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Numerical Modelling and Experimental Investigations of Thermal Performance of Reflective Insulations

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Abstract

Reflective insulations are being used in attics, flat roof and wall systems. Numerical modelling and experimental investigations were conducted to assess the thermal performance of assemblies with reflective insulations. In this paper, the present model was used to verify the use of the ASTM C-518 test method for measuring the effective thermal resistances (R-values) of sample stacks comprising reflective insulations. Two tests were conducted on sample stacks using heat flow meter apparatus. The sample stack consists of two EPS layers and a reflective insulation installed in between. The model predictions agreed with measured heat fluxes within $\pm 1\%$. The paper also discusses the combined effect of heat transfer by convection and radiation in the airspace facing the reflective insulation, showing that the derived R-value from the test data resulted in underestimation of the effective R-value of the sample stack.

Keywords: Reflective insulation, furred-airspace assembly, low emissivity material, thermal modelling, thermal resistance test method, R-value, heat flow meter, ASTM C-518, ASTM C-1363, airflow, heat transfer by convection, conduction and radiation.

Introduction

One of the means to reduce the operating costs is to limit the heat transmission through building envelope. According to the Reflective Insulation Manufacturers Association International (RIMA-I), reflective insulation is defined as “*thermal insulation consisting of one or more low-emittance surfaces, bounding one or more enclosed air spaces*” [1]. Currently, reflective thermal insulation is being used in home attics and wall systems [2]. In this application, the reflective insulation has at least one reflective surface that faces airspace.

Enclosed airspaces always contribute to the overall thermal resistance (R-value) of a system but the presence of a reflective surface increases the thermal resistance of that airspace. Within an airspace, there are three modes of heat transfer: conduction, convection and radiation (see [3-7] for more details). The contribution of the enclosed airspace in roofing or wall systems to the R-values depends on:

- (a) The emissivity of all surfaces bounded the airspace.
- (b) Size and orientation of the airspace.
- (c) Direction of heat transfer through the airspace.
- (d) Temperatures of all surfaces of the airspace.

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Any surface of adjacent materials that faces a transparent medium (e.g. airspace) absorbs and emits long-wave thermal radiation (e.g. surfaces of wood furring and drywall in furred-airspace assembly [3, 4, 5, 6 and 7]). The amount of radiative heat transfer of this surface depends on its temperature and emissivity. Most of construction materials have a surface emissivity of 0.9 (ASHRAE 2009 [8]).

The contribution of the reflective insulation on the thermal performance of wall systems was investigated by the authors [3-7]. In these wall systems, a low emissivity material such as foil was installed within a Furred-Airspace Assembly (FAA). A parametric study was conducted in order to investigate the effect of low emissivity of foil bounded to XPS foam when used within a furred – airspace assembly [3]. The results showed that the modeled wall system with foil emissivity of 0.05 increased the effective R-value by ~10% in the case of the indoor and outdoor temperatures of +20°C and -20°C, respectively [3]. Recently, the present model was benchmarked against the experimental data of a full-scale above-grade wall system (8' (2438 mm) x 8' (2438 mm)) consisting of 2" x 6" wood frame construction with stud cavities filled with friction-fit glass fibre batt insulation and a foil bonded to wood fibreboard installed in a furred-airspace assembly (the foil was facing the airspace and the interior finishes). A test was conducted in the Guarded Hot Box (GHB) to determine the effective thermal resistance of this wall system [9]. This test was conducted in accordance with ASTM C-1363 test method [10]. Results showed that the predicted R-value of this wall system was in good agreement with the measured value [4]. The present model was used to investigate the effect of outdoor and indoor conditions on the steady-state and transient thermal performance of a foundation wall system (including the above-grade and below-grade portions of the wall) having FAA that incorporates a low emissivity material (foil) [5 and 6]. To quantify the contribution of a FAA with foil bonded to EPS foam on the energy savings, reference walls were considered (identical to these foundation walls but without FAA). Results showed that at steady-state condition, the effective R-value of wall with FAA can vary by as much as ~3%, depending on the soil, outdoor and indoor temperatures through the year. Moreover, these wall configurations resulted in an energy savings of ~17% more than the same walls but without FAA [5 and 6].

