
| | | n.a. | n.a. | | 20.8 | 9.7 | – | – | n.d. | [23] |
| | | n.a. | n.a. | | 20.8[e] | 9.7 | – | – | n.d. | |
| | | n.a. | n.a. | | 0.0[f] | 25.0 | – | – | n.d. | |
| BBA | 2006–2007 | 30 | ±25 and ±70 | 0.16 | n.a. | n.a. | 1.69[g] | – | – | [39] |
| | | 30 | None[a] | 0.16 | n.a. | n.a. | 0.91[g] | – | – | |
| Fraunhofer IBP | 2007–2008 | n.a. | None[a] | 0.05 | n.a. | n.a. | – | – | 1.00 | [24] |
| Dublin Institute of Technology | 2009 | 25 | 50 and 32 | Not measured | 25.6 | n.a. | – | – | 1.68 ± 0.30[i] | [25] |
| | | 25 | 95 and big[h] | | 26.7 | n.a. | – | – | 1.00 | |
| | | | 95 and big[h] | | 27.1 | n.a. | – | – | 0.70 | |

n.d. means ‘data cannot be determined from the results.

n.a. means ‘data not available’.

[a] During these measurements the foil insulation material was not built into a construction but was tested as a single material. The material thus bordered the adjacent air.

[b] More values for three heat flow directions and different cavity widths can be found in the report. The measured values range from just below 1.1 m$^2$ K/W to around 1.4 m$^2$ K/W for two cavities of 30 mm and from just below 1.3 m$^2$ K/W to around 2.0 m$^2$ K/W for two cavities of 60–65 mm.

[c] The test equipment had a slope of 45°.

[d] Measured by TNO.

[e] During this measurement there was an additional cold surface (−25 °C) on the cold side of the specimen simulating the effect of night-sky radiation on the roof component.

[f] During this measurement there was an additional hot surface which emitted 600 W/m$^2$ of heat towards the outer surface of the roof component simulating the effect solar radiation.

[g] This value also includes thermal bridge effects caused by a wooden frame. The measured were performed under a slope of 45°.

[h] One side of the insulation material directly bordered on the air of the room (the smaller surface film coefficient is considered in this value).

[i] This value includes the gypsum board on one side of the construction.

**Table 3**
Overview of studies into the thermal performance of reflective multi-foil insulation materials using the guarded hot plate method.

| Guarded hot plate method | | | | | | | |
|---|---|---|---|---|---|---|---|
| Research institute | Year | Uncompressed thickness [mm] | $\varepsilon_{\text{folie}}$ | $\Delta T$ [K] | $T_{av}$ [°C] | $R_{\text{tot}}$ [m$^2$ K/W] Heat flow | Sources |
| WTCB | 2006 | 7.5 | $0.06 \pm 0.01$ | 10 | 10 | $0.205 \pm 0.004$ | [21] |
| | | 18.8 | $0.18 \pm 0.02$ | 10 | 10 | $0.602 \pm 0.012$ | |
| | | 19.2 | $0.19 \pm 0.11/0.16 \pm 0.13$ | 10 | 10 | $0.469 \pm 0.009$ | |
| Fraunhofer IBP | 2007–2008 | n.a. | 0.05 | n.a. | n.a. | 0.5 | [24] |

plates. As a consequence, the results of the hot plate measurements only include the thermal resistance of the insulation material itself.

The thermal resistances measured with the guarded hot plate apparatus are also lower than the results of the hot box measurements by the Fraunhofer IBP [23,24] and the last two measurements of the Dublin Institute of Technology [25]. The difference comes from absence of surface resistances.

## 4. In situ and lab measurements with a heat flow metre

In situ measurements with a heat flow metre were performed by the Building Research Establishment [26], Alba Building Sciences Ltd. [27,28] and the University of Reunion [29]. Moreover lab measurements with a heat flow metre apparatus have been performed by the National Physics Laboratory [22]. The results of these studies are presented in Table 4. It is here important to mention that Saber [41] showed that a heat flow metre in accordance with standard ASTM C-518 underestimates the effective *R*-value of materials or products that include radiation shields in combination with wide cavities (more than 25 mm). The main reason lies in non-uniform convective flows in these cavities.

