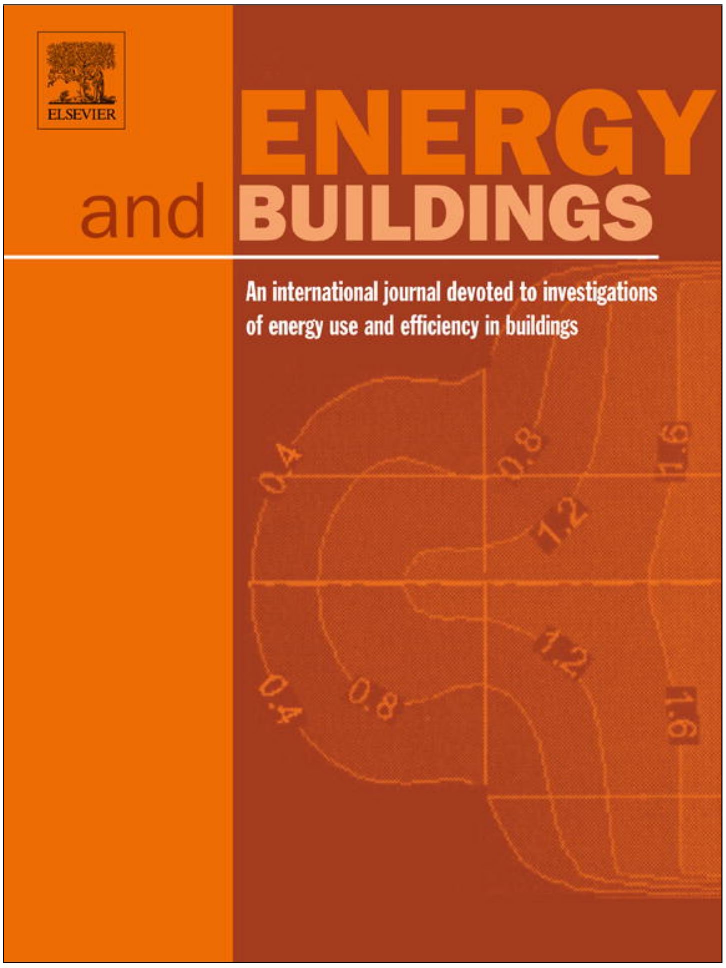
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Experimental and numerical investigations for comparing the thermal performance of infrared reflecting insulation and of mineral wool

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ABSTRACT

Some manufacturers of infrared reflective insulation products claim that their relatively thin products feature the same high thermal performance as 20 cm mineral wool. They maintain that their products cannot be described through conventional methods of building physics, their thermal efficiency can only be determined by in situ tests.

Two identical buildings, which allow comparative measurements of different roof systems under identical boundary conditions, are located at an outdoor testing facility in Southern Germany. In one of the attics a conventional roof system using mineral wool has been installed. Infrared reflective insulation has been applied to the other roof system. The products have been chosen to have the same thermal efficiency as specified by their manufacturers. Extensive comparative measurements have been carried out. Conventional laboratory measurements of the insulation products have been done and compared to the results of the in situ measurements. Furthermore, the examinations have been completed with dynamic calculations.

The result is that the examined roof system with infrared reflective insulation shows typical insulation characteristics yet with lower thermal resistance. The values of the common laboratory measurements have been confirmed through the results of the in situ measurements. Thus, the infrared reflective products (Fig. 1) can be described using traditional building physics.

1. Introduction

Energy efficiency is one of today's most discussed topics. Energy is largely used for the heating of buildings. To decrease the consumption of heating energy, heat loss through the building envelope must be reduced. Therefore, there is a need for insulation products with a high level of thermal performance. Thermal resistance is used as a parameter in classifying insulation products according to their thermal performance. To compare the quality of different kinds of insulation, it is imperative to determine thermal resistance, in accordance with generally accepted standards. Some manufacturers of infrared reflecting insulation claim that, the thermal resistance of their products can only be demonstrated by in situ tests and not by conventional methods of building physics. In some cases, values of thermal resistance are provided which were determined according to unknown methods. They are not comparable to those determined according to common standards. This matter, among others, is described in [1,2]. Investigations are already undertaken before. [3] illustrates studies of multi-layer heat insulation systems for framed construction and highlights the improvement gained by using surfaces with low emissivity. [4] includes in situ investigations of multi-foil insulation carried out on some wall and floor constructions. The results indicate that they match NPL guarded hot-box measurements. During the CEN Workshop 36 "Evaluation of thin multi-layer Reflective Insulation Products by in situ testing" [5] it was not possible to reach a consensus on an in situ test protocol which could fully assess the thermal reflective characteristics of thin multi-layer reflective insulating products.

Therefore, it is important to discuss the results of experimental and numerical investigations, in which conventional roof systems insulated with mineral wool and roof systems with infrared reflecting multifoil insulation have been compared under identical boundary conditions. The compared insulation materials are chosen to have the same thermal resistance as stated by the manufacturer.

2. Test conditions

At the outdoor testing site of the Fraunhofer Institute for Building Physics in Holzkirchen, south of Munich (Fig. 2), there are two buildings, typical one-family sized and identical in construction.

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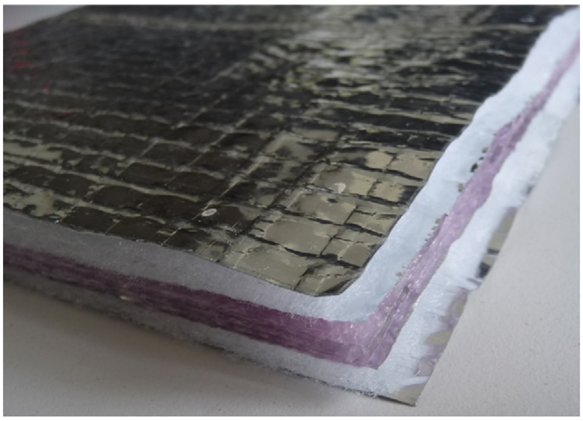


Fig. 1. Infrared reflecting insulation material (RI).

Fig. 3. Twin houses (view from south west).

