TECHNICAL NOTE

Thermal Insulation System Made of Wood and Paper for Use in Residential Construction

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Abstract

This article introduces an insulation system that takes advantage of the low thermal conductivity of still air and is made of wood and paper. The insulation, called the Mirrorpanel, is constructed as a panel of closely spaced layers of coated paper and held together in a frame of wood or fiberboard. Panels have been fabricated and tested at the laboratory scale, whole wall scale, and the building scale. A 1.2-m by 2-m by 0.185-m-thick wall section had an apparent thermal conductance of only 0.204 W m^{-2} K^{-1} including the structural wood frame, which is equivalent to a US R-value of 27.9 h ft^2 °F Btu^{-1} (3.8 h ft^2 °F Btu^{-1} $in.^{-1}$ for the 7.3-in.-thick wall section). The Mirrorpanel could be used as an environmentally friendly alternative to foam insulation in high-performance residential buildings and would fulfill the continuous insulation requirements in the 2012 version of the International Energy Conservation Code.

Buildings account for about 40 percent of the energy consumed in the United States (Gordon and Holness 2008), and there are efforts, both within the building codes and through voluntary standards and certifications, to reduce the energy consumed by buildings. One way to improve the energy efficiency of buildings is to increase the amount of insulation. The 2012 International Energy Conservation Code (IECC) has more stringent insulation requirements than the 2009 version, which it replaced, especially for wall systems (International Code Council 2012). The code requires that wood-framed walls in climate zones 6 to 8 have both insulation in the wall cavity and ''continuous insulation,'' which is uninterrupted by the thermal bridging of the studs.[1] Currently, the easiest solution to meet this code requirement is the use of a continuous layer of foam insulation on the exterior of the wall.

While the continuous layer of exterior foam meets the code requirements and improves the energy efficiency of the building, there are several drawbacks to this approach. From an environmental standpoint, foam insulation is produced from nonrenewable fossil fuels. Studies have shown that foam insulation such as polyurethane, expanded polystyrene, extruded polystyrene, and polyvinyl chloride has 10 to 24 times the environmental impact of natural insulation materials made from cork or cellulose (Papadopoulos 2005). Foam insulation also has higher embodied energy and higher global warming potential than cellulose or cork insulation (Aycam and Tuna 2013). In addition to the environmental aspects of foam insulation, there are practical considerations as well. Foam insulation is vapor tight, which limits the possibility of moisture in the wall system drying to the outside. Furthermore, continuous foam insulation on the outside of the house introduces constructability issues when flashing windows and doors and attaching the

[1] A map of the different climate zones is available from the International Energy Code Council. Zones 6 to 8 include portions of or the entirety of the following states: Maine, Vermont, New Hampshire, New York, Wisconsin, Minnesota, Iowa, North Dakota, South Dakota, Wyoming, Montana, Colorado, Utah, and Washington.

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cladding material. Here we present a multilayer alternative insulation material made primarily from forest products.

Heat transfer can occur through convection, conduction, and radiation. The goal of any insulation material is to minimize the heat transfer through these mechanisms. In the United States, insulation materials are described by their thermal resistance, or R-value, which is the reciprocal of the effective thermal conductivity (in units of Btu in. h^{-1} ft^{-2} $°F^{-1}$) multiplied by their thickness. In Europe, it is common to describe the materials by their thermal conductance, or U-value, which is the thermal conductivity (λ in units of W m^{-1} K^{-1}) divided by the thickness (usually in units of W m^{-2} K^{-1}). Note that the R-value and U-value are reciprocals of each other but are typically presented with different units, and the U-value also contains the surface resistance.

The thermal conductivity of air, in the absence of convection, is quite low ($R = 5.61$ in^{-1} or $\lambda = 0.0257$ W m^{-1} K^{-1} at 20°C), although in most circumstances, air freely moves by convection, rendering it useless as an insulation material. However, when the air is confined within a thin layer, self-convection does not occur, and heat can only be transferred through the air by conduction and radiation (Alifanov et al. 2009, Antar and Baig 2009, Tenpierik and Hasselaar 2013). The Mirrorpanel is designed to reduce convection and consists of thin, parallel layers of paper.