The in situ measurements with a heat flow metre conducted by the Building Research Establishment (BRE), most measurements of the University of Reunion[1] and the lab measurements from NPL also show thermal resistance values in the same order as the hot box measurements discussed previously: between 1.0 and 1.9 m$^2$ K/W depending on heat flow direction [22,26]. In all cases, the same construction property is measured: the thermal resistance of the reflective multi-foil insulation itself plus the thermal resistance of the two adjacent non-ventilated air cavities (and in some cases including a small thermal resistance of some other materials). The difference between the two measurement situations is that the hot box measurements are conducted in a laboratory in a controlled environment while some measurements with heat flow metre are done in actual buildings. This difference is clearly visible in the differences in specified uncertainties.

The thermal resistance values of reflective multi-foil insulations measured by Alba Building Sciences Ltd however are significantly higher than the lab measurements [27,28]. Moreover, it is striking that Alba Building Sciences twice measured the same facade of a building on Victoria Road, Aberdeen, only one month after each other resulting in a factor 2 difference in measured thermal resistance of the reflective multi-foil insulation in this facade (1.86 m$^2$ K/W versus 2.44 m$^2$ K/W). After inspection, the researchers concluded that the multi-foil insulation during the first measurement (1.86 m$^2$ K/W) was inaccurately installed and that air leaks disturbed the heat flows.

One other interesting study, not presented in Table 4, was conducted in 2010 at Eindhoven University of Technology ([14] referring to [42]). van der Meijden ([14] referring to [42]) was interested whether the reflective foils inside the insulation material have any effect on the total thermal resistance of the system. To be precise, he investigated whether 4 layers of 9 mm polyester wool with reflective foils only on the outside have the same thermal resistance as 4 layers of 9 mm polyester wool with both reflective foils on the outside of the material and in-between each layer. Fig. 6 presents some of the results. As can be seen, adding reflective foils between the layers of polyester wool (+3+7 and +5; blue line) further increases the thermal resistance. He repeated the test with (translucent) 0.2 mm thick polyethylene film instead of reflective foil. This improved the performance as well, but less than the multi-reflection stop. Four reflective stops give a better result than two reflective stops.

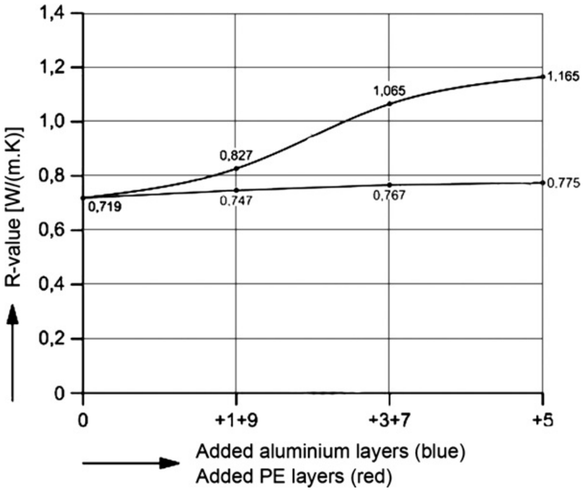

**Fig. 6.** The influence of additional reflective layers on the thermal resistance of reflective multi-foil insulation.

Adapted from [14].

Finally, the study done by Pasztory et al. [43] should be mentioned. With the objective of developing a new, cheap and robust reflective multi-plate insulation measurements were conducted on samples with differing number of radiation shields and differing width of the cavities between these shields. These measurements were conducted using a heat flow metre apparatus according to ISO8301:1991 [44]. By increasing the number of radiation barriers, and as a result decreasing the width between the barriers, the effective thermal conductivity of the system decreased. This decrease was not linear however. The first inserted radiation barrier reduced the effective thermal conductivity of the system more strongly than additional barriers.

## 5. Comparative measurements with test houses

Many research institutes conducted studies into the thermal performance of reflective multi-foil insulation materials using comparative measurements between two test houses

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[1] According to Miranville et al. [29], the higher thermal resistance value in winter with a naturally ventilated upper air cavity measured by the University of Reunion results from the high wind speeds in the cavity resulting from the trade winds. According to them these higher air speeds increase the thermal resistance of the roof construction.