Fig. 3 shows the south–west view of these so called twin houses. They are not shaded and have gabled roofs with 30° inclinations. The surface area of each roof amounts to approx. 98 m^2. The gable walls are oriented towards the east and the west. Only the attics of the houses have been used for the investigations. Each building consists of one room and is accessible from the ground floor through an air-tight, insulated hatch. To avoid heat loss on the ground floor, they were heated to 21 °C during the measurements. In addition, the ceilings of the ground floors are well insulated. The windows of the gable walls are insulated and closed by roller blinds from the outside and wooden boards from the inside.

From December 2007 to May 2009, various measurements were carried out over periods of several weeks. One roof system is insulated with infrared reflecting insulation (RI) and the other with mineral wool (MW). They were compared under identical boundary conditions. Altogether two different infrared reflecting insulation systems (Fig. 4) and three different mineral wool systems (Fig. 5) were examined. All installations were carried out using state-of-the-art technology and the instruction rules given by the manufacturers.

Fig. 2. Outdoor testing site of the Fraunhofer Institute for Building Physics in Holzkirchen.

3. Measurement set-up

An extensive measurement and control system was installed in both houses. Six measurement axes were arranged in each house to precisely analyse thermal performance: three on the southern and three on the northern side of the roof (Fig. 6). Temperature sensors were installed on all measurement axes over the entire cross section in each building component layer. The mineral wool was equipped with three to four additional intermediate temperature sensors depending on the thickness of the insulation material. Heat flow sensors were mounted on the plasterboard covering at each measurement axis. The measurement axes were arranged mid-span between two rafters. Furthermore, thermal bridges (rafter crosses batten) were analysed along the main measurement axes 2 and 5. In order to record all heat losses, heat flows and surface temperatures were also measured on gable walls, jamb walls and on the floor. Air temperature was measured in five positions at three different heights. Humidity and operative temperature were also measured. The attics were heated to 21 °C during the winter measurement periods. The electric power of the radiator was measured and used as a parameter for the heat losses. All decisive measurement data for cooling and ventilation were measured during the summer measurement period. Meteorological boundary conditions were recorded by the Institute's own weather station.

4. Energy consumption of different roof constructions

In the winter of 2007/2008 the RI roof construction 1 with internal reflective insulation (Fig. 4) was compared with three different mineral wool roof constructions (Fig. 5) during the following three measurement periods:

1. RI roof construction 1 – MW roof construction 1 (2007/12/11 to 2008/01/21)
2. RI roof construction 1 – MW roof construction 2 (2008/02/19 to 2008/03/06)
3. RI roof construction 1 – MW roof construction 3 (2008/03/20 to 2008/04/30)

In all three measurement periods, it was determined by Blower Door tests, before and after each period, that both attics are very air

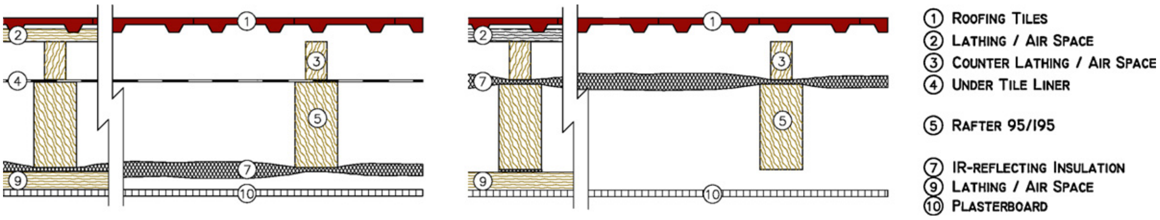


Fig. 4. RI roof construction 1 (under-rafter insulation) and 2 (over-rafter insulation).

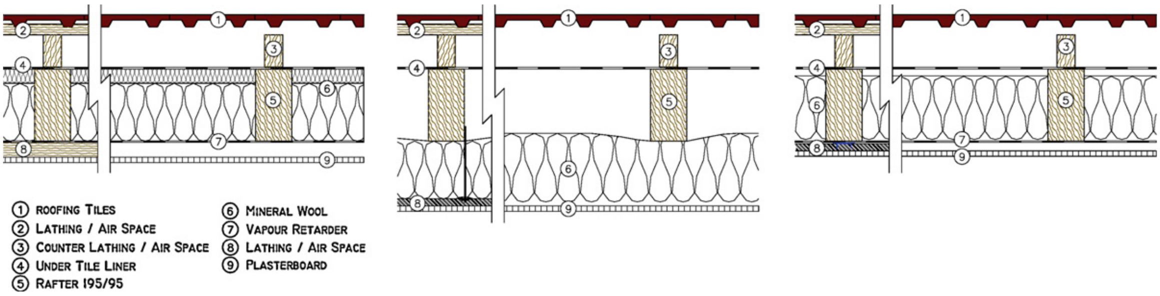


Fig. 5. MW roof construction 1 (20 cm inter-rafter insulation, WLG 035), 2 (20 cm under-rafter insulation, WLG 040, ventilated) and 3 (18 cm inter-rafter insulation, ventilated, WLG 035).

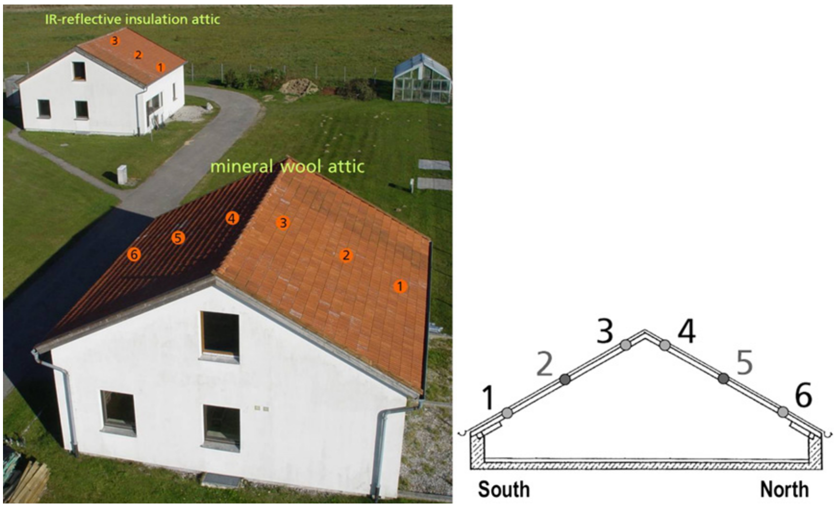


Fig. 6. Measurement axes.

