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Evaluation of reflective insulation systems in wall application by guarded hot box apparatus, and comparative investigation with ASHRAE and ISO 15099

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HIGHLIGHTS

- Full scale testing of innovative configurations of reflective insulation systems.
- Experimental assessment of the interior thermal performance of reflective systems.
- There is great deviations from the R-values derived from simulations.
- Discussions on the reasons of discrepancies between various evaluation methods.

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ABSTRACT

In view of discrepancies in former studies on reflective airspaces and reflective insulation systems, two innovative guarded hot box experiments (as the most credible experimental testing method) were conducted in this investigation. Full-scale testing of innovative wall configurations of reflective insulation systems with guarded hot box apparatus were performed according to the ASTM C1363 in energy laboratory of BHRC. In order to verify the assessment methods, and conduct a comparative survey with the most credible calculation methods, the results were compared with ASHRAE data, and with results derived from ISO 15099. Two EnergyPlus models using zone heat balance method and ISO 15099 (as the interior convection algorithm) were developed according to the specifications of the tested specimens. Simulations results showed 56.1% and 60.1% differences from the first and second guarded hot box experiment results respectively. Comparisons proved that in spite of good agreement between results derived from ASHRAE and ISO 15099, these calculation methods significantly overestimate the airspace R-values (up to 85.1%). Simplifications resulting from presumptions related to the computation methods, such as one-directional heat transfer by negligence of thermal bridges inside the cavities, and isothermal assumption of bounding surfaces of the airspace, are the main reasons of incompatibilities (the guarded hot box tests showed average 10.1% temperature variations in each interior surfaces of the assembly). The greatest temperature variations is seen in the surfaces of the reflective insulation layers, which shows the influences of the surface properties on the interior convection currents, which is not considered in ASHRAE and ISO 15099 correlations. The guarded hot box investigations also proved that the thermal conductivity of bubble foil insulation materials highly depends on temperature conditions, which can be possibly due to the enclosed air gaps inside the insulation material, and needs complementary studies. Moreover, imperfect airtightness of interior layers, and non-uniform thickness of interior air cavities increase the influences of inevitable thermal bridges in common real application of reflective insulation systems.

1. Introduction

The excessive use of energy and carbon emissions makes it necessary to search for appropriate renewable energy sources and energy efficiency measures. Building sector accounts for more than

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Nomenclature

C	Heat transfer coefficient	$\varepsilon_{eff}h_r$	Radiation coefficient
R_T	Total thermal resistance of a building assembly	ε_{eff}	Effective emissivity
q''_{LWX}	Net long wave radiant exchange flux between zone surfaces	Ra	Rayleigh number
q''_{SW}	Net short wave radiation flux to surface from light	ρ	The density of the air
q''_{LWS}	Long wave radiation flux from equipment in zone	g	The acceleration due to gravity
q''_{ki}	Conduction flux through the wall	Cp	The specific heat of air
q''_{sol}	Transmitted solar radiation flux absorbed at surface	μ	The viscosity of air
q''_{conv}	Convective heat flux to zone air	$T_{m.f}$	The mean temperature in Kelvin
h_c	Conductive/ Convective coefficient	Υ	Tilt angle
h'_c	Convective heat transfer coefficient	Nu	Nusselt number

one third of final energy consumption globally [1]. Thermal insulations are among the solutions to decrease the heat loss through building envelope, and they can be classified into four groups of bulk, reflective, vacuum and insulation systems using nano-technology [2]. Conventional insulation systems, such as fiberglass, mineral wool, expanded polystyrene (EPS), extruded polystyrene (XPS) are among bulk technology systems. These systems improve the thermal performance of the building envelope by reducing solid conduction (due to high porosity), gas conduction (for e.g. by using low conductivity gases trapped in closed-cell foam insulation, creating a partial vacuum, etc.) and convection. However they are not effective in reducing heat transfer by radiation, which is often a major heat transfer mode in building envelope [3]. Moreover, different challenges in utilization of the innovative insulating technologies such as; health and safety considerations, high costs, and uncertainties about their hygrothermal and long term behavior make their common application dependent to more improvements and studies [4,5]. Reflective insulations can be used in reflective insulation systems and radiant barriers [6]. Reflective insulation systems, which are the focus of this paper, include low-emissivity surfaces and adjacent airspace(s). Reflective insulation systems are defined as "*thermal insulation consisting of single or multiple low-emittance surfaces, in contact with one or more enclosed airspaces*" [3]. Reflective insulations are used as low-emittance surfaces in reflective insulation systems. Reflective insulations consist of paper, and/or plastic (as the core material) to trap air and reduce convective and conductive heat transfer, in addition to the layers of low emissivity materials like aluminum foil or metalized films, which significantly reduce the heat transfer by radiation [7]. The second component of a reflective insulation system is the air gap (enclosed air cavity). In leakage-free enclosed airspaces, the air movement and the heat transfer can be reduced considerably. According to the Australian Institute of Refrigeration, Air Conditioning and Heating Technical Handbook (AIRAH) [8], by adding a reflective material facing the air gap, the still air provides the further insulation resistance level and this enclosed assembly becomes a reflective airspace. Generally, thermal resistance of reflective airspaces is influenced by factors such as mean air temperature and temperature difference across the air cavity, emissivity of all surfaces surrounding the air cavity, air gap size and orientation [2,9]. According to the literature reviews, thermal resistance of reflective airspaces has been evaluated by measurements and calculation models. Measurement studies have been conducted by guarded hot box apparatus, guarded hot plate apparatus, heat flow meter and calorimeter. Researchers were using guarded hot box and guarded hot plate to measure the heat transfer coefficient and thermal resistance of these systems since 1930's [10]. However the capability of the guarded hot box apparatus to evaluate full-scale systems (due to its dimensions), would decrease the amount of the measurement errors compared to guarded hot plate [11]. Heat flow meter apparatus, also can be used to assess small specimens of reflective insulation systems, which usually restricts the air gaps to less than 50 mm [7]. Moreover, previous studies [12] showed that using ASTM C518 [13] to perform measurements on small specimens by heat flow meter, will underestimate the effective R-value of the testing assemblies with reflective insulation. However, the author solution was matching the size of the heat flux transducers in the heat flow meter to the top and bottom surfaces of the specimen to make it possible to perform more accurate measurements. Another shortcoming of the hot plate or heat flow measurement is the significant difference of the emissivity of hot & cold plates from the actual building materials with higher emissivity [14]. Thermal resistance of assemblies with reflective insulation is the sum of conductive heat resistance of insulation material, and conductive, convective and radiative heat resistance of airspace(s). Most inaccuracies and differences between measured values in reflective airspaces usually occur because of variations in airtightness, ventilating or none ventilating and thermal bridges in air cavities of experimented samples [9]. The low thermal mass of reflective insulations also justifies the conductance of tests under steady-state conditions (such as guarded hot box evaluations). Moreover, literature reviews proved that the guarded hot box experiments are the most accurate tests in evaluation of reflective airspaces and reflective insulation systems.

Extensive performed guarded hot box experiments and data gathered by Robinson and Powell [15] formed the basis of airspace R-value tables in American Society of Heating, Refrigerating and Air-conditioning Engineers HVAC fundamentals Handbook (ASHRAE) [16] and AIRAH handbooks [10,17]. It has been used as the basis of validation and making comparisons between various measurement and calculative studies. studies conducted for Cold Climate Housing Research Center (CCHRC) proved that the measured airspace R-values using heat flow meter in accordance to ASTM C518 were lower than the presented values in ASHRAE [18]. The same conclusion was also made from evaluations using large calibrated hot box to evaluate wall assemblies, which stated that the measured R-values for reflective airspaces were significantly lower than the listed ASHRAE R-values [19,20]. Goss and Miller [10] compared airspace R-value data from guarded hot box measurements [21] and calculated thermal resistance values using Yarbrough's [22] convection equation and the standard Stefan-Boltzman radiation equation, which proved that the measured values were lower than the calculated ones for both types of reflective and none-reflective airspaces (for non-reflective airspace thermal resistance values were in agreement to within about 6% while for reflective airspaces the difference was between 6% to more than 37%). In view of these discrepancies, different investigations have been conducted in order to present numerical models for predicting the thermal resistance value of reflective airspaces. As shown in Table 1, generally ASHRAE provided a basis for

Table 1
Studies on calculation models of reflective airspaces.

