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Experimental investigation of the influence of temperature on thermal conductivity of multilayer reflective thermal insulation

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ABSTRACT

The apparent thermal conductivity of several insulation materials was measured over a range of temperatures. A newly developed multilayer reflective insulation system called Mirrorpanel was tested against existing products. Mirrorpanel samples were prepared using layers of aluminum foil (emissivity of 0.11) and coated paper (emissivity of 0.52) separated by air spaces of approximately 5 mm, with fiberboard structural spacers. Steady-state heat flux was measured in the laboratory for 500 mm × 500 mm samples including several Mirrorpanel configurations as well as expanded polystyrene and polyisocyanurate foam insulations. The mean temperature ranged between 0 °C and 35 °C with a temperature difference across the sample of 10 °C. For all insulation materials, the apparent thermal conductivity increased linearly with temperature above 5 °C, and the slope was steeper for the Mirrorpanel samples than the foam insulations. The apparent thermal conductivity of the Mirrorpanel made from aluminum foil was greater than that of polyisocyanurate but less than that of expanded polystyrene. The significant difference of thermal conductivity of lower and higher emissivity reflecting layers highlighted the importance of this parameter in thermal insulation. The steep temperature dependence of the Mirrorpanel should be considered during design of the building envelope for summer and winter conditions.

1. Introduction

Among the four main sectors (agriculture, industry, transportation and buildings), the residential and commercial building sector is the largest energy consumer, it is about 40% in the US [1–3]. According to the IPCC,[1] 19% of the total GHG[2]s' emissions can be linked to the building sector in the world (IPCC 2014). In numerous countries energy efficiency rules for new construction have become tighter. There are many studies dealing with the energy efficiency of the buildings' different components, for example with the cladding, electrical, structural and mechanical systems [4–6]. Most of the energy consumed in buildings is used for heating and cooling. In the boreal climate zone most of this energy is used for heating, in the tropical zones for cooling, and in the temperate zones for both heating and cooling. Heating and cooling loads are strongly tied to the insulation levels of the building envelope.

Many common insulation materials are porous, and heat transfer through the materials involves conduction through the solid matrix, gas phase conduction, convection, and radiation through the pores and surfaces. The apparent thermal conductivity of insulation materials depends on multiple factors, including structure, density, temperature, and moisture content. Fibrous insulations such as glass fiber, mineral wool, and cellulose fiber take advantage of the low thermal conductivity of air by segmenting it into small voids. Plastic foam insulations use blowing agents that are trapped within the cellular structure; these gases are typically heavier than air and thus have a lower thermal conductivity.

The apparent thermal conductivity of insulation materials is often reported for a mean reference temperature but can vary considerably with temperature. Insulation materials in the building envelope are exposed to a wide range of temperatures in service, depending on the interior and exterior conditions. Materials for which a large fraction of heat transfer occurs by radiation, such as low-density fibrous and cellular materials, generally exhibit the greatest increase in apparent thermal conductivity with temperature [7]. The effect of temperature (among other factors) on the apparent thermal conductivity of insulation materials has been investigated experimentally by many researchers [8–12].

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[1] Intergovernmental Panel on Climate Change.
[2] Green House Gas.

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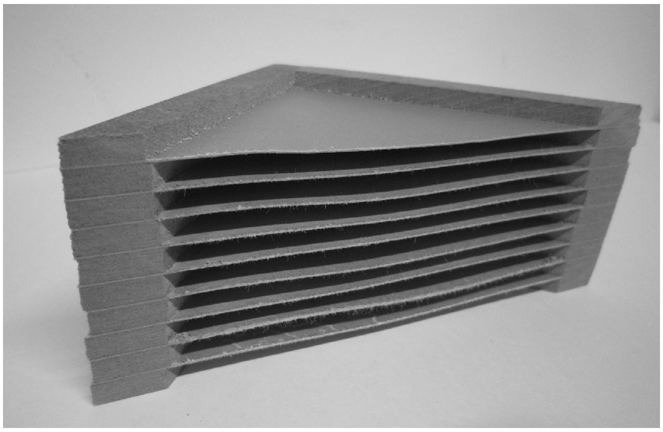

Fig. 1. Cross-sectional view of laboratory-scale Mirrorpanel.