Table 1
Energy balance of winter 2007/2008 (comparison of different roof constructions).

Winter 2007/2008 energy balance of various measurement periods		2007/12/11–2008/01/21 (41 days–984 h)		2008/02/19–2008/03/06 (17 days–408 h)		2008/03/22–2008/04/30 (17 days–408 h)	
Climate conditions (mean values)	Outdoor temperature Global radiation Wind velocity	−2.0 °C 46 W/m² 2.1 m/s		−4.9 °C 108 W/m² 3.9 m/s		−5.4 °C 162 W/m² 3.0 m/s	
		MW attic 1	RI attic 1	MW attic 2	RI attic 1	MW attic 3	RI attic 1
Heat losses, gables, jamb walls, floor (calculated by measured heat flows)		172 kWh	184 kWh	47 kWh	57 kWh	108 kWh	121 kWh
Heat losses by infiltration air change (according to EN 832 [6] by means of tracer gas measurement)		33 kWh	45 kWh	33 kWh	17 kWh	50 kWh	23 kWh
Energy use for heating (measured)		617 kWh 100%	1264 kWh 205%	195 kWh 100%	369 kWh 189%	439 kWh 100%	806 kWh 184%
Heat losses through the roof (calculated by energy balance)		412 kWh **100%**	1035 kWh **251%**	115 kWh **100%**	295 kWh **257%**	281 kWh **100%**	662 kWh **236%**
Estimated max. measurement error		±20 kWh	±31 kWh	±17 kWh	±22 kWh	±32 kWh	±41 kWh

tight: RI: $n_{50} \cong 0.7\,h^{-1}$; MW: $n_{50} \cong 0.6$–$1.0\,h^{-1}$. During the measurement periods infiltration heat losses were determined by Tracer Gas measurement. The attics were heated to a temperature of 21 °C using electrical radiators. The heating energy consumption serves as a parameter for the heat loss. The total energy consumptions of both attics for all three measurement periods are compared in Table 1, which features summarized transmission heat losses through all envelope surfaces except the roof, infiltration heat losses, energy consumption for heating and transmission heat losses through the roof surface areas (calculated by the energy balance). Heat losses through all envelope surfaces excluding the roof were low during all three measurement periods due to their highly thermal insulation. The heat losses by infiltration were also very low due to the high air-tightness of the buildings. Heat losses through the roof can be determined by developing an energy balance, since all other heat flows are measured directly. In all three measurement periods, twice as much energy was consumed for heating the attic which uses reflecting insulation material than in the attic with mineral wool insulation. As for the heat losses through the roof surface areas alone, in all three measurement periods the losses were 2.5-times higher for the RI roof in comparison to the MW roof. These statements refer to the cumulated values of each measurement period.

The analysis of single days with extreme weather conditions (low radiation – high radiation, windless – strong wind) shows fluctuations in these factors: on days with high radiation the ratio changes in favour of the RI roof. Due to the lower thermal resistance of the RI roof, not only are the heat losses higher than in the MW roof but also the heat gains due to radiation. Hence during days with high radiation, heat losses are reduced. Furthermore strong wind may change the ratio between the measurement results of the RI and the MW attic. Strong wind may cause air flow through the outer section of the mineral wool. As shown in a field study described in [7] this factor reduces the insulating effect depending on the wind direction relative to the orientation and design of the roof. The temperature sensors, which are equidistantly installed, show that the temperature profile over the cross section of the insulation is no longer linear. This means that the section with air flow has a lower thermal resistance than the undisturbed section.

The influence of radiation is represented by the example of a high-radiation day (January 8, 2008). Fig. 7 shows the prevailing weather conditions at that time. Due to radiation the proportion of the energy consumption for heating was reduced in the RI attic as well as in the MW attic on that day: at night, the energy consumption of the RI attic was approximately 2.1-times higher than that of the MW attic. In the afternoon this figure decreases to 1.8 due to solar radiation. In Fig. 7 the line at the bottom shows the profile of heat flows from the inside to the outside for January 8. The mean values along all measurement axes are illustrated separately for the southern and the northern roof. At night, heat losses through the RI roof were almost three times higher than those through the MW roof. During the day, heat flows were reduced due to increased outdoor temperature (northern and southern roof) and the influence of solar radiation (southern roof). The absolute reduction of the heat flows is clearly higher in the RI roof than in the MW roof. This fact is characteristic of a roof construction with a low thermal insulation effect.

5. Energy consumption in the attics with varying air-tightness

In the winter of 2008/2009 the influence of air-tightness on the proportion of energy consumption in the attics was determined. For this process, the RI roof construction 2 with external reflective insulation (Fig. 4) and the MW roof construction 3 (Fig. 5) were analysed. Different values of air-tightness were measured during three periods:

1. very air-tight ($n_{50} \simeq 0.7\,h^{-1}$)
2. limit value according to EnEV [8] naturally ventilated buildings ($n_{50} \simeq 3\,h^{-1}$)
3. not air-tight ($n_{50} \simeq 10\,h^{-1}$).

The attic's air-tightness was adjusted by drilling holes in the roof construction until the accompanying Blower Door measurement reached the required value. The attic spaces were heated to 21 °C by electrical radiators and the energy consumption was measured. The heat losses and the energy use for the heating of both attics for all three measurement periods are listed in Table 2. For all three levels of air-tightness the energy consumption of the RI attic was more than twice as high than that of the MW attic. Heat loss through the roof can be calculated by the energy balance. In all three measurement periods, heat losses through the RI roof were three times higher than those through the MW roof. Therefore, provided that air-tightness is equal in both attics, the influence of air-tightness is negligible as concerning the proportion of the cumulated energy consumption of the two attics. This proportion, however, is modified by the influence of wind. During days with strong wind, the proportion changed in favour of the RI attic due to the reduced insulating effect of the mineral wool caused by air flow. The proportion of energy consumption and the heat losses in both attics were higher in winter 2008/2009 than in winter 2007/2008. The RI roof construction 2 of 2008/2009 (Fig. 4) with only one adjacent unventilated air layer had less of an insulation effect than the RI roof construction 1 of 2007/2008 (Fig. 4) with two adjacent air layers.