Note that in the previous studies [3, 4, 5 6, and 7], the orientation of the enclosed airspace was vertical. As indicated earlier, the reflective insulations can also be used in home attics, and flat and sloped roofs. In these types of applications, enclosed airspace would have a zero or non-zero slope with a horizontal surface. Recently, Craven and Garber-Slaght [2] tested a number of reflective insulation products at the Cold Climate Housing Research Center (CCHRC) to quantify the contribution of enclosed airspace to the R-value of an assembly. In that study, the ASTM C-518 test method [11] was used with FOX-314 heat flow meter [12] that accommodates product samples up to 12" (304.8 mm) in width and length, and thickness up to 4" (101.6 mm). Craven and Garber-Slaght [2] tested a number of sample stacks with different types of reflective insulations (12" (304.8 mm) x 12" (304.8 mm) in area) to allow for air gap below the reflective facer material. The support structure for the air gap was a hollowed piece of EPS (12" (304.8 mm) x 12" (304.8 mm) x 1" (25.4 mm)), cut in such a way that the exposed center air space, not the edges of the EPS spacer, was situated over gypsum board (12" (304.8 mm) x 12" (304.8 mm) x ½" (12.7 mm)). The air space was 8" (203.2 mm) x 8" (203.2 mm) in area and 1" (25.4 mm) thick. The sample stacks were placed horizontally between the upper cold plate and lower hot plate of the FOX-314 heat flow meter. Two types of reflective insulations were tested (referred to in this paper as Type-A and Type-B). The thicknesses of Type-A was 1" (25.4 mm) and 2" (50.8 mm), and the thickness of Type-B was 1" (25.4 mm). All tests were performed at an average temperature of 75°F (12.8°C), with upper and lower surface temperatures of 55°F (12.8°C) and 95°F (35.0°C), respectively (upward heat flow through the samples).

The ASTM C-518 test method is suitable for evaluating a thermal resistance of a sample when the heat flow through it is by conduction (one-dimensional heat flow). In the case of testing a sample stack such as described above using this test method, the heat transfer through it will be by conduction, convection and radiation. This represents a multidimensional heat transfer through the sample stack where the middle layer with air cavity acts as thermal bridge. The use of heat flow meter apparatus according to the ASTM C-518 test method when there are thermal bridges present in the sample may yield results that are unrepresentative of the assembly (see [11] for more details). Alternatively, the ASTM C-1363 test method using the GHB can be used to determine the effective thermal resistance of sample with thermal bridges [10].

According to the ASTM C-518 test method [11], the thermocouples embedded in the surfaces of the upper and lower plates of the heat flow meter measure the temperature drop across the specimen and the Heat Flux Transducer (HFT) embedded in each plate measures the heat flow through the specimen. The uncertainty of the measurements in this test method is $\pm 2\%$ [11]. Testing a sample using this method only requires preparing the sample and installing it between the hot and cold plates (i.e. no need to instrument the sample itself). As such, this test method sounds simple, accurate and a cost effective test. However, the question is “can the ASTM C-518 test method still be used to measure the effective thermal resistance of sample stack such as described above?”. The objective of this study is to answer this question.

Comparison of Reported Lab Measurements and Model Predictions

As indicated earlier, Craven and Garber-Slaght [2] measured the R-value of sample stacks with different types of reflective insulations (Type-A and Type-B) in accordance of ASTM C-518 [11] using FOX-314 heat flow meter [12]. In that study, the emissivity of the foil bonded to the insulation of Type-A and Type-B were not measured. However, the authors stated that for shiny metal surfaces, the emissivity is around 0.05 – 0.1 according to ASHRAE (2009) [8]. The measured R-values of three sample stack are compared with the predicted R-values using hyglRC-C model [3 -6] in Figure 1 when the foil emissivity of these reflective insulations was 0.05 and 0.1. The predicted R-value of the sample stack with 2” (50.8 mm) thick of Type-A was 8.0% and 6.9% higher than the measured R-value for foil emissivity of 0.05 and 0.1, respectively (Figure 1a). For the sample stack with 1” (25.4 mm) thick of Type-A, the predicted R-value was also 8.5% and 6.8% higher than the measured R-value for foil emissivity of 0.05 and 0.1, respectively (Figure 1b). Additionally, for the sample stack with 1” (25.4 mm) thick of Type-B, the predicted R-value was 9.1% and 7.3% higher than the measured R-value for foil emissivity of 0.05 and 0.1, respectively (Figure 1c). It is surprising that the predicted R-value is consistently higher than the measured R-value (in accordance of ASTM C-518 test method [11] using FOX-314 heat flow meter [12]) by approximately the same percentage for different types of reflective insulations. In a previous study [4], however, the prediction of the present model for R-value was in good agreement (within 1.2%) with the measured R-value in GHB (in accordance of ASTM C-1363 test method [10]) for wall specimen having a reflective insulation and furred-airspace assembly. So, the question is “why was the predicted R-value found to be consistently higher than the measured R-value by approximately the same percentage for different reflective insulations using the ASTM C-518 test method with FOX-314 heat flow meter?”.