The use of low-emissivity surfaces for reducing heat radiation has been well known for a long time. The first developments were performed for aerospace applications such as thermal insulation of spacecraft, where there is no air outside or inside of the insulation layer. Radiant barriers and reflective surfaces have been shown to reduce heat transfer into buildings [13–15]. Multilayer reflective foils were used as core materials in vacuum insulation technology and were found to considerably reduce the radiant heat transfer [16]. Kwon [17] and Kwon and Kim [18,19] showed a low-emissivity hybrid insulation in South Korea, which combines many layers of reflective aluminum foils and honeycomb-structure air cells of polyethylene foam. Mavromatidis et al. [20,21] studied a multilayer thermal insulation in building applications placed in combination with two air gaps and developed a numerical approach to determine the influence of the air gap thickness on the overall thermal resistance of the wall.

An economical multilayer reflective thermal insulation was developed by Pásztory et al. [22] for residential wood-frame construction. The initial investigation focused on the relationship between the number of reflective aluminum–polyethylene sheets, the size of the air space between sheets, and the apparent thermal conductivity. Subsequent work examined the performance of a similar insulation system where the reflective aluminum foil was replaced by paper with a low emissivity coating. This system has been characterized with small and large-scale laboratory measurements and has been installed in a test house [23, 24]. All prior laboratory measurements were conducted at a single mean temperature according to standard methods.

The primary objective of this study is to investigate the temperature dependence of the apparent thermal conductivity and the importance of the surface emissivity by comparing aluminum foil and coated paper. Additional objectives are to compare insulation materials using mostly thermal reflectance to the traditional foam insulations and to investigate the contribution of cover plates (OSB) of the panels to the thermal resistance.

2. Materials and methods

In this experimental study, apparent thermal conductivity measurements were conducted for various multilayer reflective insulation specimens, known as Mirrorpanel (Fig. 1), under different mean temperature conditions. Nine types of specimen panels were prepared for measurements according to Table 1.

In the case of panels 1–3, both sides of the paper sheets were coated with low emissivity paint. For panels 1–6, where multilayered designs were chosen, a supporting frame was constructed made of MDF (medium density fiberboard) spacers with 10 mm width and ∼5 mm thickness at the four sides of the panel so that the specimen had 500 mm × 500 mm horizontal dimensions. The supporting frame was divided by the inserted layers of paper sheets/aluminum foils (perpendicular to the heat flow) to 8 sections of the same thickness of ∼5 mm. Each multilayered panel contained 9 sheets of low emissivity material, i.e. 8 air layers were formed in the panel geometry. For the case of panel 1 and panel 4, the bottom and top air cavities were not closed until the specimen was placed into the measurement unit, but during measurement the heater and cooler plates sealed the investigated insulation system creating two additional air gaps on the top and bottom. As for the low emissivity layers, the thickness of paper was ∼0.4 mm, whereas this dimension for aluminum foils was ∼0.04 mm. Without OSB panels, the nominal height of each measured specimen (multilayered ones as well as closed cell foams) was 50 mm, although for layered samples there were slight differences due to fabrication imperfections. In every case the real measured thickness was taken into account for calculation of thermal conductivity. The thickness of OSB panels was ∼12 mm, and in the case of panel 2, 3, 5 and 6 the total height of the specimens was ∼74 mm. Three replicates of panel types 1–6 were prepared. For panel types 2, 3, 5, and 6, the same three pairs of OSB were used consistently on the top and bottom sides to minimize any thermal effect of inhomogeneity in the OSB.

In the case of closed cell foam panels 7–9 only one specimen per case was measured due to the fact that these are commercial insulation materials with well-known thermal properties, and our goal was to compare their insulation capability with multilayered systems examined in this study.

The apparent thermal conductivity was measured by the hot plate method, by means of measurement equipment built for examining one dimensional heat transfer problems. The measurement unit contained a cooling plate at the bottom and heating plate on the top. To ensure even heat flow lines perpendicular to the specimen, external heat insulation with thickness of 150 mm was used on each vertical side of the measured sample. On top of the examined specimen a heating plate with the same horizontal size was placed, which consisted of a series of heating element wires equally distributed to establish nearly uniform heating over the top surface of the measured sample. On the middle of heating plate, a heat flux sensor with size of 120 mm × 120 mm with an accuracy of 0.1 W/m^2 was inserted to monitor heat flux through the specimen. Temperature measurements were performed by using a pair of thermocouples on both the heated and cooled side of the sample, by attaching the sensors in the middle area of the heating and cooling plates in the measurement unit. Temperatures and heat flux values were processed by data acquisition software, and apparent thermal conductivity was calculated for each measurement step. Establishing desired temperature on heated and cooled side of the specimen was utilized by a controller unit, which controlled both heating and cooling devices.