6. Thermal resistance *R*: in situ – laboratory

At the accredited testing laboratory of the Fraunhofer Institute for Building Physics in Stuttgart the thermal resistance of the insulation materials of the first measurement period in winter 2007/2008 was determined according to standard test methods such as the hot plate and the hot box method. During hot plate method testing, the specimens are installed between two heating and cooling plates. A constant heat flow flows through the test specimens in the stationary temperature state. Thermal conductivity is determined by the heat flow, the mean temperature difference between the sample surfaces and the dimensions of the samples. During hot box method testing the specimen is installed between two rooms with different air temperatures. The heat flow characteristic of the heat transmission coefficient flows through the test specimen in the steady state. Table 3 shows the values of thermal resistance R determined for the insulation materials. The measurements taken using the hot box method with vertical installation of the insulation material, resulted in a value which is two times higher than that of the value from the measurements taken using the hot plate method with horizontal and compressed installation of the insulation material. These different values may be used for the related position in the roof: at mid-span the roof construction complies with the vertical construction, at the rafter where the insulation material is compressed by the mounting parts, the lower value of the hot plate method measurement applies. In addition, emissivity of the infrared reflecting insulating foil was measured.

The essential question is whether the thermal properties determined by means of standard test methods can be transferred to the reflective insulation. For this purpose, the values of thermal resistance calculated by means of characteristics measured in the laboratories were compared to the in situ values of thermal resistance resulting from measurements based on the total roof constructions from the plasterboard covering to the under tile liner.

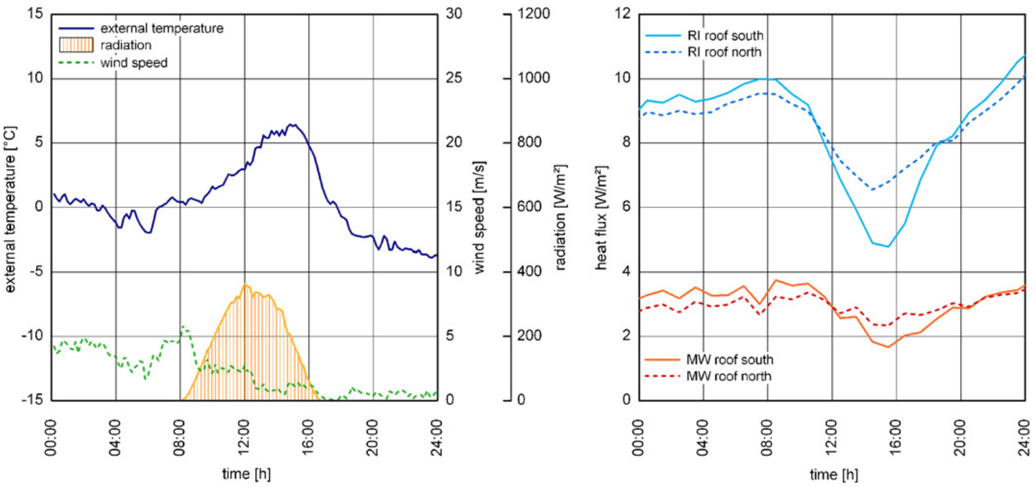


Fig. 7. Weather conditions and heat flows on a high-radiation day (January 8, 2008).

Table 2
Energy balance of winter 2008/2009 (comparison of different values of air-tightness).

Winter of 2008/2009 Energy balance of different measurement periods		$n_{50} \simeq 0.7\,h^{-1}$ (48 days–1152 h)		$n_{50} \simeq 3\,h^{-1}$ (36 days–864 h)		$n_{50} \simeq 10\,h^{-1}$ (44 days–1056 h)	
Climate conditions (mean values)	Outdoor temperature Global radiation Wind velocity	−2.2 °C 44 W/m² 2.1 m/s		−1.0 °C 84 W/m² 3.6 m/s		−8.6 °C 199 W/m² 2.8 m/s	
		MW attic 3	RI attic 2	MW attic 3	RI attic 2	MW attic 3	RI attic 2
Heat losses, gables, jamb walls, floor (calculated by measured heat flows)		200 kWh	205 kWh	160 kWh	138 kWh	82 kWh	70 kWh
Heat losses by infiltration (according to EN 832 [1] by means of tracer gas measurement)		116 kWh	128 kWh	174 kWh	146 kWh	Strong fluctuations	
Energy use for heating (measured)		790 kWh	1787 kWh	642 kWh	1336 kWh	426 kWh	852 kWh
		100%	**226%**	**100%**	**208%**	**100%**	**200%**
Heat losses through the roof (calculated by energy balance or at $n_{50} \simeq 10\,h^{-1}$ by measured heat flows)		474 kWh	1454 kWh	308 kWh	1052 kWh	205 kWh	687 kWh
		100%	**307%**	**100%**	**342%**	**100%**	**335%**
Estimated max. measurement error		±25 kWh	±25 kWh	±31 kWh	±41 kWh	±16 kWh	±19 kWh

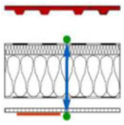
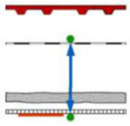
The thermal resistance is composed of the *R*-values of all individual layers. According to DIN EN ISO 6946 [11], the *R*-values of the adjacent air layers are determined as 0.16 m² K/W for surfaces with high emissivity and as 0.51 m² K/W for surfaces with low emissivity. Altogether, the thermal resistance of the total mineral wool roof construction from under tile liner to plasterboard covering is $R = 6.0$ m² K/W accordingly the thermal resistance of the infrared reflecting insulation roof construction is $R = 2.1$ m² K/W (Table 4). Hence, the thermal resistance of the RI roof construction consists of 50% thermal resistance of the air layers adjacent to the reflective insulating foil.