**Table 4**

Overview of studies into the thermal performance of reflective multi-foil insulation materials based on in situ or lab measurements with a heat flow metre.

In situ and lab measurements with a heat flow apparatus

| Research institute | Year | Uncompressed thickness [mm] | Thickness of cavities aside the insulation material [mm] | $\varepsilon_{\text{folie}}$ | $\Delta T$ [K] | $T_{av}$ [°C] | $R_{\text{tot}}$ [m$^2$ K/W] | | | Sources |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Heat flow ↑ | Heat flow ↓ | Heat flow → | |
| BRE (in situ) | 2005 | 25 | $2 \times 25$ | Not measured | n.a. | n.a. | – | – | $1.72 \pm 0.31$ | [26] |
| | | 25 | 430 and 15 | | | | $0.96 \pm 0.19$ | – | – | |
| | | 25 | 15 and crawl space | | | | – | $1.85 \pm 0.31$ | – | |
| Alba Building Sciences Ltd (in situ) | 2006 | 25 | 100 and 25 | Not measured | 23.8 | n.a. | – | – | ±1.90[a,b] | [27,28] |
| | | 25 | 100 and 25 | Not measured | 19.6 | n.a. | – | – | ±3.48[a,c] | |
| | | 25 | 100 and 25 | Not measured | 25.2 | n.a. | – | – | ±3.61[a] | |
| NPL (lab) | 2007 | 23 (average) | Total cavity 85 mm | Not measured | 20 | 10 | 1.73 | 2.47 | – | [22] |
| | | | Total cavity 85 mm | Not measured | 20 | 25 | 1.70 | 2.19 | – | |
| University of Reunion | 2012 | 25 | n.a. | Not measured | n.a. | – | 1.44[d] | – | – | [29] |
| | | 25 | n.a. | Not measured | n.a. | – | 1.47[e] | – | – | |
| | | 25 | n.a. | Not measured | n.a. | – | 6.24[f] | – | – | |
| | | 25 | n.a. | Not measured | n.a. | – | 1.66[g] | – | – | |

n.a. means ‘data not available’.

[a] These values were derived from the measured *U*-values of the entire wall. The following were assumed for the calculation: thermal conductivity of granite and plasterboard is 2.2 resp. 0.17 W/(m K); only outdoor boundary resistance of 0.04 m$^2$ K/W was assumed due to the way of measuring.

[b] This value is the result of a first measurement in the house Victoria Road 139b, Aberdeen from February 2006 [27].

[c] This value is the result of a second measurement in the house Victoria Road 139b, Aberdeen from March 2006 [28].

[d] Summer conditions and upper air cavity naturally ventilated; slope of the roof was 20°.

[e] Summer conditions and no air cavity naturally ventilated; slope of the roof was 20°.

[f] Winter conditions and upper air cavity naturally ventilated; slope of the roof was 20°.

[g] Winter conditions and no air cavity naturally ventilated; slope of the roof was 20°.

**Table 5**

Overview of studies into the thermal performance of reflective multi-foil insulation materials based on comparative measurements with test houses.