It is expected that the combined effect of heat transfer by convection and radiation in the air cavity would result in higher heat fluxes on the middle portion of the top and bottom surfaces where the Heat Flux Transducers (HFTs) were located. Thus, the measured heat fluxes may not represent the actual heat passing through the whole sample stack since these measurements would depend on the size of HFTs (4” (101.6 mm) x 4” (101.6 mm) in the FOX-

314 heat flow meter [12]). Depending on the shape of heat flux distribution on the top and bottom surface (12" (304.8 mm) x 12" (304.8 mm) in area), using the measured heat fluxes to derive the R-value may result in determining lower R-value. Neither the measurements of heat fluxes were reported nor were the emissivity of the reflective surfaces measured [see 2]. To enable the judgment whether the predicted R-value or the derived R-value from the test data information should be used to represent the effective R-value of assembly with reflective insulations, two stack samples were tested using the same test method (ASTM C-518) as the tests conducted at CCHRC [2]

Verification Tests

Two tests were conducted in an attempt to answer the question raised earlier. These tests were conducted in accordance of ASTM C-518 test method [11] to measure the R-values of two sample stacks with and without aluminum foil. These tests were conducted using a heat flow meter that accommodates samples up to 12" (304.8 mm) in width and length, and thickness up to 4" (101.6 mm). As shown in Figure 2, the sample stack consists of two 12 inch (304.8 mm) x 12 inch (304.8 mm) x 1 inch (25.4 mm) EPS specimens and an air cavity (8 inch (203.2 mm) x 8 inch (203.2 mm) x 1 inch (25.4 mm), [2]) created in the center of another EPS layer (12 inch x 12 inch x 1 inch, see Figure 2c), which was placed between the upper and lower EPS layers. The first test was conducted without installing foil in the specimen. The second test was conducted after installing an aluminum foil on the bottom surface of the upper EPS layer (i.e. foil facing the airspace, see Figure 2a and b). The emissivity of the aluminum foil was measured and found to be 0.2.

Before conducting these two tests, the thermal conductivity of EPS layer (12 inch x 12 inch x 1 inch) was measured using the same test method (ASTM C-518) and the same heat flow meter. To ensure the repeatability in the measurements, the thermal conductivity test was conducted for three EPS samples of same size. The measured thermal conductivity of each EPS sample was 0.03455, 0.03467 and 0.03470 W/(m.K) with an average value of 0.03464 W/(m.K). The value of the average thermal conductivity was used in the numerical simulations. In all tests, the specimens were placed between two horizontal plates, at a constant temperature difference between the upper and lower plates (Figure 2). Also, all tests for both sample stacks and single EPS layers were performed at an average temperature of 75°F (23.9°C), with upper and lower surface temperatures of 55°F (12.8°C) and 95°F (35.0°C), respectively. Note that these test conditions were similar to that were conducted by Craven and Garber-Slaght at CCHRC [2]. The NRC test results showed that the measured R-value in the case with aluminum foil ($\epsilon = 0.2$) was 9.814 ft² hr °F/BTU (within a standard deviation of $\pm 1.07\%$). Also, the measured R-value in the case without aluminum foil ($\epsilon = 0.9$) was 9.112 ft² hr °F/BTU (within a standard deviation of $\pm 0.86\%$).

Comparison of Measurements and Model Predictions

Figure 3 shows a comparison between the predicted R-value and measured R-value for the cases with foil ($\epsilon = 0.2$) and without foil ($\epsilon = 0.9$). As shown in this figure, the predicted R-values for the two cases of sample stacks with and without foil were 7.5% and 9.7%, respectively, higher than the measured R-values. Accordingly, the present model consistently predicts higher R-values than the measured R-values by approximately the same percentage not only for the tests conducted at CCHRC but also for the tests conducted at NRC. Further investigations were needed to understand why the predicted R-value was consistently higher than the measured R-value, and which R-value would represent the effective R-value of the sample

stacks. In these investigations, data analyses and a number of comparisons between the model predictions and measurements were carried out and presented next.

Since the measured temperatures at the interfaces between the sample stacks and the upper cold plate (55°F, 12.8°C) and the lower hot plate (95°F, 35.0°C) of the heat flow meter were taken as temperature boundary conditions in the numerical simulations, an accurate model should be able to predict the measured heat fluxes at these interfaces. The combined effect due to heat transfer by convection and radiation in the air cavity results in non-uniform heat flux distributions on both the top and the bottom surfaces of the sample stack where the Heat Flux Transducers (HFTs) are located. A full description of the convection loops (6 loops) due to the multi-cellular airflow in the cavity that greatly causes a non-uniformity of the heat flux distributions on the top and bottom surfaces of the stack sample is available in [16].