The in situ thermal resistance $R_{in\ situ}$ of both roof constructions has been determined for a comparison. Standard ISO 9869 "thermal insulation – building element – in situ measurements of thermal resistance and thermal transmittance" [12] describes the heat flow method used for determining the thermal resistance. This method does not supply any exact values, but allows an assessment under real conditions. During the first measurement period in the winter of 2007/2008 constant weather conditions prevailed on December 11 and 12, 2007 (Fig. 8), thus making it suitable to determine the in situ thermal resistance. The time span from December 11, 6 p.m. to December 12, 6 a.m. (Fig. 8) has been selected to determine the

Table 3
Laboratory.

Material	Mineral wool	Infrared reflecting insulation	
Thermal resistance *R* [m² K/W]	5.69	1.00	0.5
Max. measurement uncertainty	±5%	±5%	±5%
Measurement method	Hot plate method	Hot box method	Hot plate method
Standard	DIN EN 12 667 [9]	DIN 52 611-1 [10]	DIN EN 12 667 [9]
Installation	Horizontal installation	Vertical installation	Horizontal installation
Emissivity ε [–]	Not measured	0.05	

Table 4
Determination of thermal resistance.

	Mineral wool	Infrared reflecting insulation
Cross section of the roof		
Thermal resistance R [m^2 K/W] (calculated from laboratory data)	6.0	2.1
Max. measurement uncertainty	±5%	±2%
In-situ thermal resistance $R_{\text{in situ}}$ [m^2 K/W] (mean value of all 6 measurement axes)	6.4	2.0
Max. measurement uncertainty	±6%	±5%

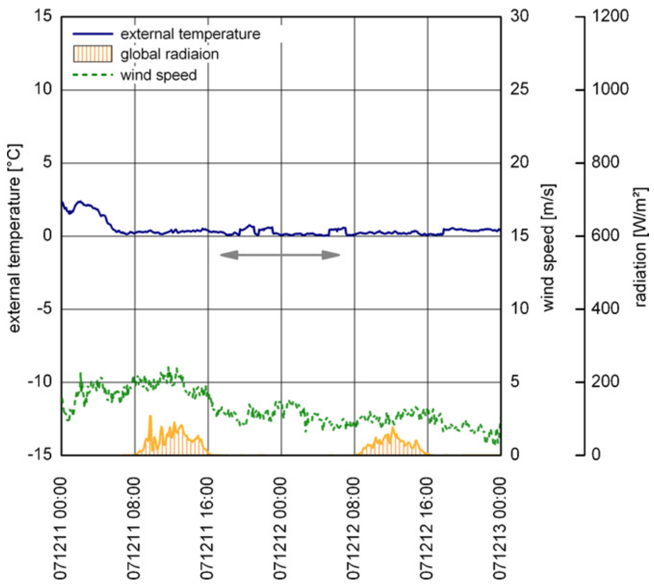


Fig. 8. Weather conditions on December 11 and 12.

in situ thermal resistance. Following ISO 9869 thermal resistance R is calculated under constant conditions as follows

$$R = \frac{\vartheta_{si} - \vartheta_{se}}{q}$$

with

ϑ_{si} internal surface temperature [°C]
ϑ_{se} external surface temperature [°C]
q heat flow [W/m^2]

The in situ thermal resistance of the roof constructions results from the respective measurements. The mean values of the in situ thermal resistance from all 6 measurement axes (Fig. 6) are also presented in Table 4: MW roof $R_{\text{in situ}} = 6.4\,\text{m}^2\,\text{K/W}$ and RI roof $R_{\text{in situ}} = 2.0\,\text{m}^2\,\text{K/W}$. The calculated R-values comply with the in situ R-values within the accuracy of the measurements. Therefore, the in situ measurements of the thermal resistance confirm laboratory measurements, i.e. thermal properties for infrared reflective insulation materials can also be determined using standard laboratory methods.

7. Measurements under summer conditions

Simultaneous measurements were also conducted in both attics in the summer of 2008. The following different boundary conditions were selected: with and without cooling, with and without mechanical ventilation, with different internal heat sources, and with and without simulated roof windows. Clear conclusions cannot be drawn from the measurements taken during the summer under the prevailing climatic boundary conditions. Various influences depending on the differences in outdoor temperature between day and night partly conflict with each other. Fig. 9 shows the behaviour of the room temperature for days without cooling with internal heat gains according to DIN 4108-2 [13]: the RI attic gained more heat during warm days and lost more heat during cooler nights. All told, the thermal performance of the RI attic is typical for an attic with a roof construction with low insulation: Higher heating-up on hot days is accompanied by more cooling down during cool nights. The qualitative assessment of insulation products cannot be accomplished by means of sum values for the thermal conditioning of the rooms (energy use for cooling, ventilation requirements, etc.). Due to the partially opposing effects definite conclusions of the insulation quality of the individual products cannot be drawn from a consideration of the values for total energy use alone. According to the prevailing climate situation and selected boundary conditions (required maximum indoor temperature, height of internal heat sources, and air-conditioning strategies) the result may be entirely different values for total energy use despite unchanged constructions.

Simulation calculations were conducted to allow the individual assessment of the different effects. In the process, individual boundary conditions can be varied and assessed. Measurements are used to validate the simulation model.

8. Simulations under summer conditions

Transient calculations using the building simulation software TRNSYS 16 have been conducted to allow the extrapolation of the results from the outdoor testing site to a larger range of boundary conditions. The focus of this calculative investigation is to assess the influence of a warm climate in summer. The two attic spaces are modelled as a one zone model with a constant floor boundary temperature. In order to take the rafters into account the model of the roofs is divided into a wood and an insulation area. The ratio of these two areas is varied to meet the measured energy consumption (conditioned space) and to correctly follow the room air temperatures in free floating case. In the RI-model the insulation is modelled using the thermal resistance from the hot plate test to take compression of the insulation at the rafters into account. To obtain a reliable numerical model of the attics investigated by measurements, the model has been carefully validated using the measured data of the tests. Concerning summers, this is achieved by the profiles of the indoor temperatures (Fig. 10). For this purpose, indoor air temperatures have been measured at five different positions: in the centre of the room at the heights of 0.1 m, 1.1 m and 1.7 m and at both sides of the room below the gable at a height of 1.7 m. It is obvious from