| Comparative measurements using test houses | | | | | | | |
|---|---|---|---|---|---|---|---|
| Research institute | year | Uncompressed thickness [mm] | Thickness of cavities aside the insulation material [mm] | $\varepsilon_{\text{folie}}$ | $R_{\text{tot}}$ [m$^2$ K/W] | | Sources |
| | | | | | Heat flow ↗ (roof) | Heat flow → (wall) | |
| Sheffield hallam University, CIM | 2004–2005 | 25 | n.a. | Not measured | 20 cm glasswool + 26% | – | [25] |
| Sheffield hallam University, CIM | 2005 | 30 | 30/40 and big | Not measured | 20 cm glasswool + 39.8%[a] | – | [25] |
| | | 30 | 30/40 and big | Not measured | 20 cm glasswool + 8.7%[a] | | |
| | | 30 | 30/40 and big | Not measured | 20 cm glasswool + 2.8%[a] | | |
| TRADA UK | 2006 | 30 | n.a. | Not measured | ±21 cm glasswool | – | [25,30] |
| WTCB | 2006 | 7.5 | 2 × 20 | $0.06 \pm 0.01$ | – | 1.73 | [21] |
| | | 18.8 | 2 × 20 | $0.18 \pm 0.02$ | – | 1.72 | |
| | | 18.8 | 2 × 10 | $0.18 \pm 0.02$ | – | 1.43 | |
| | | 19.2 | 2 × 20 | $0.19 \pm 0.11/0.16 \pm 0.13$ | – | 1.55 | |
| | | 19.2 | 1 × 10 | $0.19 \pm 0.11/0.16 \pm 0.13$ | – | 1.15 | |
| Fraunhofer IBP | 2007 | 25 | 120 + 160 and 60 | Not measured | ±20 cm glass wool (heat supply)/±3.33 (heat flow metre) | – | [31] |
| SFRIMM | 2007 | n.a. | 140 and 40 | Not measured | 20 cm glass wool l + 28.4% | – | [25] |
| CSTB | 2005–2006 | n.a. | 80 and 100 | Not measured | 20 cm glass wool – 50.2% | | [32] |
| Fraunhofer IBP | 2007–2008 | n.a. | 120 + 195 and 45<br>120–240 | 0.05 | 2.0 | – | [24,33,34] |
| TNO Q&S | 2010 | 24[b] | n.a. | Not measured | – | $2.36 \pm 0.02$ | [35] |
| | | 40[b] | n.a. | Not measured | – | $3.42 \pm 0.02$ | |

n.a. means 'data not available'.

[a] The first measurement was conducted with an indoor temperature of 21 °C and an outdoor temperature of −5 °C; the second measurement with 21 °C and 0 °C; the third measurement with 21 °C and 5 °C.

[b] The outer layers were made of 2 × 8 mm bubble foil and not of reflective foil.

[21,24,25,30–32,35]. The results of these studies are presented in Table 5.

This type of study is not standardized but in principle can be explained as follows. Two identical test houses or roof constructions are built; one is insulated with 200 mm mineral fibre insulation with "known" (better: presumed) thermal resistance and functions as a reference; the other is insulated with reflective multi-foil insulation and functions as the test case; next, both test houses are subjected to identical (real or simulated) weather conditions and the energy demand for maintaining a constant indoor temperature is monitored; this energy demand is then compared between the two houses; finally the thermal resistance of the reflective multi-foil insulation is estimated from a this comparison on energy demand and the "known" properties of mineral fibre insulation. So, if the energy demand in both test houses is identical, then the multi-foil reflective insulation is supposed to have the same thermal resistance as the 200 mm mineral fibre insulation. If the energy use of the test house with the multi-foil reflective insulation is *x*% higher/lower, then the thermal resistance of the multi-foil insulation is supposed to be *x*% lower/higher than of the mineral fibre insulation.

The results of the comparative measurements are not very consistent with each other. WTCB's measured values using test houses are in agreement with their hot box results and their calculated values [21]. Also the comparative measurements by the Fraunhofer IBP from 2007/2008 [24,33] and the measurements from CSTB [32] resulted in thermal resistance values which are only slightly higher than measured by other research institutes using the hot box technique. The thermal resistance of reflective multi-foil insulation materials with a thickness of around 20 mm was found to be in the order of 1.5–2.5 $m^2$ K/W by WTCB, Fraunhofer IBP and CSTB. However, the studies by Sheffield Hallam University, Trada UK, Fraunhofer IBP from 2005 to 2007, SFRIMM and TNO Q&S found much higher thermal resistances, even up to 6.1 $m^2$ K/W using the comparative test method [25,30,31,35]. In the next section the most important causes for these differences are identified.

## 6. Discussion of differences between measurement results

A closer look at the results of the comparative measurements shows us that the thermal resistance of reflective multi-foil insulation derived from these measurements is based on the known thermal resistance of 200 mm mineral fibre insulation, which is around 5.0 $m^2$ K/W. However, such a comparison is only allowed if both test houses are exactly identical. This criterion however is not always met. Three factors play an important role here: air tightness of both test houses, the role of ventilated and non-ventilated air cavities, and the influence of thermal bridges.