Figure 1 schematically shows how the Mirrorpanel works. Paper is placed in parallel planes with a small air gap (~5 mm). These thin air layers will minimize convection, and heat transfer between adjoining layers is dominated by the conduction of the air (which is low) and radiation. To minimize radiation between layers, the paper is coated with a radiation reflecting low emissivity coating, shown in Figure 2. By placing multiple layers in parallel, the total thermal resistance of the panel can be customized to meet the desired level of insulation.

The essence of the Mirrorpanel insulation system is that it is composed of multiple, closely spaced layers of paper with a low emissivity coating ($\varepsilon = 0.35$). There are several possibilities of how this could be used in combination with other construction materials as insulation. One possibility is that it could be implemented as the insulation material in a structural insulated panel. The Mirrorpanel could also be attached to a rigid panel, such as plywood or oriented strand board, and then used as exterior insulation, which could meet the ''continuous'' insulation requirement within the IECC.

Here, we summarize the thermal and moisture properties of the Mirrorpanel and highlight its potential uses in residential construction. Although the Mirrorpanel is not under commercial fabrication, laboratory-scale, full-wall, and test-house prototypes have been constructed, and we present the thermal performance measured from these prototypes in the ''Results'' section. The Mirrorpanel can be constructed in different configurations such as exterior insulation or potentially as the insulative material inside of a structural insulated panel. Thicker panels can be constructed by increasing the number of layers to increase the R-value. Unlike foam insulation, the Mirrorpanel is constructed from renewable forest products resources. Mirrorpanel insulation sequesters carbon during the life of the building and represents a new potential market for forest products building materials.

Materials and Methods

Laboratory measurements

Laboratory-scale measurements were performed on Mirrorpanels that were 500 by 500 mm with thicknesses ranging between 64 and 73 mm. An example of the laboratory panel is shown in Figure 3, which shows the end cut off to illustrate the construction method. Paper layers (0.5 mm thick) were glued to a 15-mm-wide spruce frame between each layer. In these measurements, the radiation reflective coating was only applied to one side of the paper, and the Mirrorpanels were covered on the bottom and the top with 4-mm-thick beech plywood. Several panels were constructed with different numbers of layers of paper to examine the effect of the layer thickness. Three different air layers were tested: 3, 5, and 7 mm. The thermal conductivity

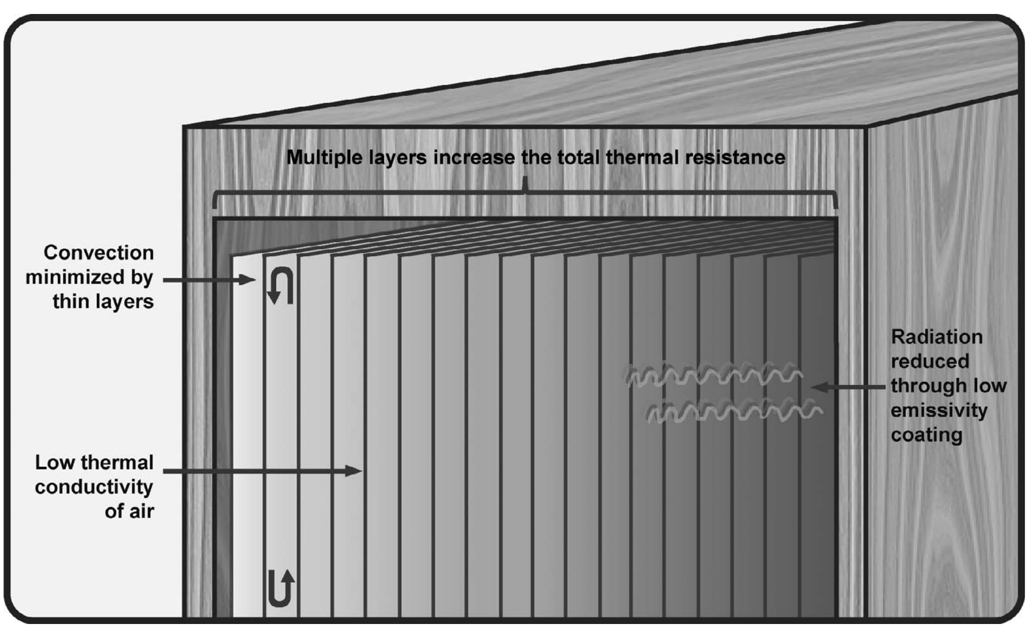

Figure 1.—Schematic drawing of how the Mirrorpanel reduces the three methods of heat transfer and provides insulation.