During each measurement process, thermal difference between the cold and the hot side of the measured sample was 10 °C, and the time difference was always 1 minute between two consecutive data acquisition steps. Valid measurement started when steady state was achieved, defined by when the fluctuation of the last fifty measurement steps was under 0.002 W/mK. All collected data were saved to a plain text file including date and time stamps. For every specimen, a full measurement series was accomplished, by incrementing mean temperature value of heated and cooled sides of experimental panels between 0 °C and 35 °C, using steps of 2.5 °C (i.e., temperature values for cooled/heated side were −5 °C/5 °C, −2.5 °C/7.5 °C, … , 30 °C/40 °C).

After data acquisition, the arithmetic mean for the last 100 time steps was calculated for each measurement case regarding mean temperature. Furthermore, for multilayered panels, the mean

Table 1
Insulation panels tested.

Panel	Insulation type	Exterior surfaces	Thickness
1	Mirrorpanel with coated paper	Nothing added	50 mm
2	Same as 1	OSB[a] both sides, no coating	74 mm
3	Same as 1	OSB both sides, coated with aluminum foil	74 mm
4	Mirrorpanel with aluminum foil	Nothing added	50 mm
5	Same as 4	OSB both sides, no coating	74 mm
6	Same as 4	OSB both sides, coated with aluminum foil	74 mm
7	Expanded polystyrene foam	Nothing added	50 mm
8	Polyisocyanurate foam	Aluminum facing	50 mm
9	Polyisocyanurate foam	Paper facing	50 mm

[a] OSB: oriented strand board.

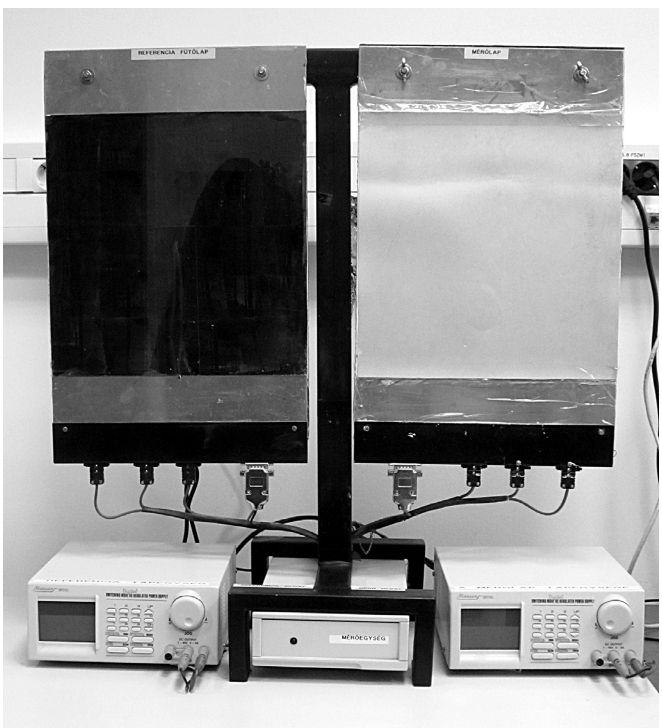

Fig. 2. Surface emissivity measurements equipment on the left side the reference plate to the right side the sample plate.

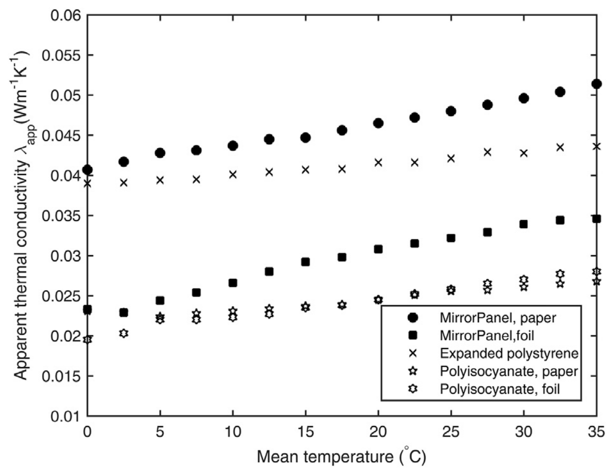

Fig. 3. Apparent thermal conductivity vs. mean temperature for the Mirrorpanels compared against commercial insulation materials.

thermal conductivity was taken for the three specimens. The numbers of specimens was enough for a case study, but not enough for statistical analysis.