### 6.1. Air tightness

The research report by Fraunhofer IBP [31] clearly shows the importance of differences in air tightness between both test houses. During the experiment both the test house insulated with 200 mm mineral fibre insulation and the test house insulated with a reflective multi-foil insulation of around 20 mm thick have an almost identical heat loss. Purely based upon this result one could conclude that the reflective multi-foil insulation (including adjacent air cavities) has an identical thermal resistance as 200 mm mineral fibre insulation. However, the investigators also conducted a blower door test in both test houses which showed that at a pressure difference of 50 Pa the air tightness in the test house with mineral fibre insulation was $n_{50} = 1.3\,h^{-1}$ while it was $n_{50} = 0.9\,h^{-1}$ in the other test house. This means that the infiltration losses in the test house with mineral fibre insulation were 45% higher. If these infiltration losses are not correctly considered, the higher air tightness of the test house with reflective multi-foil insulation is incorrectly attributed to the thermal resistance of this insulation material. The investigators from Fraunhofer IBP also determined the thermal resistance of the reflective multi-foil insulation material in the roof with a heat flow metre apparatus as 3.33 $m^2$ K/W. This is approximately two thirds of the value of 200 mm mineral fibre insulation.

In a follow-up study by Fraunhofer IBP in 2007–2008, the researchers attempted to get the air tightness of both test houses as close together as possible and as small as possible [24]. In that study a 20–22 mm thick reflective multi-foil insulation was found to have a thermal resistance of 2.0 $m^2$ K/W including air cavities. Also the study by CSTB [32] shows that, if the air tightness of both test houses is practically identical, the test house insulated with a 20–25 mm thick reflective multi-foil insulation uses twice as much energy to maintain a constant and the same indoor temperature as the test house insulated with 200 mm mineral fibre insulation. Higher air tightness should thus not be attributed to an intrinsic construction property as thermal resistance.

### 6.2. Ventilated or unventilated air cavities

Another factor that influences the result of the measurements with test houses is whether the cavity alongside the reflective multi-foil insulation is ventilated or not (or weakly ventilated). NPL studied the effect of opening the cavity on the cold side of a roof construction on the thermal resistance of the reflective multi-foil insulation including cavity [22]. In case of a ventilated air cavity, the thermal transmittance of the entire construction, i.e. its *U*-value, was 9% higher compared to the construction with non-ventilated air cavity. This implies that the thermal resistance of the total construction is a factor 1/1.09 smaller. This can be explained by the fact that in a well-ventilated air cavity the surrounding surfaces have a temperature close to the temperature of the air with which the cavity is ventilated.[2] As a consequence, the insulating performance of the cavity is reduced; the resistance that remains is the convective boundary resistance between the surface of the reflective multi-foil insulation and the air, the magnitude of which depending on the velocity of the air flow.

### 6.3. Thermal bridges

A third factor that may lead to differences in the results of hot box measurements and measurements using the test houses can also be found in the report by Fraunhofer IBP [31] and in the paper by Belusko et al. [16]: thermal bridges. Because in the test houses the mineral fibre insulation and the reflective multi-foil insulation may be installed at a different position in the roof construction, i.e. between versus below the beams of the roof structure, the extent of the thermal bridges caused by for instance these roof beams may be different in both houses. Moreover, because of differences in installation, differences in 3D heat flows may occur. Both factors may result in an overestimation of the thermal resistance of the reflective multi-foil insulation compared to the mineral fibre insulation.

## 7. Calculation model for reflective multi-foil insulations

A description of the computation scheme for calculating the thermal resistance of multi-foil thermal insulation materials can be found in NEN-EN-ISO6946:2008 Annex B [45] but also in many

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[2] A surface film resistance causes a small temperature difference.

standard textbooks on building physics. In this model the heat transfer through a cavity with a certain thickness and with length and width more than 10 times the thickness is divided into conduction, convection and radiation. In very thin, non-ventilated or weakly ventilated cavities convection can be neglected[3]; the resulting heat transfer coefficient then is the sum of the conductive and radiative heat transfer coefficients. In wide cavities conduction can be neglected; the resulting heat transfer coefficient then equals the sum of the convective and radiative heat transfer coefficients.