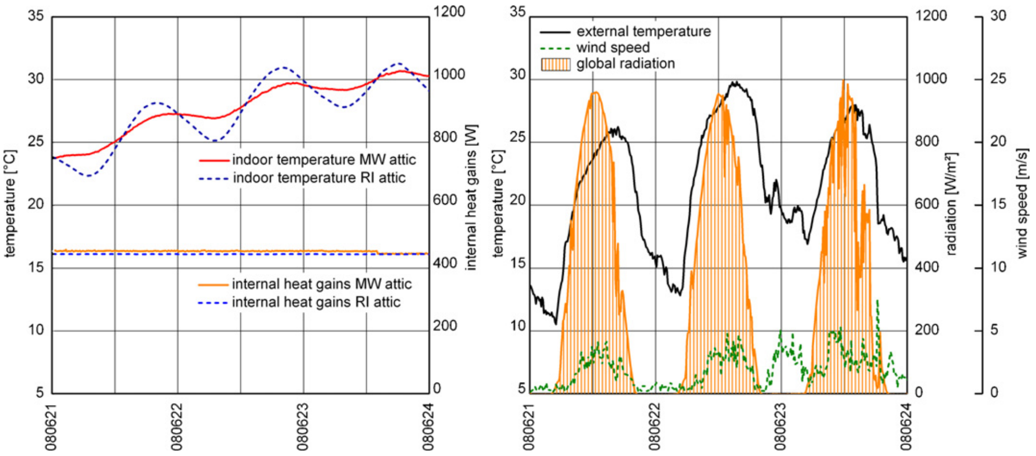


Fig. 9. Indoor temperature in both attics during period without cooling (internal heat gains 425 W acc. DIN 4108-2).

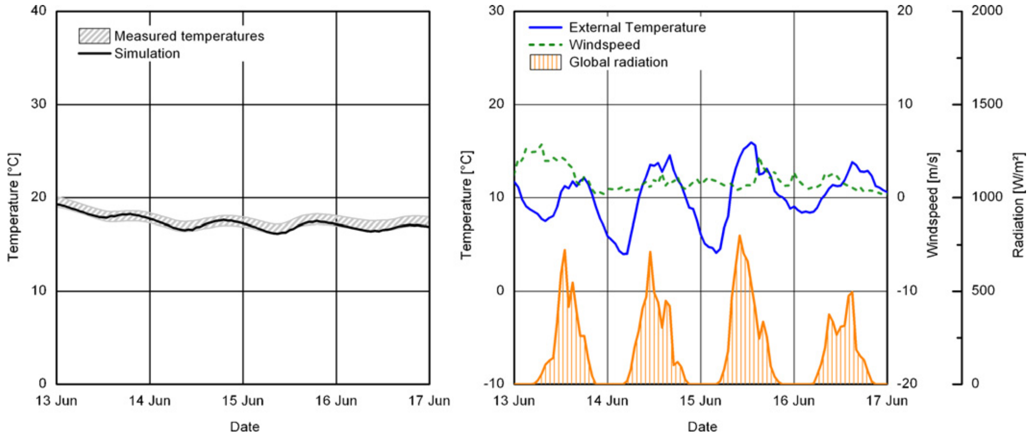


Fig. 10. Measured and calculated indoor air temperatures of the RI attic and the outdoor climate from June 13 to 17.

the example in Fig. 10 that the calculated indoor air temperatures are always within the range of the measured temperatures.

In this investigation, the net energy demand of the attics ideal cooling system for maintaining a certain air temperature serves as a characteristic for the energetic quality of the different variations. The used and the calculated quantities of heating energy of the measurements in winter have been compared to allow for the validation of the heating energy demand (Table 5). This analysis shows that the deviations always remained under 10% for the mineral wool attic and under 5% for the RI attic. The quality of these results clearly shows that it is possible, without any problems, to assess infrared reflective foil insulation materials by means of conventional building physics.

The following boundary conditions are to be varied in the simulations:

- Outdoor climate: Carpentras (F), Porto, etc.
- Infiltration air exchange: 0–1 h^{-1}
- maximum admissible indoor temperature
- window surfaces and their orientation
- internal heat sources

To assess the impact of a hot outdoor climate, three cities in southern Europe have been selected: Carpentras (F), Porto (P) and Madrid (ES). These three southern climates are compared with each other as well as with an average and an extremely hot summer in Germany. Fig. 11 clearly shows that in all climate zones with a considerable net cooling demand the MW attic always needs less energy than the RI attic to maintain an indoor air temperature of less than 26 °C. This fact complies with the performance according to the conventional theory, since the higher thermal resistance of the mineral wool construction prevents the hot outdoor temperature from penetrating into the building. This similar performance allows the conclusion that the results analysed for the climate in Madrid are valid for all hot climate zones.

The basic variation has an infiltration air exchange of 0.3 h^{-1}. To investigate the influence of infiltration on the summer performance of the building, this air exchange is varied from 0.0 to 1.0 h^{-1}. As shown in Fig. 12 the energy demand for the cooling of the construction with foil insulation material is higher for each investigated air exchange. This influence is generally minor in the hot

Table 5
Comparison of the measured net heating energy consumption and calculated heating energy demand.

Period of measurements	House	Consumption (measurement) [kWh]	Demand (calculation) [kWh]	Deviation
Winter 1	RI	1244	1268	1.9%
Winter 1	MW	597	647	8.4%
Winter 2	RI	806	773	4.1%
Winter 2	MW	439	413	5.9%

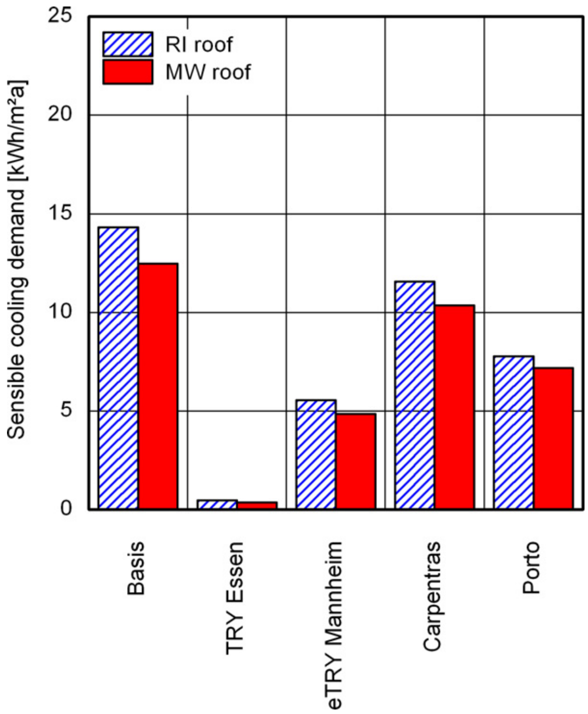


Fig. 11. Influence of the outdoor climate on the net cooling energy demand of the attics (basic variation: Madrid).

climate of Madrid. The diurnal cycle of the indoor temperatures and cooling energy demand shows that during the day, more hot air penetrates into the building due to a higher infiltration, but cooling of the attic at night is also higher. Thus, these two opposing effects nearly cancel each other out.

