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Multi-layer heat insulation system for frame construction buildings

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ABSTRACT

One of the most important research areas today is in energy-efficient technologies such as heat insulation in buildings. In this research, insulation panels with multilayer, low-emissivity aluminum–polyethylene sheets were prepared and investigated. The results of the study showed that surface emissivity and convection currents have important influence on heat flow. The aluminum–polyethylene sheets were effective in reflecting heat and reducing heat transfer by radiation. They also divided the air space in the insulation system, resulting in the reduction of convection currents and convection heat transfer. The heat insulation system was built without micro heat bridges. Consequently, heat conduction was not increased by micro heat bridges resulting in lower effective thermal conductivity than the commonly used insulation materials. The connection between heat resistance and the number of sheets was not linear. The first inserted sheet had the highest effect and each additional sheet had less influence on heat resistance.

1. Introduction

1.1. Problem description

Energy consumption can be divided into four main areas: agricultural, industrial, transportation, and building sectors. The residential and commercial building sector is the largest energy consumer [1]. In the United States, the energy used to construct and operate buildings constitutes 48% of the total energy use. In most developed countries, regulations concerning the required energy efficiency for new construction have become stricter. The European Union also regulates the energy efficiency of buildings by directives and incentives.

There are several studies dealing with the energy efficiency of the different components of buildings such as the cladding, electrical, structural and mechanical systems [2–4]. The state of energy efficiency of existing buildings has been under investigation and the results of a four-year study showed a notable improvement in the United States [5]. In buildings, most of the energy is used for heating and cooling; therefore, regulations are targeting the improvement of heat insulation systems. Most of this energy is used for heating in the boreal climate zone, for cooling in the tropical territories, and for both heating and cooling in the temperate zone. Insulation efficiency depends on how long the energy can be kept inside or outside the building. There are optimization methods for calculating the minimal cost of buildings, initial cost of heat insulation materials, and the cost of energy used for heating and cooling [6,7]. Investment cost of insulation is determined by the present market price; however, the price of energy cannot be predicted easily for the lifetime of a building. Rising energy prices and strict building regulations force the construction of buildings with better heat insulation systems, both in the walls and the roofs. The heat insulation system with higher thermal resistance (*R* value) usually requires more space in the wall, resulting in the need for more material and therefore, higher costs. Ultimately these factors create a need for the research and development of more effective insulation materials and systems. More efficient insulation systems have a higher thermal resistance at a given thickness and thus occupy less space in the wall.

The overall objective of this study is the development of a new, economical, high-efficiency heat insulation system for residential housing by using multiple thermal reflection sheets. The investigation includes the analysis of the effects of changing the number of reflecting layers, ranging from zero to nine, within the same total insulation thickness.

1.2. Theory

Traditional insulation materials such as fiberglass, rock wool, and polystyrene foam use the high insulation capacity of air by segmenting it into small compartments. The heat conductivity of air is 0.025 W/m K at 20 °C if the air molecules are not moving in the same direction (the convection effect is zero), and if the size or thickness of the air layer is more than 1 mm [8]. Despite the relatively high

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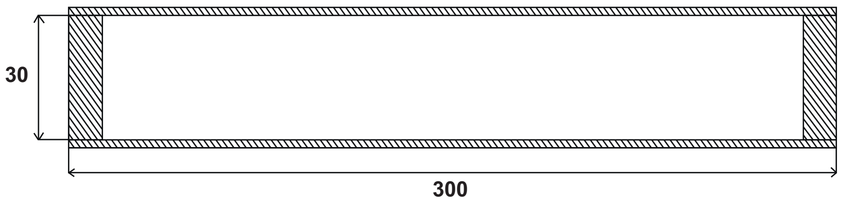

Fig. 1. Cross sectional view of experimental Panel 1.

insulation value of air, the above-mentioned insulation materials have heat conductivity value of around 0.04 W/m K. The difference between the insulation values of air and of the insulation materials comes from the higher heat conductivity of the solid component (filament of fiber glass, rock wool, and polystyrene) of the insulation materials acting as heat bridges. Thus, one possible solution to decreasing the heat conductivity of an insulation material is to decrease the effect of heat bridges.