The size of the HFTs of the heat flow meter used in the tests conducted at NRC is 6 inch x 6 inch. The HFT's were installed at the centers of the upper and lower plates. Figure 4 shows sample results of the measured heat fluxes on the top and bottom surfaces of the sample stack with aluminum foil ($\varepsilon = 0.2$) at steady-state condition. Figure 5a and b show the predicted local heat fluxes at the top and bottom surfaces of the sample stacks in the cases with and without foil, respectively. As shown in these figures, higher heat fluxes are predicted on the middle portions of the top and bottom surfaces than that close to the edges. In the case with foil, the percentages of the maximum change in the heat fluxes on the top and bottom surfaces, respectively, are about 25% and 33% (Figure 5a). These percentages are 36% and 37% in the case without foil (Figure 5b). However, in order to use the ASTM C-518 test method [11], these percentages have to be ~0% (i.e. uniform heat flux distribution or one-dimensional heat flow through the sample stack). Consequently, it is obvious that with HFTs installed at the center of top and bottom surfaces having smaller size than the size of these surfaces results in measuring higher heat fluxes. Due to the non-uniformity of the heat fluxes on these surfaces, the measured heat fluxes are not representative to the actual heat passing through the whole sample stack. In this case, using the measured heat fluxes to drive the experimental R-value ($R = \Delta T/q$, ΔT was controlled to be constant in the tests) would result in underestimation for the effective R-value.

Since, the effective R-value has to be estimated based on the actual heat passing through the whole sample stack (or average heat flux based on area-weighted of whole sample stack), the predicted effective R-value is higher than the derived R-value using the measured heat flux. The authors are therefore postulate that the non-uniformity of heat flux in the test apparatus, in combination with the heat flux measured only in the central area explain the difference between measured and predicted R-value from the tests that were conducted at both NRC and CCHRC [2].

Benchmarking the Present Model

To show the non-uniformity of the predicted heat fluxes at the top and bottom surfaces of the sample stacks with and without foil, Table 1 lists the maximum, minimum and the area-weighted average heat fluxes based on whole surface area of 12" (304.8 mm) x 12" (304.8 mm) ($\bar{q}_{12 \times 12}$). For the purpose of benchmarking the present model by comparing its predictions against the measurements, this table also lists the predicted area-weighted average heat fluxes at the middle of the sample stack on surface area of 6" (152.4 mm) x 6" (152.4 mm) ($\bar{q}_{6 \times 6}$) and the measured values using HFTs of the same surface area. The standard deviation (STDEV) in all measurements of heat fluxes was less than 2%. As shown in Table 1, all measured and

predicted $\bar{q}_{6 \times 6}$ on the top and bottom surfaces of the sample stacks with and without foil are in good agreement (within $\leq \pm 1.0\%$).

As indicated earlier, the effective R-value for the sample stack should be obtained based on the actual heat passing through the specimen or $\bar{q}_{12 \times 12}$. Just for the purpose of comparison, the predicted $\bar{q}_{6 \times 6}$ and the measured heat fluxes were used to derive the R-value and compare it with the effective R-value (i.e. based on $\bar{q}_{12 \times 12}$). Since the predicted $\bar{q}_{6 \times 6}$ and the measured heat fluxes on the top and bottom surfaces are not equal (see Table 1 and Figure 6a), the mean value of the heat fluxes on both the top and bottom surfaces ($\bar{q}_{6 \times 6, \text{mean}}$) were used to derive the R-values. The obtained results are plotted in Figure 6b. As shown in this figure, the derived R-values based on the predicted $\bar{q}_{6 \times 6, \text{mean}}$ and the mean measured heat fluxes using 6" x 6" HFTs are in good agreement (within $\pm 0.6\%$) for the sample stacks with and without foil.

Using the ASTM C-518 test method to measure heat flux with heat flow meter with HFTs that are smaller than the sample stack size (6" x 6" for the NRC's heat flow meter, and 4" x 4" for the CCHRC's FOX-314 heat flow meter [2 and 12]) resulted in underestimation for the effective R-value. Depending on the value of the foil emissivity, the derived R-value from the test data underestimated the effective R-value by 7.5% and 9.7% for the cases with foil ($\varepsilon = 0.2$) and without foil ($\varepsilon = 0.9$), respectively (see Figure 6b).