Research	Calculation model	Results
[22]	one-dimensional model according to experimental results [15]	Made comparisons between calculation results from this model and Hollingsworth's and his earlier experimental results. It was found that this one-dimensional calculation model significantly over-predict R-values compared to experimental results. Recommended the need for a multi-dimensional model.
[11]		Recommended the use of two and three dimensional analytical models to anticipate the R-values of reflective airspaces.
[11,23]		Developed a three-dimensional finite element analysis which could predict the experimental results well.
[17]	• Reflect2 and Res2: two methods based on the hot box measurements [15] • Reflect3: third method with incorporation of Yarbrough's polynomial curve fit algorithms Aluminium Foil Insulation Association (Australia) the same as [24] recommended the third method as a software for calculating the thermal resistance of reflective airspaces • Fourth method: based on simplified algorithms introduced in ISO 6946 [25]	For airspaces less than 10 mm results from all four methods have good agreement, due to the absence of convection in these cases. Nevertheless, when the air gap increases, natural convection starts to dominate, and the difference between results related to above mentioned methods increases. This is because of the differences in assessment of the convective component of the heat transfer. Findings proved that: For 5–20 mm air gaps; results derived from first and second methods have less than 4% difference, and the results were in agreement within 10% and 4% if ISO 6946 results were not included.
[12]		Developed a simulation model and compared its results by the listed R-values in the ASHRAE handbook for various inclination angles and heat flow directions. The author found considerable differences for vertical cavity (horizontal heat flow).

development of calculation models and making comparisons in former studies.

The R-values from Robinson and Powell's experiments are only relevant to ideal conditions i.e. uniform air space thickness, parallel surfaces with no air leakage into or out from the cavity or between the cavities, if more than one air layer is used. Due to the feasibility of difference between the actual field conditions with these mentioned "perfect" conditions, necessary attention should be paid when applying the R-values that are published in the above mentioned handbooks (ASHRAE and AIRAH) [10]. Studies on the effect of non-uniform thickness of the cavities showed that the thermal resistance can decrease up to 50–90% compared to the cases with uniform thickness [17,26]. In addition, thermal conductivity of insulation materials with reflective surfaces also highly depends on temperature conditions across them [27], which can lead to deviations in assessment of reflective insulation systems.

According to literature reviews, in some investigations researchers did comparisons between the ISO 15099 [28] and measurement and prediction methods in accordance with available standards or handbooks. ISO 15099 standard presents detailed calculation correlations for evaluating the thermal performance of windows, doors and shading devices. Uvslokk and Arnesen [29] performed a comparative survey between the thermal resistance values obtained by calculation and measurement methods. Calculations were accomplished according to ISO 15099 and EN ISO 6946 [30]. The authors believed that ISO 15099 is the most updated international standard for heat transfer calculation in closed cavities while algorithms in ISO 6946 for natural convection are more simplified hence produces lower R-values for air gaps. To perform the measurements: a large hot box and heat flow meter in a timber frame wall of full height (2.4 m) were used. It was found that calculated values by ISO 15099 were well comparable to U-values measured by hot box apparatus. However, measured values from heat flow meter gave a higher R-value of cavities, considered by the authors as too high, because of the small size of the circular metering area of heat flow meter, and the inadequate location of the probe at the middle height of wall. From the plotted curves:

i) Up to air gap thickness of 20 mm; calculated values according to ISO 15099 and EN ISO 6946 showed very good agreement.
ii) After 20 mm thickness of air gaps; R-values became constant under EN ISO 6946. Fricker and Yarbrough's [17] graph for wall calculation (horizontal heat flow) using ISO 6946, also showed the constant R-values after this thickness. This proved that the optimum thickness of air gap under ISO 6946 is about 20 mm, and for greater thicknesses, there is no sensible change of the thermal resistance value.

Baldinelli [14] stated that with certain conditions, which is the temperature difference below 5 K and average temperature of surface limited to 273–313 K range, the differences of R-value produced by ISO 6946 and ISO 15099 were less than 6%. The author restricted the application of simplified calculation model of ISO 6946 to the presence of the aforementioned conditions. The author's investigations also showed the comparability of the measurements according to ISO 9869 [31] and the calculated values by ISO 6946. He found that guarded hot plate and hot box gave a slightly higher thermal resistance, which is probably due to the limited measured airspaces by these methods, which restricts the convective currents as found in real field conditions.

Discrepancies between results derived from measurements by different methods, and between calculations and measurement results, and defects and limitations in various evaluation methods have made uncertainties about enclosed reflective airspaces and reflective insulation systems to still remain. It also makes former investigation results unreliable for assessing the real application of reflective airspaces and reflective insulation systems. The objectives of this study were to verify the results from the most credible experimental and computational methods, make comparisons between them, and probe for reasons of [feasible] unconformity in results derived from these methods. In order to reach to these research objectives; this study aims to:

- Evaluate reflective insulation systems by the most authentic experimental test method. Disagreements and defects in former experimental studies, and their focus on the performance of [usually] single reflective airspace rather than the reflective insulation systems with multiple airspaces made the conductance of these tests essential. In spite of the previous investigations, the goal is to perform the tests by controlling all the effective parameters on the performance of full scale reflective systems (such as air tightening, specifications of the airspaces, monitoring the interior conditions of the airspaces and etc.).

- Develop a calculation model based on the most credible computational models and in accordance with the experimental test specimens in order to make comparative studies. Literature studies prove that the assessment of reflective insulation systems with several airspaces by numerical models, and comparative investigation with the similar experimental data is rare.
- Conduct a comparative survey with the ASHRAE listed airspace R-values. Literature survey indicates incompatible results derived from comparative studies with ASHRAE (experimental, and numerical), which highlights the need for this investigation.
- Analyze the similarities and differences of the results derived from the abovementioned evaluation methods and search for the feasible explanations.

2. Methodology

As it was discussed in former section, guarded hot box evaluation is the most accurate test method of reflective airspaces and reflective insulation systems. ASHRAE data (which is derived from the most extensive guarded hot box experiments) has been utilized as the basis of validation and development for different experimental and numerical studies of reflective insulation systems, respectively. In addition, according to literature reviews ISO 15099 is among the most credible standards for evaluation and prediction of thermal resistance value in enclosed cavities. In this study, two different configurations of reflective insulation systems were tested by guarded hot box apparatus according to ASTM C1363 [32]. Full scale testing of innovative configurations of reflective insulation systems with multiple airspaces and measuring the thermal conditions inside the configuration (in order to obtain comprehensive knowledge about the thermal performance of reflective insulation systems) were conducted in this step. Then the results obtained from the experimental tests were compared to the ASHRAE data, and simulation results. EnergyPlus models using ISO 15099 (as the convection calculation method inside the airspaces) were developed in accordance with the test specimens and conditions to perform simulations. Moreover, application of ISO 15099 for performing calculations in vertical enclosed cavities (in accordance with experimental test specimens) was compared with ASHRAE data. Finally the results and differences were analyzed and the related discussions are presented.