Heat transfer occurs in three different ways: conduction, convection and radiation. Heat conduction is the transfer of heat due to molecular collisions. In solid materials, the molecules are nearly in contact with each other. This close proximity results in an easy transfer of thermal energy. To achieve higher thermal resistance, it is better to have increased spacing between molecules such as in the gaseous phase. With gas, heat transfer by conduction depends on the velocity of the molecules, which in turn is determined by the mass and temperature of the molecules. Heavier gas molecules are known to have significantly slower velocities than the molecules of a gas with a very low molecular mass. Therefore, a heavier gas with slower velocities has a lower thermal conductivity than that of a lighter gas.

Convection is the process whereby heat is transferred by the mass movement of molecules from one place to another. In free convection, the formation of convection currents depends on the property of the gas, the temperature difference, and the size of the air cavity. These are best quantified using the dimensionless Grashof and Prandtl numbers. The Grashof number indicates the ratio of the buoyancy force to the viscous force acting on a fluid while the Prandtl number indicates the ratio of the momentum and thermal diffusivities. The probability of forming a circulation pathway for the gas is very low if the product of the Grashof number and Prandtl number is below 1000 [9]. It can be noted from the equations for the Grashof and Prandtl numbers that decreasing the distance between boundaries reduces the likelihood that flow circulation will occur. This is largely due to the increase in the ratio of flow boundary interaction, thus a higher portion of laminar flow layer.

Radiation is heat transfer involving the change in energy form from internal energy at the source to electromagnetic energy for transmission then back to internal energy at the receiver. It plays a very important role in the heat transfer process both in gases and in vacuum [9]. In a closed air field, a very high percentage of heat transfer is transmitted via radiation if there is a temperature difference between the surrounding plates. Heat radiation is not influenced by the type of gas or the width of the air field but the direct visibility of plate surfaces is necessary. Transmitted radiant heat energy decreases significantly when a baffle is installed between the plates. Energy quantity conveyed by radiation will be 50% less if the baffle has the same surface emission property as the bounding plates. Increasing the number of baffles will increase the heat resistance of the air field. After n number of baffles, the heat amount transmitted by radiation will only be $1/(n+1)$th part of the original. There are materials that absorb a high amount of incident radiation and there are materials that reflect more than 95% of the radiation. To increase heat resistance, it is better to use a surface with a very low emissivity (e.g. aluminum). A thin aluminum foil has a higher reflecting property than that of an aluminum plate [10], but the foil has a very low tensile strength. An aluminum foil reinforced with polyethylene is commercially available and was used in this study. The aluminum–polyethylene sheet has the mechanical integrity to withstand rough handling during manufacture and construction, while retaining low emissivity. The aluminum side of the sheet has a surface emissivity of 0.05 while the polyethylene side has a surface emissivity of 0.5.

The use of low-emissivity surfaces for reducing heat radiation has been well known for decades. This technology has been developed for space applications, like the heat insulation of spacecrafts. Heat reflection is important in space: there is no air pocket that is used in traditional heat insulation materials and radiation energy is higher than on Earth. Alifanov et al. [11] investigated the modeling and other technical issues related to multilayer insulation systems. The multilayer reflecting foil as core material was used in vacuum insulation technology and it was found that when using multilayer reflecting foils, the radiation heat transfer decreased significantly [12]. The effect of radiant barriers with the combination of different insulation materials was investigated both theoretically and experimentally in hot climates and it was found that the foils could reflect a high percentage of heat energy and the effectiveness of foils at higher temperature was higher [13,14]. The reflected energy ratio can be increased on a light color roofing membrane after cleaning its soiled surface [15]. In addition, increasing the number of air cavities in a hollow block (building unit) increased the thermal resistance. However, the number of air cavities used did not increase the thermal resistance linearly [16].

Building on the above described theories and experimental results, a new insulation system with multiple reflecting aluminum–polyethylene sheets and multiple narrow air cavities was developed for wood-frame residential construction.

2. Materials and methods

To investigate the effect of the number of reflecting aluminum–polyethylene sheets within the same insulation thickness, a series of experiments was conducted using a panel with the same shape and size. The size of the panel was limited to 300 mm × 300 mm for it to accommodate the heat conductivity measuring device. Each panel contained three parts: the bottom plate, the top plate, and the space between the two plates (which henceforth will be referred to as the air field). The bottom and top plates of the panel were made from 4-mm thick beech plywood. The side elements were made from 15 mm × 30 mm spruce lumber. Thus, the distance between the bottom and top plates was 30 mm and kept constant throughout the series of experiments (Fig. 1).