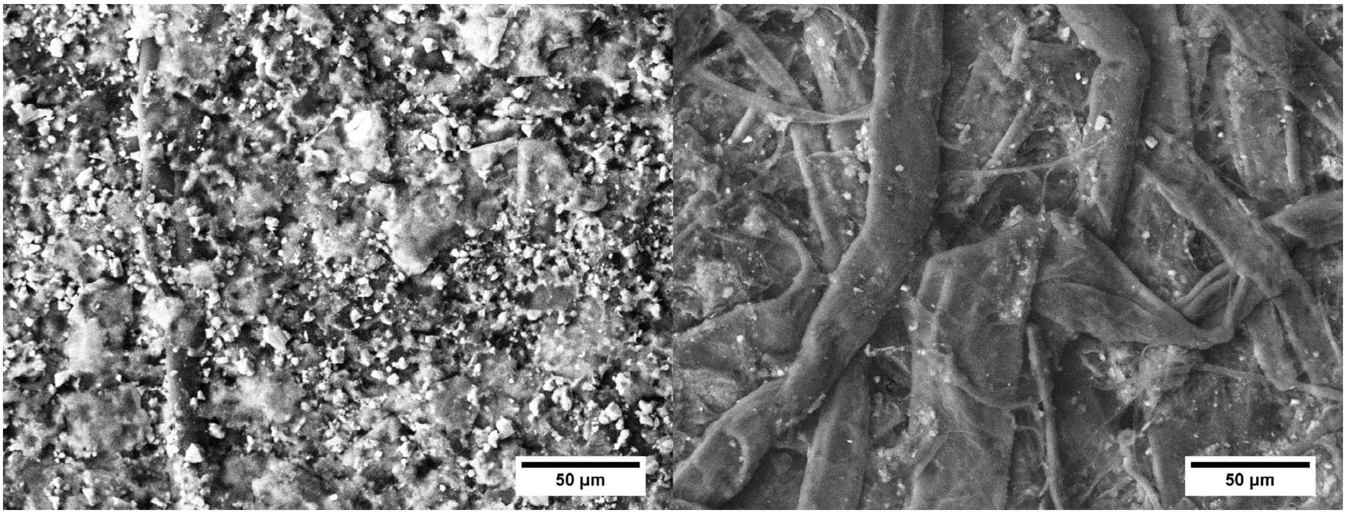

Figure 2.—Scanning electron microscope images of the paper after (left) and before (right) the application of the radiative reflective coating.

was measured by heating one side of the sample to 40°C, while the other side was set at approximately 25°C. The sides of the Mirrorpanel were covered by an insulation layer 200 mm thick to ensure the one-dimensional heat flow inside the specimen. Temperature data on the upper and lower side as well as heat flux perpendicular to the surface of the Mirrorpanel were recorded once a minute, and apparent thermal conductivity was calculated from the last 100 recorded data points of the steady-state condition.

Figure 3.—Laboratory-scale Mirrorpanel that was later sectioned to show the construction technique.

Whole-wall measurements

For the whole wall, a large panel was constructed that measured 2 by 1.2 m with a frame made of 160-mm-thick spruce studs. The perimeter studs were 30 mm wide and there was an additional 60-mm-wide stud in the center of the panel. The panel was covered with fiber-reinforced gypsum boards (12.5 mm thick) on both sides. The panel used a 5-mm air gap between layers, so the 160-mm-thick panel had 31 layers of paper that were coated on both sides. To maintain the 5-mm gap between layers, occasional small polyurethane foam spacers (5 mm thick) were placed between the layers. Equivalent heat conductivity measurements were taken by an accredited third party laboratory (Non-Profit Limited Liability Company for Quality Control and Innovation in Building), by means of the hot box method according to the EN 1934 standard (European Committee for Standardization 2000). The temperature difference across the panel was 25°C; one side was maintained at 25°C and the other side at 0°C.