3. Guarded hot box tests

In this study, two distinct tests were conducted by guarded hot box apparatus in the Energy Laboratory of Road, Housing and Urban Development Research Center (BHRC). The construction procedure of the BHRC guarded hot box apparatus, and the calibration of it's components were conducted according to ASTM C1363 [32], for conducting evaluations on wall specimens. Figs. 1 and 2 show the schematic of the BHRC guarded hot box. The overall dimension of the BHRC guarded hot box apparatus is $3.0\,\text{m} \times 3.0\,\text{m} \times 1.2\,\text{m}$, and its metering chamber is a $2.0\,\text{m} \times 2.0\,\text{m} \times 0.6\,\text{m}$ room. The test specimens are placed between the guarded and climatic chambers. The dimensions of the specimens are $3.0\,\text{m} \times 3.0\,\text{m}$. The guard hot box forms a 50 cm width surrounding area around the metering chamber. When the steady-state condition is reached, the temperatures of metering box and guard box are kept equal. Therefore, the faces between the guard and the metering zones can be considered as adiabatic.

Two wall configurations of reflective insulation systems were investigated in order to evaluate the thermal performance of reflective insulation systems and reflective airspaces. In the first experiment, a reflective configuration with one layer of reflective insulation and two adjacent airspaces was investigated, while in the second test a configuration with two layers of reflective insulation and three adjacent airspaces was explored. In both tests;

i) The specimens were installed on a cement block wall structure (with thickness of 150 mm and conductivity of 0.231 W/m K) which faced the metering chamber.
ii) The reflective insulations were installed on studs and runners made of 20 mm thick furring strips.
iii) According to former investigations [33,34], the optimum thickness of reflective airspaces is 19 mm and 15–18 mm, respectively. So, by considering the construction constraints all the furring strips have 19–20 mm thickness, which was the same as the thickness of airspaces in all the configurations.
iv) Bubble foil insulation which included reflective surfaces with the emissivity of 0.05 on both sides, and with overall thickness of 16 mm was used as the reflective insulation in both evaluations. Insulations were punched to the stud and runners in order to maintain the same insulation thickness in the whole cavity.
v) The last layer in specimen configurations, which faced the climatic chamber, was made of gypsum boards (with thickness of 12 mm and conductivity of 1.5 W/m K).
vi) All the construction procedures of the specimens were in accordance with ASTM C1363 guidelines.
vii) The whole measurement processes were conducted according to ASTM C1363. The first and last surface temperatures of the specimens were measured by nine thermocouples in the measuring area.

In the following paragraphs the properties of each experiment will be demonstrated in details.

3.1. First experiment specifications

In the first evaluation, a configuration with one layer of reflective insulation and two 20 mm adjacent enclosed airspaces was constructed and tested. The reflective system installed on the cement block wall by stud and runners, and the gypsum boards were installed as it was explained previously. Foil tapes, with the same emissivity as the reflective insulation (ε=0.05), were used for air tightening the specimen. Figs. 3 and 4 show the construction procedure and the section of the test specimen. The steady-state condition was reached in one week, and the measurements were performed during three days. Table 2 presents the measurement specifications of the first test.

3.2. Second experiment specifications

In the second experiment, a reflective insulation system with two layers of reflective insulation and three adjacent 20 mm airspaces was constructed. Fig. 5 shows the section of the tested configuration in this experiment.

The first test configuration included two airspaces with one reflective surface which faced cement block and gypsum board surfaces. However in the second experiment, airspace with two face to face reflective surfaces was tested in addition to aforementioned airspaces. The second experiment has two main differences with the former experiment:

i) In order to evaluate the thermal performance of each reflective airspace layer, the surface temperatures inside the specimen were measured by multiple thermocouples (surface

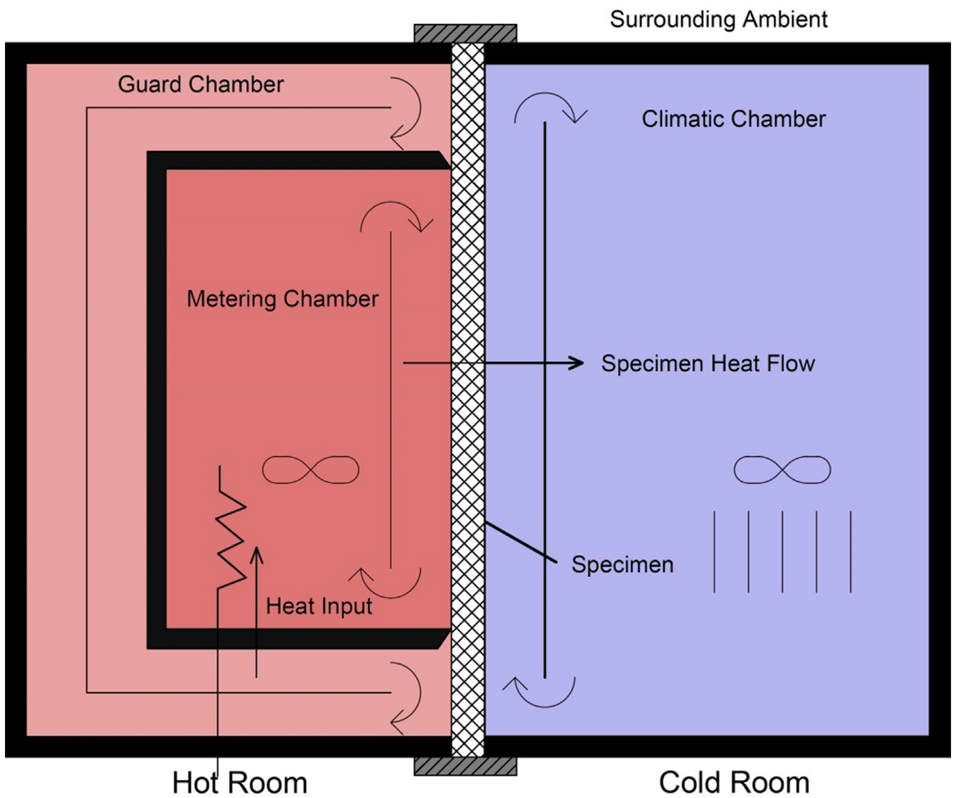

Fig. 1. Schematic structure of the BHRC guarded hot box apparatus.

Fig. 2. BHRC guarded hot box apparatus; guard and metering chamber (left), climatic chamber (right).

temperatures of the insulations, and interior surface temperatures of the gypsum boards, and cement block). The surface temperatures of the outside faces of the specimen were also measured, as performed in the first experiment (exterior surface temperatures of the gypsum boards, and cement block layer as shown in Figs. 6 and 7).

ii) All of the three air cavities were air tightened around the measuring area according to ASTM C 1363 (Fig. 7), in order to prevent the (feasible) influences of surrounding areas on convective currents inside the cavities.

The measurement specifications of the second experiment are presented in Table 3.

4. Measurement results

In steady-state conditions, the heat flux across a building envelope assembly [16] is defined by:

$$Q = A\,U(t_o - t_i) = A(t_o - t_i)/R_T \quad (1)$$

Fig. 3. Construction procedure of the first experiment.

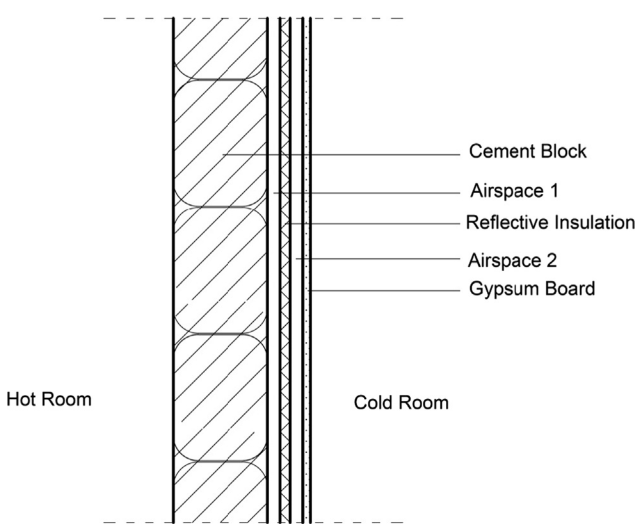

Fig. 4. Section of the first test specimen (reflective insulation material contained reflective surfaces on both sides).