Heat conductivity measurements were performed at atmospheric pressure in accordance with ISO 8301 (ASTM C 518) [17] standards. The temperatures of the heating plate and the cooling plate were maintained at 15 °C and 5 °C, respectively, for six experimental panels:

Panel 1: The 30-mm air field was bordered by plywood surfaces with 0.9 emissivity.

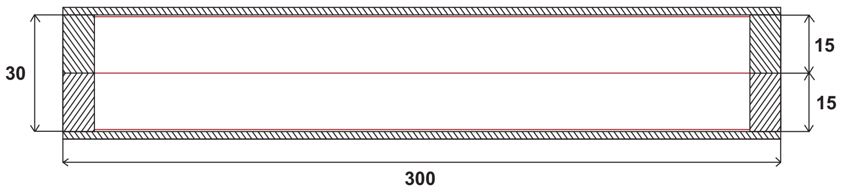

Fig. 2. Experimental setup for Panel 3 showing the air cavities that were divided by an aluminum–polyethylene sheet.

Panel 2: The inner surfaces of the bottom and top plates were lined with a 0.05-emissivity aluminum foil. In comparison to the previous panel, only the surface emissivity property was changed.

Panel 3: The side elements of Panel 2 were cut into two parts and an aluminum–polyethylene sheet was glued in between. Thus, the sheet divided the 30-mm distance between the top and bottom plates into two equal air cavities that were parallel with the plates (Fig. 2.). Henceforth, the terms "air cavity" and "air space" will be used interchangeably to refer to the space between a sheet and a plate, or the space between sheets (see description for Panels 4–6). This is different from the term "air field", which as mentioned earlier is the whole space between the top and bottom plates.

Panel 4: The air field was divided into four equal cavities using two additional aluminum–polyethylene sheets. Thus, the panel consisted of three stretched sheets and four air cavities (7.5 mm thickness/air cavity).

Panel 5: The air field was divided into six equal air cavities using two additional aluminum–polyethylene sheets.

Panel 6: The air field was divided into 10 equal air cavities (3 mm thickness/air cavity) using nine aluminum–polyethylene sheets.

Heat transfer through each of the panels was modeled using THERM, a computer program developed at the Lawrence Berkeley National Laboratory. The program, based on the finite element method, was specifically chosen for this study because of its ability to analyze radiation heat transfer in the air cavities found in the different panels that were investigated. The top and bottom plate boundary conditions were assumed to be isothermal at 15 °C and 5 °C, respectively. Other assumptions included adiabatic boundary conditions on the sides of the panel and one-dimensional heat flow in the direction normal to top and bottom plates.

3. Results

The overall heat transfer coefficient or *U* factor measures the rate of heat transfer through a building element over a given area. Fig. 3 shows the experimental results for the *U* factor of the different panel types. Also shown in the figure are the *U* factors calculated using THERM. To allow for the comparison of the results with the thermal conductivity of stagnant air, the thermal conductivity of the air field was calculated. The bottom and top plates were made from the same material with the same thickness and thus had the same heat resistance or *R*-value (m^2K/W). Since the panel consisted of three parts in series, the total heat resistance is just the sum of the individual resistances:

$$\frac{1}{U_{\text{total}}} = R_{\text{total}} = 2R_{\text{plate}} + R_{\text{airfield}} \tag{1}$$

where U_{total} is the experimentally obtained *U* factor of the whole panel, R_{total} is the heat resistance of the whole panel, R_{plate} is the heat resistance of the bottom or top plate, and R_{airfield} is the heat resistance of the air field. From the experimental parameters and results, the effective heat conductivity of the air field $\lambda_{\text{airfield}}$ was calculated as follows:

$$\lambda_{\text{airfield}} = \frac{\delta_{\text{airfield}}}{((1/U_{\text{total}}) - 2(\delta_{\text{plate}}/\lambda_{\text{plate}}))} \tag{2}$$

where δ_{airfield} is the thickness of the air field (0.03 m), δ_{plate} is the thickness of the bottom or top plate, λ_{plate} is the heat conductivity of the bottom or top plate. The beech plywood used for the bottom and top plates had a thickness δ_{plate} of 4 mm and a heat conductivity λ_{plate} of 0.16 W/m K [18]. The results of the calculation are presented in Table 1. To obtain the magnitude of convective relative to conductive heat transfer, the average Nusselt numbers of the air field for the different panels as calculated using THERM are also included in the table.