In order to ensure that the higher cooling of the foil constructions at night at a modified indoor temperature does not become dominant, thus inverting the energetic performance of the two investigated roof constructions, different maximum indoor air temperatures were investigated. Fig. 13 shows the net cooling demand for both constructions in dependence of the maximum admissible indoor air temperature. In this case, too, the energy demand of the

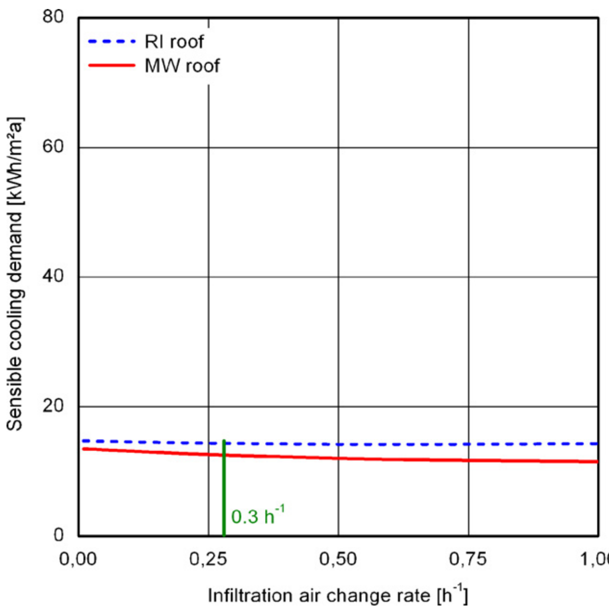


Fig. 12. Net energy demand for cooling in dependence of the infiltration air exchange rate, indoor temperature 26 °C – the green line marks the values of the basic variation (Madrid, 0.3 h^{-1}).

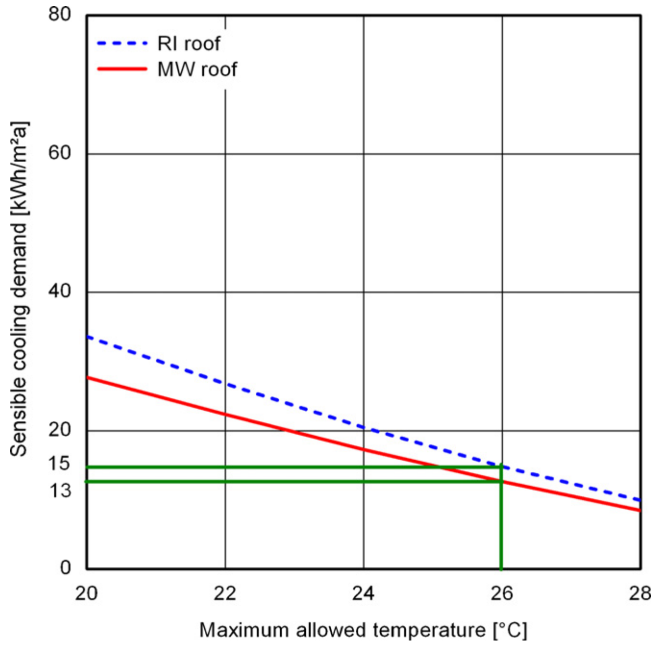


Fig. 13. Net cooling demand in dependence of the adjusted target temperature of room cooling. Infiltration air exchange 0.3 h^{-1}; internal heat sources 5 W/m^2 – the green line marks the values of the basic variation (Madrid, 26 °C).

foil insulation material always lies above that of the mineral wool roof.

The windows of the simulation models are "closed" (opaque) as they were during the measurement. To assure that this does not have a significant influence on the result, windows of 1 m^2 in size in the eastern and western gable walls have also been analysed (Fig. 14). As a matter of fact, the net cooling demand increases due to the additional solar gains, the dominance of the construction with foil insulation material, however, is constant concerning energy consumption, independent of the orientation of the attics.

To clarify whether and which daily profile is critical for internal heat sources, one variation with constant internal heat sources and one variation with a diurnal cycle (Fig. 15) have been taken in consideration. The result is a difference of no more than 5%. This is why further assessments have been made by using constant heat sources. The height of the internal heat sources proves to have the decisive effect on the net cooling demand. Fig. 16 clearly shows that an intersection of the two lines of the net cooling demand occurs at a height of the internal heat sources of 10.1 W/m^2. With higher heat sources the mineral wool construction shows a higher

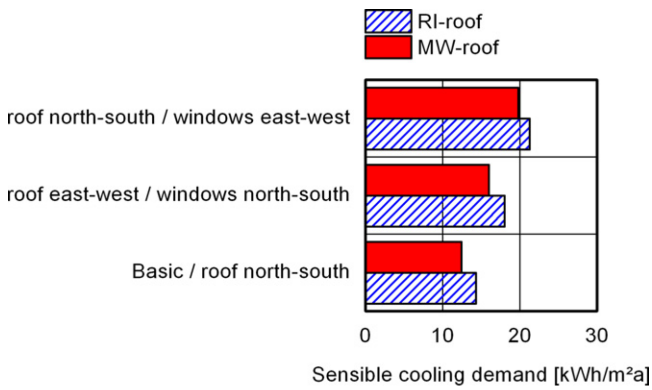


Fig. 14. Influence of window surfaces and orientation on the net cooling demand of the RI and the MW attic.