Table 4 shows the calculations of the thermal properties of the whole assembly in the first experiment. Knowing the thermal resistance of cement block wall (0.64 m^2 K/W) and gypsum boards (0.08 m^2 K/W), the thermal resistance of reflective insulation system is 0.61 m^2 K/W (which includes the thermal resistances of reflective insulation and two adjacent airspaces).

As it was explained in former sections, all the surface temperatures of the building assembly were measured by T-type thermocouples in the second test. Due to the feasible presence of convective currents in air cavities [17,35,36], there were two thermocouples installed on each surface of the assembly (in the upper and lower levels of measuring area) to assess each surface temperature precisely. The placements of thermocouples inside the test specimen are shown in Figs. 8 and 9. Thermocouples were placed in the exact opposite in each row, in order to make it possible to measure the heat flow through each layer of assembly precisely. Finally, each surface temperature was calculated through averaging the measured values of the upper and lower thermocouples.

Table 5 indicates the calculation process of the thermal resistance value in reflective building assembly in the second test. Temperature differences across each layer of the assembly were evaluated by the obtained values with thermocouples.

4.1. Error analysis

The surface to surface temperatures across the assemblies (in the first and second tests) were utilized to estimate the errors in each experiment (Tables 2 and 3). Table 6 presents the error analysis of the guarded hot box tests. The errors were defined by:

$$\frac{\delta U}{U} = \frac{\delta \Delta T}{\Delta T} + \frac{\delta A}{A} + \frac{\delta Q}{Q} = \frac{\delta R}{R} \quad (2)$$

5. Comparative survey

5.1. Comparisons between guarded hot box test results and ASHRAE data

As in the first experiment the thermal conditions inside the airspaces were not measured, it was not possible to compare the first

Table 2
The measurement specifications of the first experiment.

Baffle air temperature (°C)	Hot room	28.9	Air velocity (m/s)	Hot room	0.4
	Cold room	3.1		Cold room	2.7
Baffle surface temperature (°C)	Hot room	28.5	Heater	Voltage (V)	17.18
	Cold room	3.1		Intensity (A)	2.72
	ΔT	25.4		Power (W)	46.73
	$T_{average}$	15.8	Fan	Voltage (V)	11.6
Wall surface temperature (°C)	Hot room	27.1		Intensity (A)	2.13
	Cold room	3.7		Power (W)	24.71
	ΔT	23.4	Total power (w)		71.44
	$T_{average}$	15.4	Total power – power off (W)		70.6376

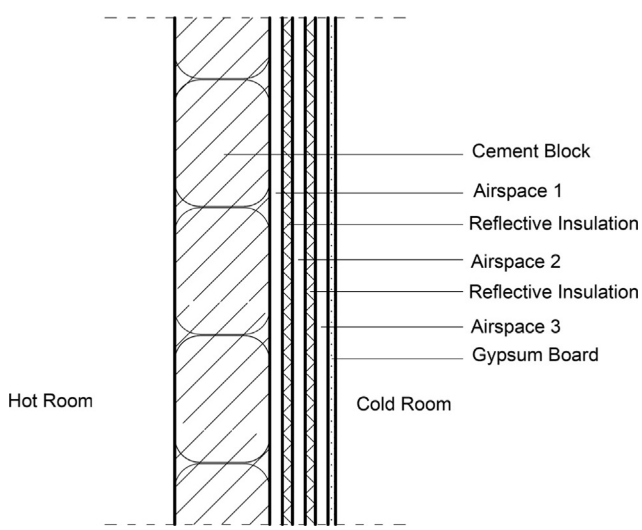

Fig. 5. Section of the second test specimen (reflective insulation material contained reflective surfaces on both sides).

guarded hot box results and ASHRAE data. Therefore, in order to achieve the research objective of verifying the former experimental test results, the measured values (in the second test) were compared by the ASHRAE data. ASHRAE presents the most extensive data about the enclosed reflective airspace properties. ASHRAE airspaces thermal resistance value is the sum of conductive/convective thermal resistance and thermal resistance value by radiation. ASHRAE values for reflective airspaces are determined from the equations [16] below:

$$R = 1/C \tag{3}$$

$$C = h_c + \varepsilon_{eff} h_r \tag{4}$$

$$\varepsilon_{eff} h_r = 0.227\varepsilon_{eff}[(t_m + 273)/100]^3 \tag{5}$$

Table 7 presents the thermal properties of 20 mm reflective airspaces in ASHRAE. However, comparisons between Tables 5 and 7 prove that; all the temperature differences across the reflective airspaces in the second experiment are lower than 3 K, and according to Table 7 presented values for thermal resistance value of reflective airspaces in ASHRAE do not provide data for temperature differences lower than 5.6 K across the cavities. Therefore, the scope of ASHRAE data for reflective airspaces was not applicable in this study.

5.2. Development of the simulation models

In order to compare results derived from ISO 15099 with guarded hot box results and ASHRAE data, an EnergyPlus model was developed according to the test conditions and thermal properties of the tested reflective insulation systems. EnergyPlus V7.2 was used for creating simulation model and performing the calculation. ISO 15099 is used in one of the EnergyPlus interior convection algorithms namely Trombe wall algorithm for modeling convection in unvented vertical cavities [37]. In 2003 Ellis [38] has validated the use of this algorithm for modeling unvented

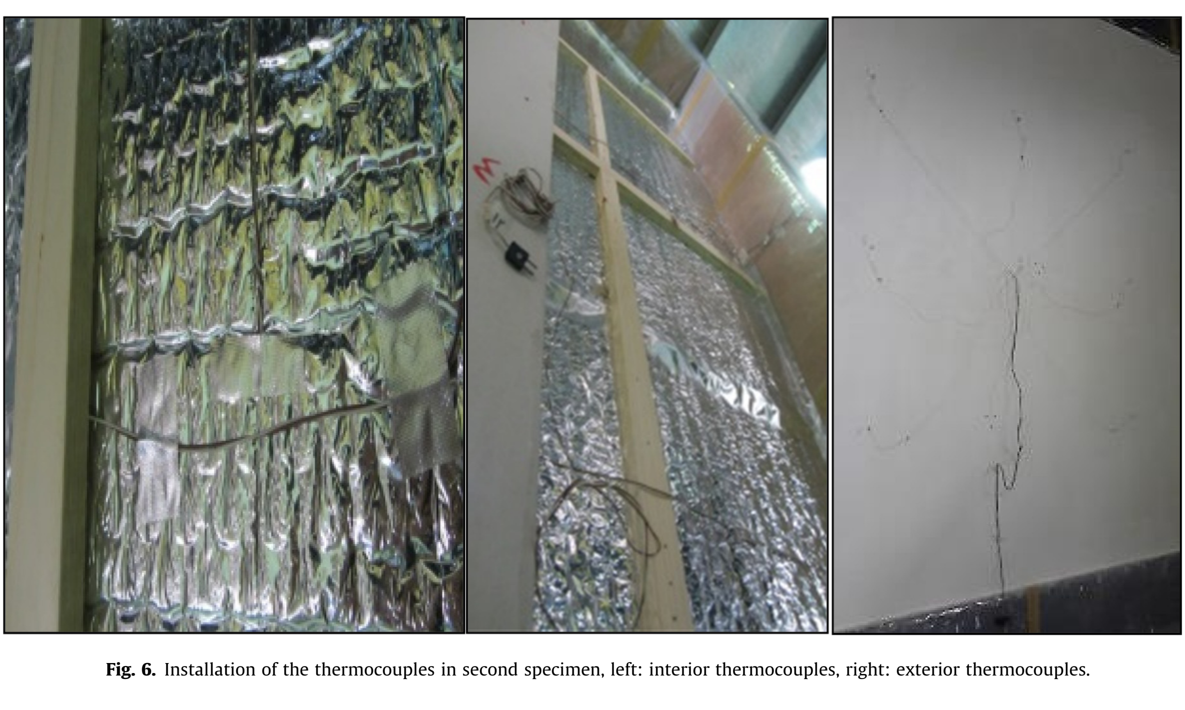

Fig. 6. Installation of the thermocouples in second specimen, left: interior thermocouples, right: exterior thermocouples.

