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Practical Correlations for Thermal Resistance of Horizontal Enclosed Airspaces with Upward Heat Flow for Building Applications

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Abstract

The thermal resistance (R-value) of an enclosed airspace depends on the emissivity of all surfaces that bound the airspace, the size and orientation of the airspace, the direction of heat transfer through the airspace, and the respective temperatures of all surfaces that define the airspace. A table is provided in the 2009 ASHRAE Handbook of Fundamentals (Chapter 26) that contains the R-values of enclosed airspaces. The ASHRAE table is extensively used by modellers, architects and building designers in the design for thermal resistance of building enclosures. This table provides R-values for enclosed airspaces for different values of airspace thickness, effective emittance, mean airspace temperature, and temperature differences across the airspace. The effect of the airspace aspect ratio (length/thickness) on the R-value is not accounted for in the ASHRAE table. However, in previous studies, it was shown that the aspect ratio of the airspace can affect its R-value.

In this paper, previous studies undertaken by the author that focused on determining the R-value for vertical enclosed airspaces and horizontal enclosed airspaces with downward heat flow are extended to investigate the effect of the aspect ratio on the R-value of horizontal enclosed airspaces under an upward heat flow condition for different airspace thicknesses and having a wide range of values for effective emittance, mean temperature, and temperature differences across the horizontal airspaces. The R-values predicted from numerical simulation are compared with those provided in the ASHRAE table. Considerations were also given to investigate the potential increase in the R-values of enclosed airspaces when a thin sheet is placed horizontally in the middle of the airspace and whose surfaces have different values of emissivity. Thereafter, practical correlations are developed for determining the R-values of horizontal enclosed airspaces for future use by modellers, architects and building designers. The simplicity of these correlations for horizontal airspaces with upward heat flow along with those that were previously developed for vertical airspaces and horizontal airspaces with downward heat flow suggests that these correlations could be included in the ASHRAE Handbook of Fundamentals.

Keywords: Reflective insulation, low emissivity material, thermal modelling, R-value correlation, airflow in enclosed airspace, and heat transfer by convection, conduction and radiation.

INTRODUCTION

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Buildings are large consumers of energy in all countries. In regions with harsh climatic conditions, a substantial share of energy goes to heat and cool the buildings [1]. Energy consumption of the building sector is high and although the situation differs from country to country, buildings are responsible for about 30-40% of the total energy demand [2]. In Europe, however, buildings are responsible for 40-50% of energy use and the largest share of energy in buildings is heating [3]. The design of building envelope roofing and wall systems with the intent of achieving energy savings can necessarily help reduce building operating loads and thus the demand for energy over time [4, 5]. This evidently can be achieved by increasing the thermal resistance (R-value) of the building envelope.

Currently, there are a number of thermal insulations that are being used in conjunction with Reflective Insulation (RI) assemblies in the building envelope. In accordance with installation guidelines of the Reflective Insulation Manufacturers Association International (RIMA-I) [6], RI products have at least one reflective surface facing an airspace. These products can be installed in wall cavities, between ceiling and floor joists, and in metallic buildings that cannot readily accommodate loose-fill or batt-type insulations. Also, RI products can be used as part of a roofing system either below the decking between rafters, within small air gaps between decking and roofing, and in air gaps created, for example, by paneling interior masonry walls [7]. In a recent study by D'Orazio et al. [8], field tests under hot climatic conditions were conducted to investigate the thermal performance of an insulated roof with RI. The objective of that study was to understand whether RI material could be effective in hot and temperate climate. The results of that study showed that the benefits of RI are quite limited when using the insulation level imposed by actual laws, which consider insulation as the main strategy for energy saving in temperate and hot climates [8].