Surface emissivity measurements were also done for the sheets and foils of the experimental multilayered panels [25]. This was accomplished by surface emissivity measurement equipment which consisted of two square-shaped measuring plates with a dimension of 300 mm by 300 mm for each, placed side by side in a common vertical plane and heated uniformly over their surfaces, two regulated power supplies for heating the plates and an electrical unit for control and measuring (Fig. 2). Thin layers of the measured specimen were glued on both front and back surfaces of the right measuring plate by thermal paste, and the left plate was for reference only. For both plates, surface temperatures were set to the same value, and that was monitored by thermocouples placed in the center of each plate. Knowing the surface emissivity of the reference plate, temperature data and heating power of each panel, the surface emissivity of the measured specimen can be calculated. Due to the fact that the two plates are side by side, heat conduction and convection by surrounding air can be assumed as identical, and the difference in heating power between the plates should come from the difference in emissivity of the reference and measured surfaces if the same radiation properties are ensured for the surroundings. The measuring method was the same as that of the thermal conductivity measurement. After steady state the average value of the last 100 measured data was calculated as the emissivity of the surface. The time between two measurements was also 1 minute. The value of emissivity of coated paper sheets was 0.52 and the aluminum foils 0.11. Inside the panel the paper or aluminum foils behaved according to the reflecting emissivity properties which influenced the thermal resistance of the whole panel.

3. Results and discussion

The apparent thermal conductivity as a function of temperature is plotted in Fig. 3 for the Mirrorpanels made with foil and paper along with three commercial insulation materials. Data are presented for the Mirrorpanels by themselves (panels 1 and 4) without the structural OSB layers on the outside. For all insulation materials, the apparent thermal conductivity increases linearly with temperature; linear regression of the data yielded $R^2 > 0.9$ in all cases. The Mirrorpanels have a steeper slope than the foam insulation materials. The Mirrorpanel made with aluminum foil layers has a lower apparent thermal conductivity than the commercially available expanded polystyrene. Overall, the polyisocyanurates have the lowest apparent thermal conductivity of any of the insulation materials tested. The differences between the two polyisocyanurate materials tested are small, and their behavior at low temperatures (below 5 °C) may be caused by concentration differences in blowing agents.

The Mirrorpanel made from aluminum foil has a lower apparent thermal conductivity than that of the one made from layers of

Table 2
Apparent thermal resistance of panels at select temperatures.

Mean temperature	Thermal resistance (m^2 K W^{-1})[a]			
	0 °C	10 °C	25 °C	35 °C
1: Mirrorpanel, paper	1.21 ± 0.04	1.12 ± 0.02	1.02 ± 0.02	0.95 ± 0.02
2: Mirrorpanel, paper with uncoated OSB	1.52 ± 0.03	1.39 ± 0.01	1.24 ± 0.02	1.14 ± 0.02
3: Mirrorpanel, paper with foil-faced OSB	1.74 ± 0.07	1.49 ± 0.01	1.31 ± 0.01	1.22 ± 0.01
4: Mirrorpanel, foil	2.15 ± 0.06	1.92 ± 0.06	1.56 ± 0.02	1.35 ± 0.17
5: Mirropanel, foil with uncoated OSB	3.31 ± 0.33	2.36 ± 0.03	1.84 ± 0.03	1.58 ± 0.01
6: Mirrorpanel, foil with foil-faced OSB	3.21 ± 0.24	2.31 ± 0.09	1.77 ± 0.09	1.57 ± 0.05

[a] Values represent mean and standard deviation of three replicates.

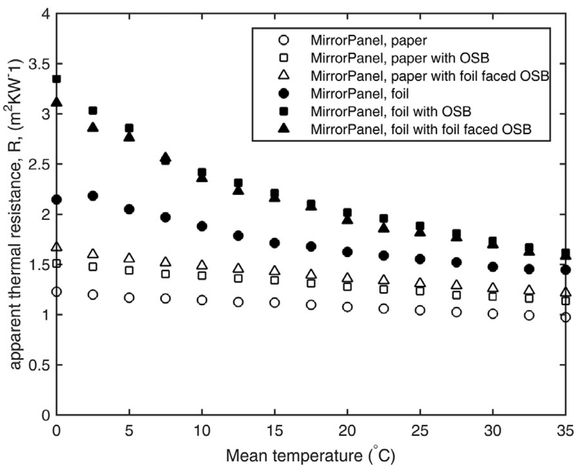

Fig. 4. Apparent thermal resistance as a function of temperature for the Mirrorpanels with OSB on the outside.

paper. This shows how important the emissivity of the layers is; the thermal conductivity of the Mirrorpanel made from aluminum foil is 43% lower at 0 °C and Mirrorpanel made of paper is 33% lower at 0 °C than the thermal conductivity of the Mirrorpanels at 35 °C. Basement value was taken the results at 0 °C.