Fig. 7. Interior air tightening procedure of the second specimen.

Table 3
Measurement specifications of the second experiment.

Baffle air temperature (°C)	Hot room	24.9	Air velocity (m/s)	Hot room	0.4
	Cold room	1.1		Cold room	3.0
Baffle surface temperature (°C)	Hot room	24.7	Heater	Voltage (V)	12.82
	Cold room	1.0		Intensity (A)	1.73
	ΔT	23.7		Power (W)	22.14
	$T_{average}$	12.9	Fan	Voltage (V)	11.80
Wall surface temperature (°C)	Hot room	23.53		Intensity (A)	2.21
	Cold room	1.3		Power (W)	26.08
	ΔT	22.3	Total power (w)		48.22
	$T_{average}$	12.5	Total power – power off (w)		47.35414

Table 4
Calculated test results of the first experiment.

Chamber	Hot room		Cold room	
Sensor Position	Baffle air	Wall surface	Wall surface	Baffle air
T_{av} (°C)	28.9	15.4		3.1
ΔT (°C)	1.8	23.4		0.6
A (m²)	4.00	4.00		4.00
R (m² K/W)	0.10	1.33		0.03
U (W/ m² K)	9.81	0.75		29.43
Q (W)	70.63	70.63		70.63

Trombe wall in EnergyPlus against the experimental data. However using EnergyPlus and applying this convection model for simulating the airspaces of reflective insulation systems was unprecedented. The model geometry and its constructions were created according to the test specimens in the guarded hot box experiments (Figs. 4 and 5). In this study, each airspace of reflective insulation systems was simulated by creating a thermal zone in EnergyPlus model. Inside zone heat balance in EnergyPlus, is calculated by the equation below:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \quad (6)$$

Total thermal resistance of reflective insulation system is the sum of conductive, radiative and convective heat resistance of the airspace(s) and the bounding surfaces of the air gap(s). Therefore, no equipment and people and short wave radiation source were assumed to be present in models, and q''_{SW}, q''_{LWS} and q''_{sol} were assumed equal to 0. Zone heat balance in simulation models was determined by:

$$q''_{LWX} + q''_{ki} + q''_{conv} = 0 \quad (7)$$

Zone heat balance method was used in EnergyPlus calculations in order to simulate reflective insulation systems. Heat transfer by conduction and radiation in thermal zones was considered restricted to the parallel surfaces with defined constructions, and all the other bounding surfaces in each zone were considered as adiabatic. Long wave radiant heat exchange between zone surfaces in EnergyPlus is calculated by equation [37] below, after determining the view factor (ScriptF coefficient) for zone surfaces:

$$q_{I,j} = A_i F_{i,j}\left(T_i^4 - T_j^4\right) \quad (8)$$

As the underlying presumption was that the radiation heat flux in each zone is limited only to the two large vertical parallel surfaces; the view factor for these two surfaces was set to 1, and for other surfaces was set to 0. In other words, these two surfaces only

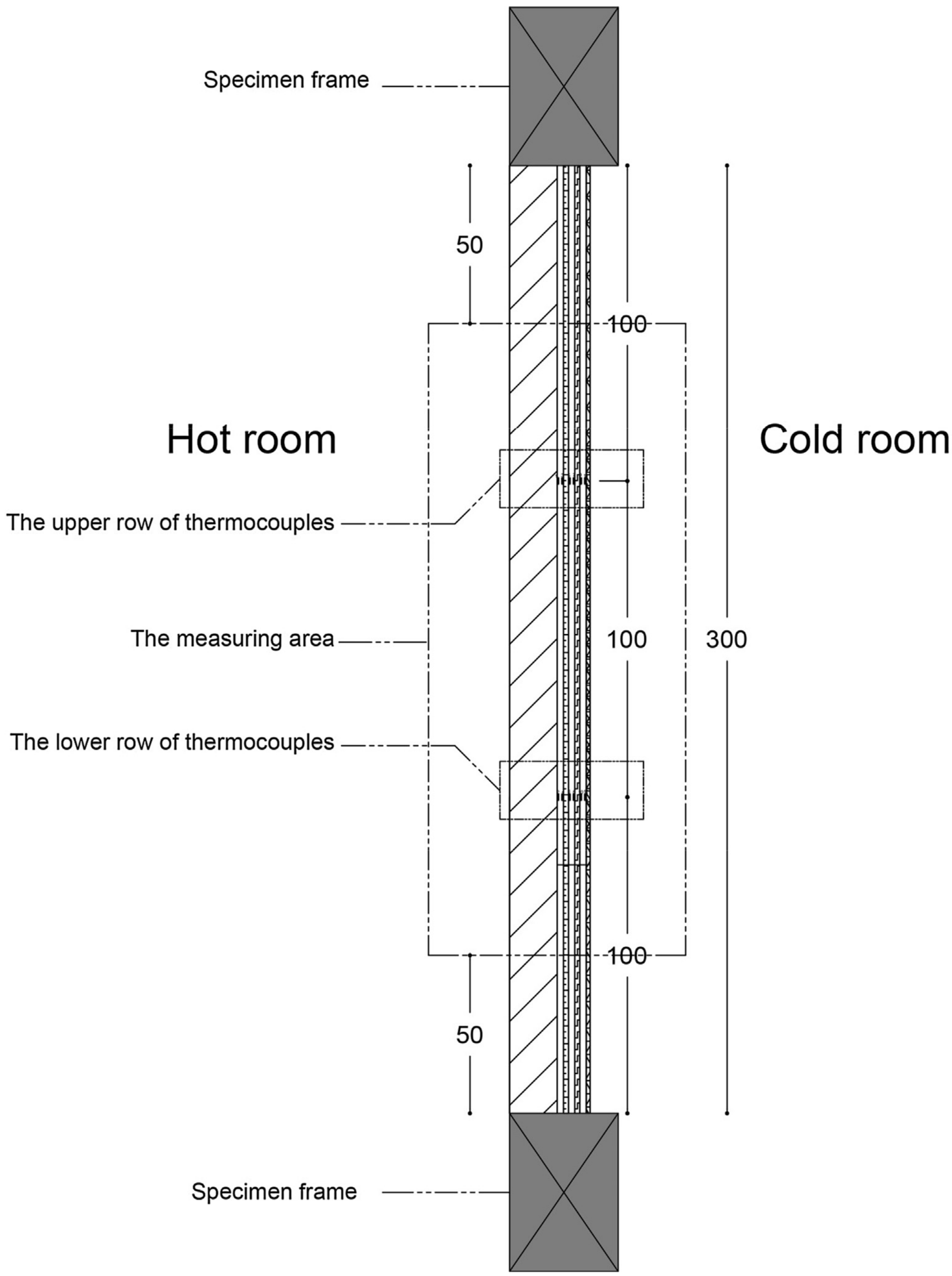

Fig. 8. Location of interior thermocouples in second test specimen.