Generally, enclosed airspaces contribute to the overall thermal resistance of a system whether or not a product having a reflective surface is installed in the system. Note that the term "enclosed" is critical since the major distinction between RIs and radiant barriers is the airspace condition, where the radiant barrier system is defined as a building construction that consists of a low emittance surface bounded by an "open" airspace [1, 9, 10, 11]. Recently, Miranville et al. [12] conducted experimental study on a roof-mounted Multi-Reflective Radiant Barrier (MRRB), installed on a dedicated test cell. Several experimental sequences were conducted to determine the thermal resistance of the roof according to several parameters and following a specific method. The mean method, well known in international standards (ISO 9869-1994) for the determination of the thermal resistance using dynamic data, was used in that study.

This paper focuses on determining the R-values of enclosed airspaces under different operation conditions. The parameters that affect the R-value of an enclosed airspace are: the physical properties of the air filling the space, the temperature and emissivity of all surfaces of the airspace, temperature differences across the airspace, the dimensions of the airspace, the direction of heat flow through the airspace and the orientation of the airspace. The R-value accounts for the contribution of heat transfer in the enclosed airspace due to heat transfer by conduction, convection and radiation.

For given operating conditions, the presence of a reflective surface augments the thermal resistance of enclosed airspaces [6, 7, 9 – 13 – 21]. The R-values of enclosed airspaces were calculated by many investigators (e.g. see [22 – 25]) for various orientations of airspaces and reflective boundaries by using heat transfer coefficient data that was published by Robinson et al. [23, 24, 25]. The heat transfer coefficient data were obtained from measurements of panels

of different thicknesses (0.625 in to 3.375 in (15.9 mm to 85.7 mm)) using the test method described in the ASTM C236-53 [26]. In those studies, the steady-state heat transmission rates were corrected for heat transfer occurring along parallel paths between hot and cold boundaries. Thereafter, the convective heat transfer coefficients were obtained from the data by subtracting a calculated radiative heat transfer rate from the total corrected heat transfer rate; and the radiative heat transfer was calculated using an emissivity of 0.028 for the aluminum surfaces.

Yarbrough [7] developed a one-dimensional, steady-state model, called “REFLECT” to provide R-values of reflective assemblies. The model was further used to help establish the sensitivity of R-values to the values of surface emissivity and as well, the location of foil surfaces inside an enclosed airspace. That model was used to calculate the R-values using the heat transfer coefficients derived by Robinson [23, 24, 25] combined with a term accounting for repeated reflection of energy between infinite parallel planes based on the Stefan-Boltzmann law. The R-values obtained using the REFLECT model are thus independent of the aspect ratio (length/thickness) of the enclosed airspace [7].

The 2009 ASHRAE Handbook of Fundamentals (Chapter 26) [22] provides a table that contains the R-values for an enclosed airspace and these were determined on the basis of the heat transfer data reported by Robinson et al. [23, 24, 25]. These values were obtained by combining the convective and radiative components of heat transfer from which the total R-value for an enclosed airspace was provided for airspaces of different thickness ($\delta = 13, 20, 40$, and 90 mm), mean temperature ($T_{avg} = 32.2, 10.0, -17.8$ and -45.6°C), temperature difference across the airspace ($\Delta T = 5.6, 11.1$ and 16.7°C), effective emittance ($\epsilon_{eff} = 0.03, 0.05, 0.2, 0.5$ and 0.82), and direction of heat flow through the airspace. Note that the effective emittance (ϵ_{eff}) of an enclosed airspace is given as [22]:

$$1/\epsilon_{eff} = 1/\epsilon_1 + 1/\epsilon_2 - 1, \quad (1)$$

where ϵ_1 and ϵ_2 are the emissivity of the hot and cold surfaces.

The information provided in the ASHRAE table [22] is being extensively used by modellers, architects and building designers to determine the R-values of building enclosures. The R-value of an enclosed airspace at other values of the parameters δ , ϵ_{eff} , T_{avg} , and ΔT that are not listed in this table, is obtained by interpolation. It is worth mentioning that the effect of the aspect ratio of the enclosed airspace on the R-value is likewise not included in this ASHRAE table [22].