The air field of Panel 1 has an effective heat conductivity of 0.148 W/m K, which is close to the heat conductivity perpendicular to the grain for hardwoods. The effective heat conductivity of the air field of Panel 2 is 0.069 W/m K, which is less than half the heat conductivity calculated for Panel 1. The difference between Panel 1 and Panel 2 was caused by the aluminum–foil lining on the inner surfaces of the bottom and top plates. In Panel 3, the foil and the division of the air field resulted in an air field effective heat conductivity of 0.048 W/m K, which is lower than the heat conductivity of Panel 2. The addition of two and four aluminum–polyethylene sheets in Panel 4 and Panel 5 resulted in lower air field effective heat conductivity values of 0.031 W/m K and 0.029 W/m K, respectively. Panel 6, the system with nine sheets and ten 3-mm-wide air cavities had the lowest air field effective heat conductivity of 0.028 W/m K.

4. Discussion

Fig. 3 shows that the *U* factors obtained experimentally and those calculated using the finite element model are in reasonable agreement and had the same general trend of decreasing value in going from Panel 1 to Panel 6. Except for Panel 1, the model underestimated the *U* factors by as little as 5% in Panel 6 and by as much as

Table 1
Effective heat conductivity and average Nusselt number of the air field of the different panel types.

Panel type	Inside surface of bottom and top plates	Number of aluminum–polyethylene sheets	Number of cavities in the air field	Thickness of each cavity (mm)	Effective heat conductivity of the air field, (W/m K)	Average air field Nusselt number
1	Plywood	0	1	30	0.148	2.2
2	Aluminum foil	0	1	30	0.069	2.2
3	Aluminum foil	1	2	15	0.048	1.0
4	Aluminum foil	3	4	7.5	0.031	1.0
5	Aluminum foil	5	6	5	0.029	1.0
6	Aluminum foil	9	10	3	0.028	1.0

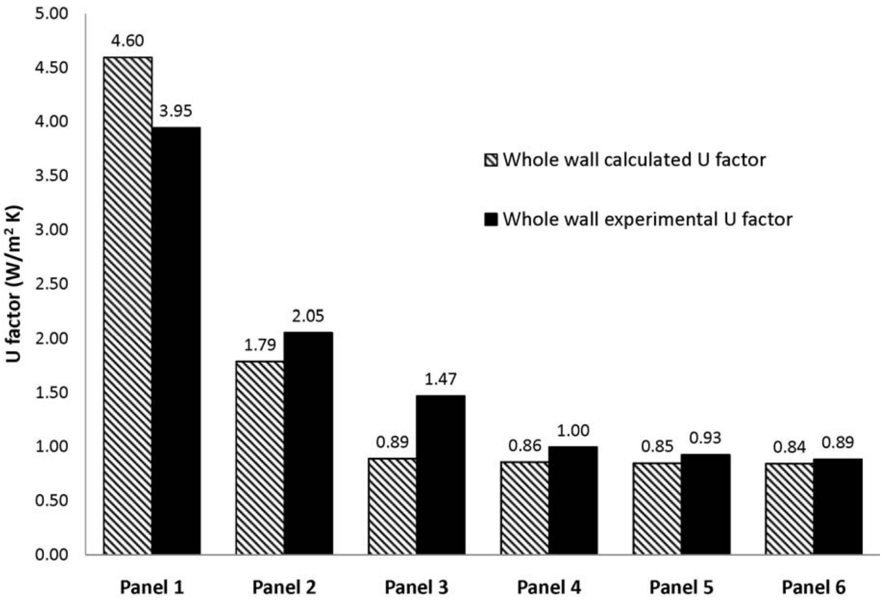

Fig. 3. Whole wall experimental and calculated *U* factors for the different panel types.

40% in Panel 3. The improvement in the insulation value of the different wall systems can be considered significant for Panel 2, Panel 3 (1 sheet), and Panel 4 (3 sheets). However, while Panel 2 had a 48% decrease in *U* factor over Panel 1, the incremental decrease was only 28% for Panel 3 (over Panel 2) and 32% for Panel 4 (over Panel 3). In the case of Panel 5 (5 sheets) and Panel 6 (9 sheets), the addition of sheets and the increase in the number of air cavities decreased the *U* factor further only by 7% and 5%, respectively. These indicate that the insulation improvement slowed down as the number of sheets increased. Similar result was reported by Antar and Baig [16] when investigating the effect of the number of cavities in building blocks with constant width.