Whole-house measurements

To evaluate the feasibility of the Mirrorpanel in single family home construction, a test house was built (Fig. 4). The test-house walls were constructed with two of the 160-mm-thick Mirrorpanels with 60 mm of additional exterior wood fiber insulation. The wooden studs (spaced 625 mm apart) of the Mirrorpanels were staggered by 300 mm between layers to minimize the effect of thermal bridging. The Mirrorpanels were constructed in the same way as the wall panels, with the exception of the spacers used to maintain the air gap, which for the test house were constructed from corrugated fiberboard. The two-story test house has a ground floor area of 1,290 ft^2 (120 m^2). The house was constructed in 2011 and was equipped with instruments to measure the temperature and relative humidity (RH) within the wall cavity and heat flux across the wall. The test house also was constructed with a seasonal heat container that collects heat during the summer months and releases it during the winter months (Horváth and Pásztory 2013).

Figure 4.—Test house constructed from Mirrorpanels.

Over 1.5 metric tons of recycled paper was used to construct the Mirrorpanels used in the test house. The paper was composed of wood cellulose constructed from carbon that came from the CO_2 content of the atmosphere. The paper had a density of 350 g m^{-2}. In total, 31 layers of paper were used in the insulation, so 10.85 kg of paper per m^2 was sequestered in construction.

Vapor permeance measurements on individual paper layers

The rate of moisture transfer through Mirrorpanel specimens was measured with a miniature diffusion cup using single-layer specimens. In this article, the term ''vapor permeance'' refers to the coefficient for moisture transfer when water vapor pressure is the driving potential, even though moisture transfer involves combined vapor and bound water diffusion (Stamm 1964). The rate of moisture transfer per unit area m_m (kg s^{-1} m^{-2}) under steady-state conditions can be expressed as

$$m_m = M\Delta p_{wv}$$

where M is water vapor permeance (kg Pa^{-1} s^{-1} m^{-2}) and Δp_{wv} is the difference in water vapor pressure (Pa) across the specimen. Vapor permeance is calculated as

$$M = \left(\frac{A \cdot \Delta p_{wv}}{\dot{m}} - Z_m\right)^{-1}$$

where A is the exposed surface area of the specimen (m^2), $\dot{m}$ is the rate of moisture transfer through the specimen (kg s^{-1}), and Z_m is the resistance to water vapor transfer from the air boundary layers at both surfaces of the specimen (m^2 s Pa kg^{-1}).

The measurement technique involved a gravimetric vapor sorption apparatus (IGAsorp, Hiden Isochema, Warrington, UK). The instrument has a microbalance with a resolution of 0.1 mg and a temperature-controlled chamber through which flows a nitrogen stream with controlled humidity, generated by mixing dry and saturated nitrogen streams. A diffusion cup with an inner diameter of 12 mm was suspended from the microbalance. A saturated solution of NaCl was placed inside the cup. Above the solution was fixed a single layer of Mirrorpanel cut into a disc with a 14-mm diameter, the edges of which had been sealed with paraffin wax. The mass of the cup assembly was measured over time, yielding a steady-state moisture transfer rate. Measurements were made at 23°C with a range of RH boundary conditions. The NaCl solution provides a constant 75 percent RH, and the chamber was set at a series of different RH levels. A detailed description of the method with error analysis is given by Boardman and Glass (2013).

Results

The results of the 500 by 500-mm laboratory-scale panels are shown in Table 1. The apparent thermal conductivity decreased as the spacing between layers became smaller. The thermal conductivity of the panel with 5-mm layers was

Table 1.—Apparent thermal conductivity of Mirrorpanels with the paper coated on one side.