see each other, and they do not have heat transfer to other surfaces of the zone. Convective heat flux to zone air is calculated by equation below:

$$q''_{conv} = h\prime_c(T_a - T_s) \tag{9}$$

In this study the Trombe wall algorithm was used to calculate the inside zone convective heat transfer coefficient. The Trombe wall algorithm is based on ISO 15099, and gives convection coefficients for air in a narrow vertical cavity that is sealed and not ventilated [37]. For a vertical cavity, it calculates the convection coefficients based on Nusselt and Rayleigh number, which mainly depends on temperature conditions across the assembly. The related equations are presented below:

$$R_{aH} = \frac{\rho^2 H^3 g c_p \left| T_{surf,i} - T_{air} \right|}{T_{m,f} \mu \lambda} \tag{10}$$

where:

$$T_{m.f} = T_{air} + 0.25\left(T_{surf,I} - T_{air}\right) \tag{11}$$

Standard Energyplus psychrometric functions are used for ρ and Cp. Thermal conductivity and Kinematic viscosity are calculated by:

$$\lambda = 2.873^{*}\,10^{-3} + 7.76^{*}\,10^{-8}\,T_{m.f} \tag{12}$$

$$\mu = 3.723^{*}\,10^{-6} + 4.94^{*}\,10^{-8}\,T_{mf.} \tag{13}$$

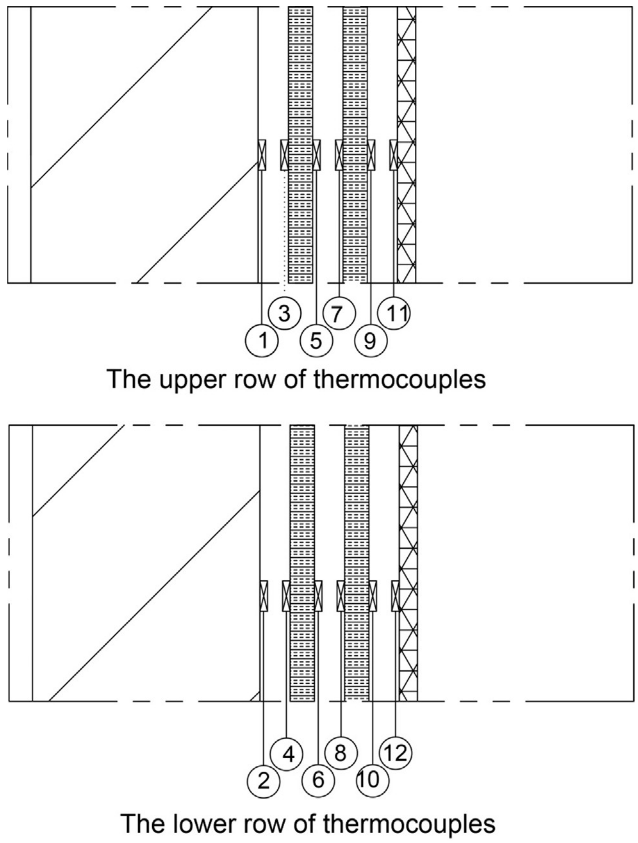

Fig. 9. Location of interior thermocouples in second test specimen.

There are four distinct cases presented for Nusselt number which are based on tilt angle in degrees and heating conditions. As this study focus is on wall application of reflective insulation systems, correlations related to the tilt angle range of $15° \le \Upsilon \le 90°$ are used. As the calculations are used for vertical airspaces and horizontal heat flow direction ($\Upsilon = 90°$). The correlations will be:

$$Ra_{cv} = 2.5^{*}\, 10^{5}\left(e^{0.72\gamma}/\sin\gamma\right)^{1/5} \tag{14}$$

$$Ra_{cv} = 973675.84^{*}10^{5}$$

If $Ra_H \le Ra_{CV}$, then:

$$Nu = 0.56(Ra_H \sin\gamma)^{1/4} \tag{15}$$

$$Nu = 0.56(Ra_H)^{1/4}$$

And for $RaCV \le RaH$:

$$Nu = 0.13\left(Ra_H^{1/3} - Ra_{CV}^{1/3}\right) \tag{16}$$

$$+0.56(Ra_{CV}\sin\gamma)^{1/4}$$

Table 6
Error analysis.

Test	δΔT (oC)	δA (m2)	δQ (W)	δU/U≈δR/R
First experiment	0.4	(∼)0.0	(∼)1.0	0.03
Second experiment	0.4	(∼)0.0	(∼)1.0	0.04

Table 7
Presented thermal properties of reflective airspaces with thickness of 20 mm for horizontal heat flow direction in ASHRAE.

ΔT	T_{mean}	R-value	
		$\varepsilon_{effective} = 0.05$	$\varepsilon_{effective} = 0.03$
5.60	32.20	0.57	0.62
16.70	10.00	0.49	0.51
5.60	10.00	0.61	0.65
11.10	−17.80	0.53	0.55
5.60	−17.80	0.63	0.66
11.10	−45.60	0.50	0.51
5.60	−45.60	0.63	0.65

Table 8
Environmental conditions applied in simulations for comparative survey with experimental tests.

Evaluation	Cold Room Temperature (°C)	Hot Room Temperature (°C)
First experiment	3.66	29.40
Second experiment	1.26	25.90

$$Nu = 0.13Ra_H^{1/3} - 284.74$$

Then:

$$h_c' = Nu(\lambda/H) \tag{17}$$

5.2.1. Environmental assumptions of the simulation models

Environmental conditions of the test specimens were created by defining thermostat and ideal loads air system in hot side of the simulation models, and by creating a weather data file by MeteoNorm V7 in order to generate the environmental conditions of the cold room of the guarded hot box apparatus (all the related values to solar radiation were assumed as 0 in the created weather data files). In order to simulate the enclosed leakage free airspaces; zone infiltration (design flow rate: flow per exterior surface area, and air change per hour) in all the simulated models were assumed as 0. In order to conduct comparative investigations between simulation results and guarded hot box test results, two sets of assumptions were applied in simulations (Table 8).

5.3. Comparative survey between results derived from ASHRAE and ISO 15099

To generalize the comparative studies, results derived from ISO 15099 were also compared by ASHRAE. Therefore, the EnergyPlus model which was created according to the guarded hot box test specimens, were used for this evaluation. The environmental

Table 5
Thermal resistance calculation of the different layers of second test specimen.

Thermal properties	Baffle air (hot room)	Cement block	Airspace1	Reflective insulation	Airspace2	Reflective insulation	Airspace3	Gypsum board	Baffle air (cold room)
ΔT (°C)	1.37	7.62	1.38	4.76	1.17	3.94	2.46	0.90	0.21
A (m^2)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
R (m^2 K/W)	0.12	0.64	0.12	0.40	0.10	0.33	0.21	0.08	0.02
U (W/m^2 K)	8.63	1.55	8.58	2.49	10.16	3.01	4.82	13.14	56.63
Q (W)	47.35	47.35	47.35	47.35	47.35	47.35	47.35	47.35	47.35

Table 9
Comparative survey between ISO 15099 and ASHRAE values for thermal properties of reflective airspaces (in the first experiment).

Variable	Air space 1[1]		Air space 2[2]	
	ASHRAE	Simulation	ASHRAE	Simulation
$\varepsilon_{effective}$	0.05	0.05	0.05	0.05
ΔT	5.6	5.6	5.6	5.7
T_{mean}	13.26	13.26	4.3	4.3
R	0.60	0.61	0.61	0.62
Difference (%)	2.1		1.5	

[1] Between cement block and reflective insulation.
[2] Between gypsum boards and reflective insulations.

Table 10
Comparative survey between ISO 15099 and ASHRAE values for thermal properties of reflective airspaces (in the second experiment).