The effective heat conductivity of the first two panels, where the difference was the applied aluminum foil lining on the bottom and top plates, demonstrated the significance of heat radiation in the air field. In Panel 1, radiation heat transfer accounted for 57% of the total heat flux, with convection and conduction accounting for 32% and 11%, respectively. Changing the surface property of the top and bottom plates resulted in a decrease in the heat conductivity by a factor greater than two. Although the heat flow by conduction and convection in Panel 2 remained the same as it was in Panel 1, radiation heat transfer was reduced significantly. The effective surface emissivity went down from 0.82 to 0.026, with a corresponding reduction in radiation heat flux from 42 W/m^2 to 1.32 W/m^2. The results indicate that besides increasing the number of air cavities in constructions, the emission properties of the inside surfaces are also important. Panel 3, which had two 15-mm-thick air cavities separated by an aluminum–polyethylene sheet, showed almost the same heat conductivity as that of a rock wool (0.045 W/m K) or a fiberglass insulation (0.04 W/m K). The sheet not only reduced radiant heat flow but also decreased the intensity of convection. Dividing the air space between the plates to less than 15 mm prevented the creation of convection currents. It also divided the temperature difference that existed between the original surfaces of the air space. The lower temperature difference resulted in a weaker force for convection. In addition, the increased number of sheets caused a multiplication of the surface thermal resistance (air film thermal resistance) because the air layer close to the surface of each sheet has a higher thermal resistance than the air cavity. Consequently, the more air surface thermal resistance is built into the system, the higher the total resistance. The average Nusselt number Nu for the air fields in Panel 3 is roughly equal to 1, compared to the Nusselt number of 2.2 for Panel 1 and Panel 2. This means that heat transfer due to natural convection currents in the cavities of Panel 1 and Panel 2 was 2.2 times that by pure conduction, while convection did not contribute to heat transfer in the air field of Panel 3.

In Panel 4, three reflecting foils were used altogether. The heat flow was further reduced due to the narrower air cavities and the additional two reflecting surfaces. The Nusselt number in this case was also equal to 1, indicating that heat transfer in the air field was only due to conduction and radiation. The air field effective heat conductivity of this and subsequent panels decreased below the heat conductivity of the most commonly used insulation materials. With increasing number of sheets, the heat conductivity of the air field approaches the heat conductivity of air (λ_{air} = 0.025 W/m K). The air field effective heat conductivity of Panel 6 was only 11% higher than that of stagnant air.

5. Conclusions

This study was intended to determine the effect of radiation in a heat insulation system that uses multiple thermal reflection sheets to divide the cavity within a wall. After analyzing the effects of changing the number of reflecting layers within the same insulation thickness, the following results can be summarized:

- Surfaces with low emission properties were found to influence heat flow and heat radiation existing in building construction significantly. More than 50% of heat flow decrease was observed when the inner surfaces of the bottom and top plate were lined with aluminum foils. In European wood frame residential buildings, polyethylene foil is commonly used as a vapor barrier with 0.9–0.95 surface emissivity. Replacing the polyethylene foil with aluminum foil or aluminum–polyethylene sheet could result in an increase in the thermal resistance of the wall construction.
- Increasing the number of reflecting sheets between the plates resulted in lower effective heat conductivities. By inserting just one sheet, it was possible to obtain a thermal resistance equal to those of commonly used insulation materials. The thermal resistance of the insulation system approached that of stagnant air as

more sheets were inserted. The relationship between effective heat conductivity and the number of sheets was not linear. The first inserted sheet had the highest effect and each additional sheet had less influence on effective heat resistance. The optimal number of sheets and the air cavity width should be further investigated for different wall constructions.

This study has resulted in the development of an efficient heat insulation system by simply using aluminum–polyethylene sheets to divide the air field within a residential building envelope. This approach proved effective in reducing heat transfer by radiation, convection, and conduction by decreasing surface emissivity, minimizing convection currents, and eliminating micro heat bridges, respectively. Full-size heat insulation panel systems with multilayer aluminum–polyethylene sheets need to be built in order to analyze the feasibility of production, to determine the heat resistance of this system in practice, and to compare results with other insulation systems.

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