The air layer between foils was ~5 mm and the thermal difference between two foil layers ~1 °C, assuming that the 10 °C difference was distributed equally between hot and cold plate. According to the principle of similarity the convection can be taken into account if the multiplication of Grashof and Prandtl dimensionless numbers is smaller than 1000 [26]. The 1 °C difference is low enough for the reliable assumption that the convection effect is negligible in both types of Mirrorpanel. Although the radiant thermal transport derives from the emissivity of the two surfaces facing each other. The resultant/integrated emissivity of paper (ε_{Paper}):

$$\varepsilon_{Paper} = \frac{1}{\frac{1}{0.52} + \frac{1}{0.52} - 1} = 0.351$$

By similar calculation the aluminum foils have 0.058 which is a much lower value. Several reports show that the surface emissivity variation is minor for aluminum in the temperature range examined [27,28,29]. Considering that the thermal conductivity of air between layers and the convection are the same in case of paper and foil Mirrorpanel the difference can be derived only from the thermal transfer by radiation.

Fig. 4 shows how the covering OSB plates affect the insulating properties of the Mirrorpanel. In Fig. 4, the apparent thermal resistance, or "*R* value" in m^2 KW^{-1} is plotted as a function of temperature for the Mirrorpanels with different OSB panels. Mean values with standard deviations (based on three replicates) are summarized at four mean temperatures in Table 2. Adding the OSB increases the apparent thermal resistance as the OSB is a poor thermal conductor. Furthermore, for the paper Mirrorpanel, the foil faced OSB performs better than the uncoated OSB as it decreases radiative heat transfer. The same trend would be expected for the foil Mirrorpanel; however, the high thermal resistance (low heat flux) makes this difficult to resolve experimentally. The foil Mirrorpanel with foil-faced OSB and the foil Mirrorpanel with uncoated OSB cannot be distinguished given the sample variability (Table 2).

The Mirrorpanels made with foil have a steeper temperature dependence than those made with paper. However, both Mirrorpanels perform better at lower temperatures, increasing their performance for use in cold climates.

4. Conclusions

The objectives of this study were to investigate the temperature dependence of thermal conductivity and the importance of the surface emissivity by comparing aluminum foil and coated paper, to compare the multi-layer reflective insulation panels to the traditional foam insulations, and to determine the effect of cover OSB plates on the thermal resistance.

The thermal conductivity of all investigated specimens increases linearly in the temperature range from 5 °C to 35 °C.

The investigation highlighted the importance of surface emissivity to the thermal conductivity in the case of reflective insulation. The increase surface emissivity from 0.058 to 0.351 caused significant decrease (43% in 0 °C) of thermal conductivity.

The thermal dependence of reflective insulations was steeper than that of foam insulations. The Mirrorpanel paper and foil have 26% and 60% higher thermal conductivity at 35 °C mean temperature relative to the value at 0 °C. However, the expanded polystyrene and polyisocyanurate foam have a change of only 11% and 15%, respectively. The lower the surface emissivity property the higher is the temperature dependence of the insulation system. Both Mirrorpanels perform better at lower temperatures, increasing their performance for use in cold climates.

The OSB increases the apparent thermal resistance of the Mirrorpanels as the OSB is a poor thermal conductor, although the specific thermal conductivity of the OSB integrated panels are higher than that of the pure Mirrorpanels.

The foil faced OSB performs better than the uncoated OSB and it has higher effect in case of the paper Mirrorpanel than that of the foil Mirrorpanel. A difference between foil faced OSB and uncoated OSB in the case of the foil Mirrorpanel could not be experimentally detected.

From the aspects of environment the paper foils are more advantageous than the aluminum foil that is why can be preferred the paper reflecting layers although this aspect was not the focus of this research, but can be topic of further investigation.

The steep temperature dependence of the multilayer reflective insulation should be considered during design of the building envelope for summer and winter conditions.

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