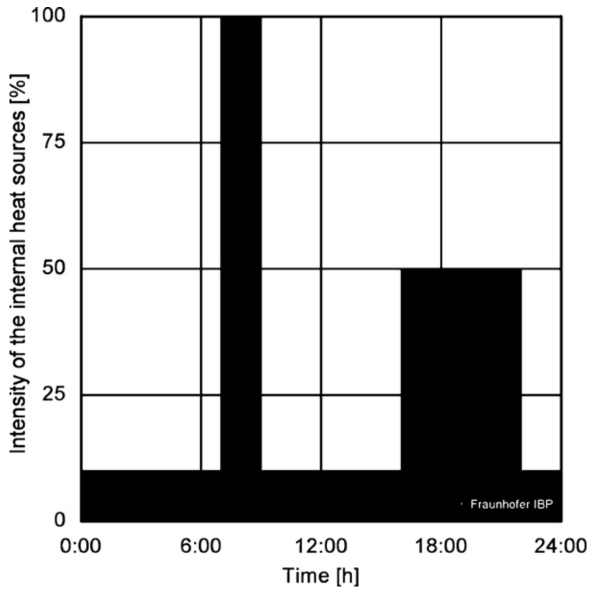


Fig. 15. Diagram of the daily load profile of the internal heat sources.

cooling energy demand. In this case the potential for energy transfer to the outside is so high that the increased cooling due to the lower insulation of the roof surfaces (RI attic) dominates over the heat inputs during the hot daytime hours. This intersection is at 8.6 W/m^2 in the variation with windows.

It should pointed out that the usual height of internal heat sources for residential buildings is between 2.1 W/m^2 (DIN V 18599-10:2007-2 [14]) and 5 W/m^2 (DIN 4108-2:2003-7 [13]), and thus must be assessed clearly lower than the resulting intersection points. This kind of internal heat source occurs only in non-residential buildings such as office buildings. The boundary conditions of this simulation, however, do not allow any direct transfer to these types of buildings.

The summarizing examination of the results of the simulation calculations shows no inconsistency with an assessment based on established methods of building physics standards. Nonetheless, it is to be observed that the values of thermal resistance to be specified must be determined according to the specific installation situation: the compressed installation (rafters) by means of the hot plate method and the contact-free installation between two air layers (compartment areas) by means of the hot box method. Moreover, in the case of contact-free installation the infrared reflecting property of the reflective insulation surface must also be taken into consideration when specifying the thermal resistance of the air layers in addition to the *R*-value of the hot box measurement. The model validation shows that both the annual and the daily performance of a building component with reflective insulation can excellently be represented by means of the conventional approach of thermal resistance. Even the higher cooling energy demand of the RI construction with its lower thermal resistance, which was to be expected according to the calculation methods of the standard, can be observed as clear tendency in the results of this simulation and the field test investigation.

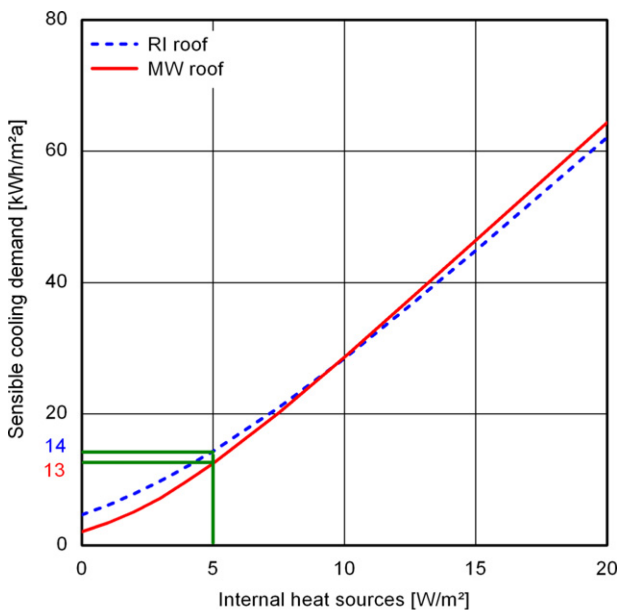


Fig. 16. Net cooling energy demand in dependence of the height of internal loads, infiltration air exchange 0.3 h^{-1}; indoor temperature 26 °C – the green line marks the values of the basic variation (5 W/m^2).

9. Summary and conclusions

During several measurement periods in winter and summer infrared reflecting roof systems were extensively compared to mineral wool roof systems. Parallel in situ measurements of two identical attics, one insulated by infrared reflecting insulation, the other by mineral wool, allow for a comparison under identical boundary conditions. The analyses were completed using transient calculations and laboratory measurement.

The results show that, the energy use for heating in winter is twice as high, on average, for all investigated RI attics in all periods, i.e. the insulation effect of the investigated infrared reflective insulation foils is more than 50% lower, on average, than that of all investigated mineral wool insulation systems. This applies in every case in which the air tightness of the building envelope is equally high in both attics. Even a permeable building envelope does not show any advantages of the reflective insulation over mineral wool insulation as long as both attics are equally airtight.

The values of thermal resistance resulting from in situ measurements after deduction of the *R*-values of the adjacent air layers validate the thermal parameters measured in the laboratory. Conventional laboratory measurements can also be applied for the energetic assessment of infrared reflecting insulation foils. Various transient calculations as well as the validation of the related numerical models confirm these findings.

Further results can be obtained through the investigation of extreme weather conditions, e.g. days with strong or low wind or days with high or low radiation. High solar radiation causes a higher reduction in the energy consumed for heating the RI attic than in the energy consumed for heating the mineral wool attic. This fact is typical of roof constructions with lower thermal insulation effect. It is important to protect the mineral wool against air flow caused by wind as this can reduce its thermal insulation effect.

The low thermal resistance of reflective insulation is advantageous if extremely high internal heat sources exist.

It is also important to note that in situ measurements cannot replace laboratory measurements. Different results may be obtained depending on the climate boundary conditions. In measurements during the summer in particular, opposing effects partially interfere with each other.

In situ measurements can be applied to validate simulation models in all cases and measurement results can be extrapolated through the use of transient calculations. The results of extensive transient calculations confirm that infrared reflective insulation materials can be assessed using established standard methods.

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