Conduction is a result of either electron or phonon (collisions of molecules or atoms) transport in matter. Since heat transfer by electrons is much quicker than by phonons, metals conduct heat more easily than plastics. Conduction can occur in solids, liquids and gases. The conductive heat transfer coefficient in a cavity depends on the thickness of the cavity, *d*, and the thermal conductivity of the substance in the cavity, λ. It is calculated as

$$h_{a;cond} = \frac{\lambda}{d} \tag{1}$$

When the molecules are not restricted in their movement at room temperature at atmospheric pressure, the thermal conductivity of air inside a cavity equals 0.025 W/(m K).

Convection is heat transfer resulting from the bulk movement of molecules typically caused by a pressure difference which may be caused by a temperature difference. Heat is then transferred as internal energy along with the molecules. Also along the interface between a solid and a gas convective heat transfer occurs. Here, the boundary resistance needs to be considered. The thickness of the boundary layer is strongly affected by the speed of the air flow passing along the surface: the higher this speed is, the thinner the boundary layer is, and the higher the convective heat transfer coefficient is. This implies that in not or weakly ventilated very thin air cavities convective heat transfer may be neglected unless large temperature or pressure differences exist. The total heat transfer coefficient for convection in an air cavity depends on the direction of the heat flow and on the temperature difference over the cavity. For a temperature difference smaller than 5 K, it equals

$$h_{a;conv} = \begin{cases} 1.25 & \text{for horizontal heat flow} \\ 1.95 & \text{for upward heat flow} \\ 0.12d^{-0.44} & \text{for downward heat flow} \end{cases} \tag{2}$$

In this equation, $h_{\text{a;conv}}$ [W/(m$^2$ K)] is the total heat transfer coefficient for convection in the cavity. For cavities with bigger temperature differences other values apply.

Radiative heat transfer between two surfaces is the net energy exchange by radiation. Every object with a temperature above absolute zero emits energy with an intensity to the fourth power of its absolute temperature. Because irradiated surfaces reflect back part of the received radiation and emit radiation themselves, radiation energy exchange occurs. The radiation heat transfer coefficient depends on the Rosseland mean temperature of the cavity to the third power, $\overline{T_r^3}$ [K$^3$], the emission coefficients of both cavity surfaces, $\varepsilon_1$, $\varepsilon_2$, and the Stefan–Boltzmann constant, $\sigma$ [$5.67 \times 10^{-8}$ W/(m$^2$ K$^4$)]. The radiation heat transfer coefficient is calculated as