Variable	Air space 1[1]		Air space 2[2]		Air space 3[3]	
	ASHRAE	Simulation	ASHRAE	Simulation	ASHRAE	Simulation
$\varepsilon_{effective}$	0.05	0.05	0.03	0.03	0.05	0.05
ΔT	5.6	5.6	5.6	6.1	5.6	5.8
T_{mean}	23. 0	23. 0	13.7	13.7	4.4	4.4
R	0.59	0.6	0.64	0.66	0.61	0.62
Difference (%)	2.8	2.1	0.9			

[1] Between cement block and reflective insulation.
[2] Between reflective insulations.
[3] Between gypsum boards and reflective insulations.

conditions were set in order to create the presented thermal conditions of air cavities in ASHRAE as close as possible. Tables 9 and 10 show that in both airspaces of the first simulated specimen, and in all three simulated airspaces of the second specimen, the differences between the results of the simulations and AHRAE values for reflective cavities are less than 3%. It proves the good agreement of results derived from ISO 15099 and ASHRAE data in evaluating reflective airspaces. Therefore, knowing the thermal resistance value of reflective insulations, the differences in calculated R-values of reflective insulation systems using ISO 15099 and ASHRAE data for performing calculations in the first and second experiments are 1.4%, and 1.6% respectively.

5.4. Comparative survey between results derived from guarded hot box tests and ISO 15099

In this step, in order to compare the results derived from simulation (using ISO 15099) with the guarded hot box results, the EnergyPlus model was tested under almost similar environmental conditions as the abovementioned conditions in the guarded hot box experiments (Tables 2 and 3). As Table 11 presents; the temperature difference across the simulation models was nearly equal to measured values across the guarded hot box test specimens. In both comparisons, the thermal resistance of reflective insulation in simulation model was assumed the same as the measured thermal resistance of reflective insulation in guarded hot box tests. In spite of the close temperature conditions of the cold and hot surfaces of the simulation models and guarded hot box specimens; difference between the measured and calculated heat fluxes across the assemblies lead to the incompatibility between the R-values derived from measurements and simulations (Eq. (1)). According to Table 11, there is almost 56–61% variation between the calculated R-values using ISO 15099 and measurement results in evaluation of reflective insulation systems. Therefore, the guarded hot box test results are not in agreement with the calculated thermal resistance values in simulation. The analysis of the discrepancies and related dissuasions are presented in following sections.

6. Discussion

Presented results in Section 5 proved that:

- The guarded hot box measurement results are not in the scope of the ASHRAE data (Section 5.1),
- Results derived from calculations using ISO 15099 are in good agreement with the ASHRAE data (Section 5.3). Simulation of the tested specimens in guarded hot box experiments showed that there is less than 3% difference for reflective airspaces, and less than 2% difference for reflective insulation systems, between the calculations using ISO 15099 and ASHRAE.
- There is significant difference between the guarded hot box measurement results and simulations (56.1% and 60.1% in the first and second experiments respectively).

Section 5 proved the necessity of investigating the differences between the simulation results and guarded hot box experiments. A common typical configuration of reflective insulation systems was tested in first experiment. Moreover, comparisons between

Table 11
Comparative evaluation between results derived from simulations and guarded hot box tests; thermal conditions and variations in thermal resistance values.

Evaluation		Cold surface temperature (Gypsum board)	Hot surface temperature (Cement block)	R-value (reflective insulation system)	R-value variation (%)
First experiment	Guarded hot box test	3.7	27.1	0.61	60.1
	Simulation	3.7	27.1	1.53	
Second experiment	Guarded hot box test	1.3	23.5	1.16	56.1
	Simulation	1.3	24.3	2.64	

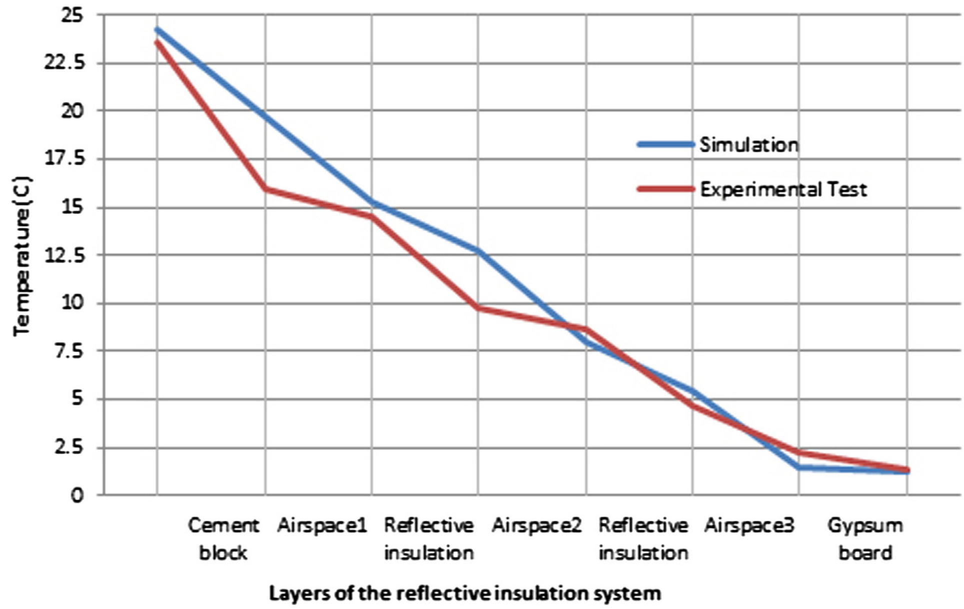

Fig. 10. Temperature drops across the reflective insulation system.

the first guarded hot box test and simulation proved the disagreement of results, and showed the necessity of examining the interior conditions of the test specimens to discover the reasons of difference. In addition it proved the importance of conducting the test by another configuration to reach to more comprehensive knowledge. Thus as demonstrated in Section 3.2, all temperatures inside the specimen were measured in the second guarded hot box experiment. Therefore the second guarded hot box test was used as the basis of the comparative survey in this section. Fig. 10 shows the temperature reductions across the reflective insulation system in simulation model and in the tested specimen, which are directly proportional to the thermal resistances of each layer. It proves higher temperature reductions in airspaces of simulated reflective system in comparison to the cavities in tested stack. In simulated reflective system the highest temperature variations occur in airspaces, however, reflective insulation materials have the highest contribution to the total temperature variation across the reflective system in the guarded hot box test. Contrary to the guarded hot box test results, in the simulated reflective insulation system the second airspace has the highest share of temperature reduction (thermal resistance) between the airspaces. All the thermal properties of the simulated reflective insulation are assumed to be the same as the tested insulation. Therefore, the main reason of differences in total thermal resistance of both models is derived from the differences in thermal resistance of reflective airspaces.

Table 12 indicates the thermal properties of airspaces in the second experimental test specimen in comparison with the simulation data. It shows that the greatest differences between the results are seen in the second airspace (between two low-e surfaces), first airspace (between the cement block and reflective insulation) and the third airspace (between gypsum boards and reflective insulation), respectively. In addition to disagreement between measured values and results derived from ISO 15099, and considering the good agreement between ISO 15099 and ASHRAE data in evaluation of reflective airspaces (Section 5.3), the differences also proves the discrepancy between the measured values and ASHRAE.

As the equations of the Sections 5.1 and 5.2 proved, the thermal resistance value of reflective airspaces (according to ASHRAE and simulation model) depends on heat resistance by convection and radiation. Moreover, surface temperatures and zone average temperatures highly influence the calculated values. Therefore, the main differences between the guarded hot box test results and the calculated values are derived from discrepancies in evaluation of surface and average temperatures in reflective airspaces. Feasible explanations are presented in the following sections.