Spacing (mm)	Conductivity (W m^{-1} K^{-1})	Panel thickness (mm)	R (m^2 K W^{-1})
3	0.047	66	1.42
5	0.053	64	1.21
7	0.059	73	1.24

Table 2.—Vapor permeance of 0.5-mm-thick coated paper.

Mean relative humidity (%)	Vapor permeance (ng Pa^{-1} s^{-1} m^{-2})[a]
40	910 ± 10
53	890 ± 50
65	920 ± 60
85	1,180 ± 130

[a] Values are means ± standard deviations.

0.0532 W m^{-1} K^{-1}, which corresponds with a US R-value of 6.8 (2.7/in. of thickness). It is important to note that in these experiments, the radiative reflective coating was only applied to one side of the paper. In a similar experiment using reflective aluminum foil, the Mirrorpanel with a 5-mm air gap had a thermal conductivity of 0.0291 W m^{-1} K^{-1}, equivalent to a US R-value of 5.1/in. of thickness (Pásztory 2013). Clearly, the radiative reflective properties of the inner layers are important to the overall thermal performance of the Mirrorpanel.

The 185-mm (7.3-in.)-thick wall section had a thermal conductance of 0.204 W m^{-2} K^{-1}, equivalent to a US R-value of 27.9 (3.8/in.). This value includes the 60-mm-wide wood studs used as a frame. Note that even though this large panel had thermal bridging on the perimeter caused by the wood studs, the panel had a higher R-value per inch than the laboratory panel (2.7/in.), which illustrates the improvement in thermal performance by coating the paper on both sides.

The test house exhibited low energy consumption for heating and cooling, which has been less than 15 kWh m^{-2} y^{-1}, meeting the passive house standard for maximum heating and cooling energy consumption. Future work will focus on modeling the thermal and moisture performance of the test-house wall to confirm its performance.

The water vapor permeance of a single layer of coated paper over a range of RH conditions is listed in Table 2. Vapor permeance does not appear to depend on RH for mean RH values from 40 to 65 percent. However, the vapor permeance does increase for a mean of 85 percent RH.

Discussion

This article introduces the Mirrorpanel and shows preliminary results of its thermal performance. In summary, the Mirrorpanel consists of closely spaced air layers. In laboratory-scale and full-wall tests, the thermal conductivity was strongly dependent on what was used to separate the layers. When the layers were spaced by foil, the thermal conductivity was equivalent to extruded polystyrene (XPS). When coated paper was used, the thermal conductivity was similar to expanded polystyrene (EPS; Table 3). Unlike polystyrene, the Mirrorpanel was constructed primarily of forest products; the paper was spaced with corrugated fiberboard and held together in wood frames. The total R-value of the Mirrorpanel can be adjusted by adding additional layers to match a necessary component; conceivably the Mirrorpanel could be implemented as a continuous exterior insulation, or potentially be used in another, as yet unrealized, configuration.

It is worthwhile to compare the Mirrorpanel with foam insulation, because both could be used to meet the continuous insulation requirements for wood-framed walls in the 2012 IECC. From an environmental standpoint, the insulation materials could be compared by the amount of embodied energy or global warming potential needed to provide a similar level of insulation to the building. The Mirrorpanel is compared with two common foam insulation materials specified in ASTM and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) standards in Table 3 (ASTM International 2010, ASHRAE 2013). For example, a 1-inch-thick sheet of extruded polystyrene has an approximate US R-value of 5 (1.13 W m^{-2} K^{-1}). Each square meter of extruded polystyrene with a US R-value of 5 requires an embodied energy of 84 MJ and results in the production of 14 kg of greenhouse gas (CO_2 equivalent; Aycam and Tuna 2013). A comparable thickness of Mirrorpanel with 5-mm spacing between the layers would have an R-value of between 2.7 and 5 depending on the layer material, an embodied energy of between 50 and 90 MJ, and would result in a product of 3 to 3.5 kg of greenhouse gas (CO_2 equivalent; Boguski 2010, Kinsella 2012). In general, the environmental impact of the Mirrorpanel is between EPS and XPS. However, the Mirrorpanel is made from renewable, forest products

Table 3.—Thermal performance and environmental impact of the Mirrorpanels and polystyrene insulation.