$$h_r = 4\varepsilon_{res}\sigma\overline{T_r^3} \tag{3}$$

$$\overline{T_r^3} = \frac{(T_1^2 + T_2^2)(T_1 + T_2)}{4} \tag{4}$$

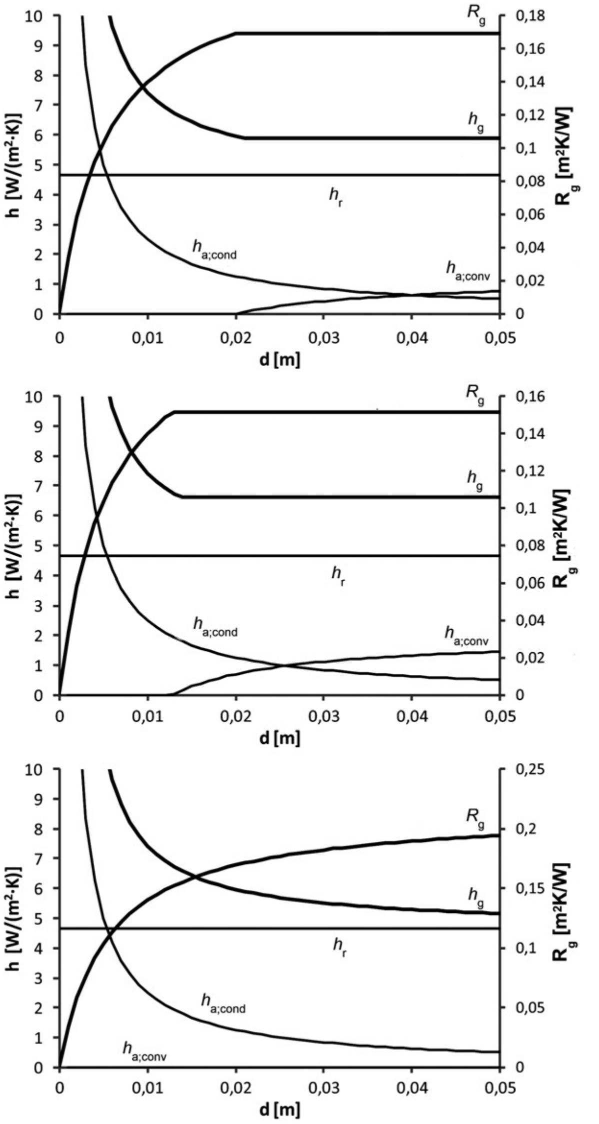

**Fig. 7.** Heat transfer coefficients for convection ($h_{a;conv}$), conduction ($h_{a;cond}$), radiation ($h_r$) and total cavity ($h_g$) and thermal resistance of the entire air cavity ($R_g$) as function of cavity thickness ($d$). Top: horizontal heat flow (in a facade); middle: upward heat flow (typically in a roof in winter); bottom: downward heat flow (typically in a floor). Calculations according to NEN-EN-ISO6946:2008. The emission coefficient of both cavity walls equals 0.95 and the temperature difference across the cavity equals 10 K.

$$\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \tag{5}$$

Particularly concerning the emission coefficients it is here also important to consider aging effects [46]. Important here for this article is also to mention that the principle of reflective multi-foil insulation is based on reducing the heat transfer coefficient for radiation by choosing materials with very low emission coefficients in the order of 0.05–0.20.

The total heat transfer coefficient, $h_g$ [W/(m$^2$ K)], and total thermal resistance of the cavity, $R_g$ [m$^2$ K/W], can now be computed from

$$h_g = h_r + \max(h_{a;cond}; h_{a;conv}) \tag{6}$$

and

$$R_g = h_g^{-1} \tag{7}$$

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[3] In a cavity thinner than approximately 20 mm for horizontal heat flow and thinner than approximately 12 mm for upward heat flow convection can be neglected. In cavities with downward heat flow convection can be neglected as well.