Based on the results presented above, measuring the effective R-value of sample stacks with reflective insulations such as presented in this study by using the ASTM C-518 test method [11] is not recommend with a heat flow meter that has HFTs with surface area less than the surface area of top and bottom surfaces of the specimen. Because the ASTM C-518 test method is quite simple, accurate (uncertainty of the measurement is within 2% [11]), and cost effective, it is worth trying to test the applicability of this method with additional measures of controlling multilateral heat flow.

After benchmarking the present model, it was recently used to quantify the contribution of reflective insulations to the effective R-value for sample stacks with different inclination angles, directions of heat flow and a wide range of foil emissivity (see [16] for more details).

Summary and Conclusions

In this paper, numerical modelling and experimental investigations were conducted to compare the thermal performance of different types of reflective insulations. The present model was used to verify the use of the ASTM C-518 test method for measuring the effective thermal resistance (R-value) of sample stack comprising reflective insulations. In the first phase of this study, the predictions of the present model were compared with the CCHRC's test data that were obtained using FOX-314 heat flow meter in accordance of ASTM C-518 test method. Results showed that the predicted R-values were consistently 6.8 – 9.1% higher than the R-values derived from the test data [2]. To verify these differences, two tests were conducted at NRC using the same conditions as in reference [2] but with different heat flow meter apparatus. It was also found that the predicted R-values were 7.5% and 9.7% higher than the R-values derived from the test data for the cases with and without foil.

Further investigations revealed that the predicted heat flux distributions on the top and bottom surfaces of the sample stack were non-uniform because of the combined effect of heat transfer

by convection and radiation inside the air cavity. Since the predicted and measured heat fluxes on the same area and same location of Heat Flux Transducers (HFTs) on the top and bottom surfaces were in good agreement (within $\pm 1\%$), and these values were higher than the area-weighted average heat fluxes based on whole surface area of the sample stack, it was evident that the derived R-value from the test data resulted in underestimation of the effective R-value of the sample stack. Since the ASTM C-518 test method is quite simple, precise and cost effective, future work is recommended to investigate experimentally the possibility of using this test method after increasing the size of the HFTs to be the same as the size of the top and bottom surfaces of the sample stacks. Thereafter, the obtained test results should be compared with modelling results in order to proof this concept.

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Table 1. Comparison of predicted and measured heat fluxes (in W/m²) on the top and bottom surfaces of sample stacks with and without foil

	Parameter		with foil ($\varepsilon = 0.2$)	without foil ($\varepsilon = 0.9$)
Predicted	Top surface	max	13.091	14.017
		min	10.512	10.338
		avg on 12"x12" ($\bar{q}_{12 \times 12}$)	12.052*	12.721*
		avg on 6" x 6" ($\bar{q}_{6 \times 6}$)	12.665	13.848
	Bottom surface	max	13.314	14.016
		min	10.040	10.251
		avg on 12"x12" ($\bar{q}_{12 \times 12}$)	12.052*	12.721*
		avg on 6" x 6" ($\bar{q}_{6 \times 6}$)	13.069	13.898
	Mean value on 6"x6" of both top and bottom surfaces ($\bar{q}_{6 \times 6, \text{mean}}$)		12.867	13.873
Measured using 6"x6" heat flux transducers	Top surface	avg using 6"x6" HFT	12.726	13.951
		STDEV (W/m ²)	0.118	0.104
		STDEV (%)	0.930	0.744
	Bottom surface	avg using 6"x6" HFT	13.114	13.759
		STDEV (W/m ²)	0.249	0.215
		STDEV (%)	1.896	1.564
	Mean value on 6"x6" of both top and bottom surfaces ($\bar{q}_{6 \times 6, \text{mean}}$)		12.920	13.855
Deviation from experiment (%)	Top surface		0.474	0.737
	Bottom surface		0.343	-1.006
	Mean value on 6"x6" of both top and bottom surfaces		0.407	-0.129

* The values on the top and bottom surfaces are equal due to energy conservation (see Figure 6a)

Figure 1. Comparison between predicted R-values with foil emissivity of 0.05 and 0.1 and measured R-values [2] for different sample stacks

Figure 2. Sample stacks tested at NRC (ASTM C-518 test method [11])

Figure 3. Comparison between the predicted and measured R-value of EPS sample stacks with and without foil

Figure 4. Sample results of measured of heat flux on the top and bottom surfaces of sample stack in the case with aluminum foil ($\epsilon = 0.2$)

Figure 5. Predicted local heat flux on the top and bottom surface of the sample stacks with and without foil

Figure 6. Comparisons between predictions and measurements for sample stacks with and without foil