6.1. Lack of accuracy in guarded hot box tests

- In spite of considering ASTM C 1363 guidelines in construction of the specimen and conductance of the test, the presence of some drawbacks in air tightening of the airspaces is a probable justification of the great differences in results. So, unwanted convection currents (outside the measuring area) or air leakage

Table 12
Analysis of the airspace thermal properties derived from the experimental test and ISO 15099.

Variable	Air space 1[1]		Air space 2[2]		Air space 3[3]	
	Test	Simulation	Test	Simulation	Test	Simulation
$\varepsilon_{effective}$	0.05	0.05	0.03	0.03	0.05	0.05
ΔT	1.4	4.4	1.2	4.8	2.5	4.5
T_{mean}	15.2	17.5	9.2	10.4	3.4	3.2
R	0.12	0.62	0.10	0.67	0.21	0.63
Difference (%)	80.7		85.1		67.7	

[1] Between cement block and reflective insulation.
[2] Between reflective insulations.
[3] Between gypsum boards and reflective insulations.

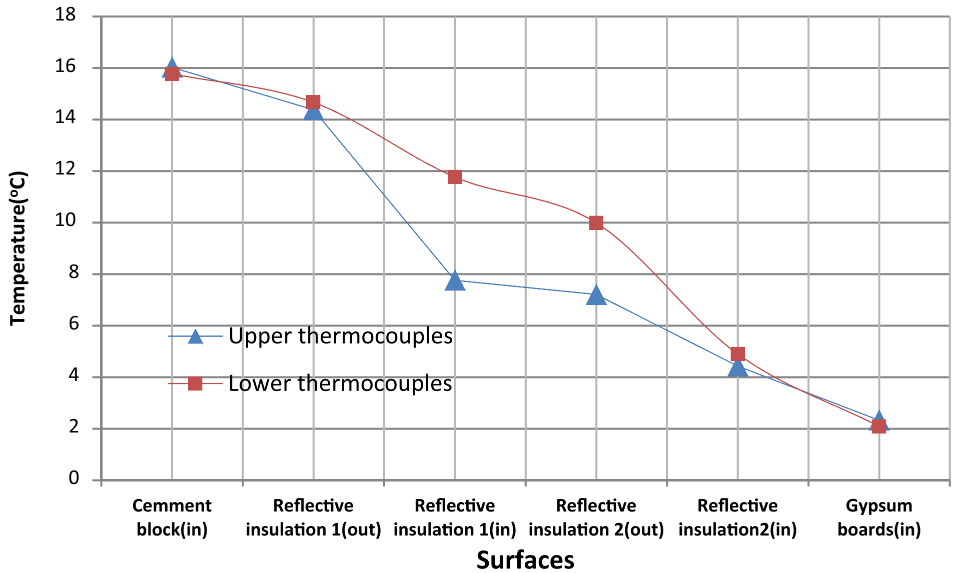

Fig. 11. Temperatures obtained from interior thermocouples.

from cavities, which greatly influence the convection currents of adjacent airspace(s) as well, can be the main cause of the incompatibility of results.

- High thermal resistance of the cement block wall to the reflective insulation system, led to relatively low contribution of the reflective insulation system in temperature reduction across the assembly, leading to a reduction in temperature differences across different layers of reflective insulation system and therefore to inevitable increase in the share of inaccuracies and errors in measurements.
- According to ASTM C1363, thermocouples which were used to measure the surface temperatures (inside the specimen), in best conditions have an accuracy of ± 0.2 K. In these conditions, the error issuing only from the thermocouples, for a temperature difference of 2 °C will be at least equal to 20%.

In spite of all mentioned problems, test results were repeated after calibration of thermocouples and other test equipment.

6.2. Differences between underlying assumptions in calculations and measurements

There are some underlying ideal (or perfect) presumptions in calculation models (such as ISO 15099) and ASHRAE, which can be the possible explanation of the differences with the results derived from the guarded hot box tests.

- Constant thickness along the cavity is another assumption in ASHRAE and ISO 15099 which usually cannot be approached in real applications, and can influence the thermal resistance of airspace.
- EnergyPlus (zone heat balance method) assumes the same surface temperature in all points of the surface in order to simplify the calculations. However, according to data obtained from the interior thermocouples there are variations in temperatures measured in upper and lower areas of different surfaces of the specimen. The measurements prove the average +10.1% differences between values obtained from lower and upper thermocouples. Therefore, the convection makes the difference in reality. Presence of temperature differences in different layers of a wall lead to significant impacts on thermal resistance of air gaps in real conditions.
- As Figs. 6 and 7 showed, bubble foil reflective insulations were used as reflective surfaces in guarded hot box specimens. Lack of uniformity and leveling in all points of the bubble foil reflective surfaces, can significantly affect the convection currents inside the cavities. However, there are not any considerations for the influences of the surrounding surfaces properties on airspace R-value in ASHRAE and ISO 15099. As Fig. 11 and Table 10 showed, the most discrepancies are seen in second airspace (between two reflective surfaces). It highlights the need for considering the surrounding surface properties (especially reflective ones) in airspace calculations.
- The mechanical supports and connections of different layers of the assembly are not modeled in the simulation. They can perform as feasible thermal bridges in real conditions, which are not considered in EnergyPlus calculations.
- In EnergyPlus model; radiation inside the cavity is restricted to the two major surfaces of the assembly, based on the presumption that there is no heat transfer by radiation to other bounding surfaces of the cavity. In practical cases where the emissivity (and thermal absorptance) of surfaces is high, the above assumption can easily be justified, but when the emissivity is lower than 0.05, it seems that the studs and runners with high emissivity can change this rule. For this purpose, complementary investigation must be performed by CFD calculations, in order to quantify the influence of studs and runners.
- The measurements proved the dependency of the thermal conductivity of reflective insulation material on the temperature conditions across it. As in the simulations the insulation R-values were assumed equal to the measurements it can be neglected in this study. However, the impacts of temperature conditions on the enclosed airspaces inside the bubble foil materials and the insulation R-value needs complementary studies.

In conclusion, all of these ideal assumptions can result in considerable errors in evaluation of reflective airspaces by experimental data, especially by considering the share of each one on the total thermal resistance of the reflective airspace.

7. Conclusion

Guarded hot box tests (according to ASTM C1363) and complementary measurements of layers' surface temperatures have been performed for approaching to a more detailed evaluation of disaggregated thermal resistance values obtained for different layers and air gaps in former studies. The results made possible a systematic comparison between experimental data, and values issued from credible standards and calculation methods. ASHRAE and ISO 15099 were used as reference for this evaluation. The results proved great difference between the measured thermal resistance and simulation results (56.1% and 60.1% difference for the first and second tests respectively). The investigations showed that the disagreement was mainly due to the differences in evaluation of the thermal resistance value in reflective airspaces. The results proved that the resistance values for reflective airspaces derived from ISO 15099 (which is also in good agreement with ASHRAE data) are much higher than the measured ones (+67.7% to +85.1%). Moreover, the guarded hot box measurements showed the average temperature variation of 10.1% in the interior surfaces of the configuration. Lack of uniformity and leveling in the entire surface of the bubble foil reflective materials can highly influence the convective currents inside the cavities. In addition the variation measured in thermal conductivity of bubble foil reflective insulation materials can be due to the influences of enclosed air gaps inside the reflective materials, which needs complementary studies. However, the comparative analysis highlighted the point that the expected values from the ISO 15099 (and ASHRAE) are obtained for ideal conditions with simplifying presumptions, such as one-directional heat transfer, by negligence of the thermal bridges resulting from mechanical supports inside the cavities, and assumption of isothermal boundary surfaces facing the air gaps. The influence of these unavoidable thermal bridges in common applications of reflective insulation systems (mainly due to the construction constraints and economic considerations) is amplified by imperfect airtightness of inner air layers, which transforms unventilated air gaps to ventilated ones. This topic also can be the scope of future research investigations.

Conflict of interest

None.

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