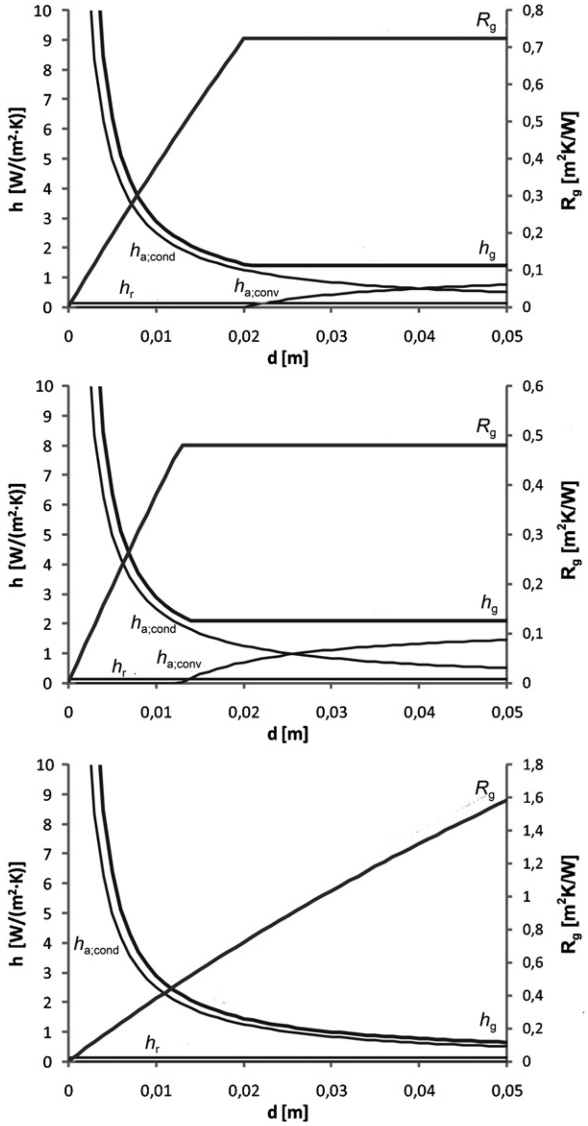

**Fig. 8.** Heat transfer coefficients for convection ($h_{a;conv}$), conduction ($h_{a;cond}$), radiation ($h_r$) and total cavity ($h_g$) and thermal resistance of the entire air cavity ($R_g$) as function of cavity thickness ($d$). Top: horizontal heat flow (in a facade); middle: upward heat flow (typically in a roof in winter); bottom: downward heat flow (typically in a floor). Calculations according to NEN-EN-ISO6946:2008. The emission coefficient of both cavity walls equals 0.05 and the temperature difference across the cavity equals 10 K.

Figs. 7 and 8 present the results of this calculation model for a cavity with horizontal heat flow (top), upward heat flow (middle) and downward heat flow (bottom) for both a cavity with two emission coefficients of 0.95 (Fig. 8) and a cavity with two emission coefficients of 0.05 (Fig. 7).

This calculation model was used by several researchers to check the results of their measurements against theory [21,22,35]. They all found a close correspondence of the thermal resistance values measured in a hot box to the theoretically predicted values for different types of materials, with a few to many layers of insulation material and reflective foils. Flamant et al. [21] for instance found the largest difference between measured and calculated thermal resistance to be 12% (product C; downward heat flow). The high thermal resistance values found by the comparative test set-ups were however not substantiated by the theory.

## 8. Conclusions

Conventional thermal insulation materials are typically tested in a laboratory with a (guarded) hot plate or with a (guarded or calibrated) hot box. The first method allows for the determination of the heat fluxes through the material alone, while the second method also allows for the inclusion of additional heat fluxes from and to its surfaces; the latter method thus allows for the thermal characterization of complete building components. Because the conditions of these two tests can be controlled, they give reliable results. Other tests, however, like the comparative tests with test houses, involve many uncontrolled variables and are very sensitive to the quality of the test houses. These latter methods therefore lead to results with high uncertainty.

Very high thermal resistances as intrinsic property of 20–30 mm thick reflective multi-foil insulation materials, of around 5–6 $m^2$ K/W, cannot be substantiated by this literature review. A thermal resistance of 1.5–2.5 $m^2$ K/W (including cavity resistances) is more likely for this type of insulation material. The upper end of this range particularly applies to floor applications while the lower end covers roof applications. It is important to stress that these values also include the thermal resistance of accompanying air cavities and are based on foil emission coefficients of around 0.05–0.2 at most. Given the same space available for insulation in the construction, solid insulation boards or blankets are thus likely to give similar or in case of wide cavities better thermal performance than reflective multi-foil insulation materials. This is especially true for applications in roofs and facades where the heat flow is upward respectively horizontal. The advantage of these reflective multi-foil insulation materials over conventional thermal insulators, however, might be that less material is needed.

From the results of this literature review, it can be concluded that the insulating performance of thin reflective multi-foil insulations is determined to a large extent by the thermal resistance of the air cavities alongside the material, to a large extent by the thickness of the insulating material and to some extent by the reflective layers. Moreover, ventilating one or both of the air cavities reduces the total thermal resistance of the building component. Since these factors have a significant influence on the value of the thermal resistance of reflective multi-foil thermal insulation materials (including air cavities), it is important that manufacturers specify the conditions under which the presented thermal resistance values are applicable. These conditions among others include the heat flow direction through the material and the thickness of air cavities alongside the material if included in the presented performance data. Only then a comparison to other insulation materials can be made.

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