Layer material	Spacing (mm)	US R (in^{-1} thickness)	Embodied energy (MJ)[a]	Produced greenhouse gas (kg)[a]	References
Mirrorpanel[b]					
Foil	5	5	—	—	Pásztory (2013)
Paper, coated one side	5	2.7	50–90	3–3.5	This work, Boguski (2010). Kinsella (2012)
Paper, coated two sides	5	3.8	50–90	3–3.5	This work, Boguski (2010), Kinsella (2012)
Type IV XPS (bulk density, 25 kg m^{-3})[c]		5	84	14	ASTM International (2010), Aycam and Tuna (2013)
Type II EPS (bulk density, 22 kg m^{-3})[c]		4	70	2	ASTM International (2010), Aycam and Tuna (2013)

[a] For 1 m^2 of insulation with a thickness of 25 mm (1 in.).

[b] Environmental impact estimates were made using the Environmental Paper Network Paper Calculator Version 3.2. For more information, visit www.papercalculator.org.

[c] R-values for extruded polystyrene (XPS) and expanded polystyrene (EPS) are given for a mean temperature of 24°C. Apparent thermal conductivity of EPS and XPS may depend on density, temperature, and aging; for further information see ASTM International (2010) and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (2013).

resources, and using forest products in construction sequesters carbon during the life of the building.

From a construction standpoint, the Mirrorpanel has a couple important differences from foam insulation. The first difference is that it could be easily constructed to have a layer of structural sheathing on one or both sides; this extra layer of sheathing could be used to directly attach the exterior cladding. Conceivably, this could be easier than the current methods for attaching cladding over foam insulation in which the cladding is attached to 1 by 3 wood strapping that is screwed through the insulation (Baker 2012, Finch et al. 2013).

Another difference is the vapor permeability. The coated paper has a vapor permeance in the range from about 900 to 1,200 ng Pa^{-1} s^{-1} m^{-2}, or 16 to 21 US perms. On the basis of these measurements, a 35-mm-thick panel targeting R-5 thermal resistance, composed of six layers of coated paper and seven 5-mm air spaces, would have a vapor permeance of 150 to 190 ng Pa^{-1} s^{-1} m^{-2} (2.5 to 3.4 US perms). Similarly, a 70-mm-thick panel targeting R-10 thermal resistance, composed of 13 layers of coated paper and 14 air spaces, would have a vapor permeance of 70 to 90 ng Pa^{-1} s^{-1} m^{-2} (1.2 to 1.6 US perms). Thus the Mirrorpanel is expected to be more vapor permeable than typical rigid foam insulation products, including extruded polystyrene and foil-faced polyisocyanurate, but similar in permeance to expanded polystyrene. Moisture transfer measurements on assembled Mirrorpanel specimens are the subject of current research.

While the thermal performance of the Mirrorpanel has been characterized, and prototypes have been constructed in the laboratory, in a wall system, and at the whole-house level, further development is needed for it to become a viable insulation system. Moisture storage and transport of the Mirrorpanel should be characterized, and economic feasibility should be explored. Once these properties are quantified, the Mirrorpanel can be implemented in a hygrothermal model, such as WUFI (also known as Wärme Und Feuchte Instationär; Künzel and Kiessl 1996), so that it can be easily designed in future construction. Further development could also focus on scaling the production of the Mirrorpanel up to the commercial scale and the optimal end layers so that it can be easily implemented in residential wood construction.

Conclusions

In this article we introduced an insulation system made primarily from forest products and showed preliminary thermal performance data. In general, the thermal conductivity and environmental impacts are similar to those of foam insulation. The Mirrorpanel has a similar vapor permeability to EPS. Further data are needed on the moisture storage and moisture transport of the entire panel before the Mirrorpanel system can be implemented in hygrothermal models to examine wall assembly moisture performance in different climates. Additionally, fabrication and distribution of the panel on a commercial scale has not been realized.

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