In this study, a numerical simulation model was used to predict the effective R-values of enclosed horizontal airspaces subjected to an upward heat flow condition for the same parameters listed in ASHRAE table [22]. The numerical model had been previously benchmarked in a number of building applications (e.g. [14, 16, 19, 28]). For the applications that are similar to this study, this model was benchmarked against thermal performance data for a wall assembly featuring a reflective insulation product. The data was obtained using a Guarded Hot Box (GHB) (in accordance with ASTM C-1363 test method [27]) for a full-scale (8 ft x 8 ft) above-grade wall system. This wall featured 2 x 6 wood framing, stud cavities filled with friction-fit glass fiber batt insulation, and a layer of foil-lined fiberboard installed to the interior side of the framing, with the foil facing a furred-airspace. Results showed that the R-value predicted by the model for this wall system was in good agreement with the measured R-value (within 1.2%) [19, 28].

A number of tests were conducted at the Cold Climate Housing Research Center (CCHRC) [13] and the National Research Council of Canada (NRC) [14, 16] to examine the thermal performance of different types of reflective insulations. The tests were conducted using a heat flow meter in accordance with ASTM C-518 test method [29]. In these tests, sample stacks including different types of reflective insulations were placed horizontally between the upper cold plate and lower hot plate of the heat flow meter (i.e. upward heat flow condition, similar to the scenario examined in this paper). As provided in references [14, 16], the heat fluxes predicted by the model were in good agreement with the measured heat fluxes (within $\pm 1.0\%$). Thereafter, the model was used to investigate the contribution of reflective insulations to the R-value for specimens having different inclination angles, different directions of heat flow through the specimens, and a wide range of foil emissivity [14].

In a previous study [14], the predictions of the R-values using the model were compared with the R-values given in the ASHRAE table [22] for an enclosed airspace of different orientation of 20 mm thick at only $T_{avg} = 32.2^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$. To investigate the effect of the aspect ratio on the R-value, three lengths of airspace were considered in that study: 4 in (101.6 mm), 8 in (203.2 mm) and 16 in (406.4 mm). That study was conducted for different values of effective emittance. The results showed that the aspect ratio affects the R-value of the horizontal enclosed airspace. Also, the effects of the inclination angle and the direction of heat flow through an enclosed airspace (20 mm thick, 8 in (203.2 mm) long) were investigated and thereafter the predicted R-values were compared to those listed in the ASHRAE table [22]. The full details of these comparisons are provided in [14].

In recent studies by the author, the model was used to conduct numerical simulations to predict the R-value of vertical enclosed airspaces [30], and horizontal enclosed airspaces with downward heat flow condition [31]. The predicted R-values were compared with R-values provided in the ASHRAE table [22] for enclosed airspaces of different thicknesses ($\delta = 13, 20, 40, \text{ and } 90 \text{ mm}$) and different conditions ($T_{avg} = 32.2, 10.0, -17.8 \text{ and } -45.6^\circ\text{C}$, $\Delta T = 5.6, 11.1 \text{ and } 16.7^\circ\text{C}$ and $\varepsilon_{eff} = 0.03, 0.05, 0.2, 0.5 \text{ and } 0.82$). The dependence of the R-value on the aspect ratio of the enclosed airspace was also investigated for these conditions. The results showed that depending on the thickness of the enclosed airspace and the operating conditions, the aspect ratio can have a significant effect on the R-value. Furthermore, practical correlations were developed to determine the R-values of vertical enclosed airspaces [30], and horizontal enclosed airspaces with downward heat flow [31] of different thicknesses (δ), and for a wide range of values for various parameters (A_R , ΔT , T_{avg} , and ε_{eff}). The results showed that the calculated R-values using these correlations were in good agreement with those obtained using the model (within $\pm 5\%$ [30] and $\pm 3\%$ [31]). A full description of the present model is available in previous publications (see references [1-5, 14-21, 32-35]).

In this paper, the previous studies in which numerical simulations were conducted to predict the R-value of vertical enclosed airspaces [30] and horizontal enclosed airspaces with downward heat flow condition [31] of different thicknesses are extended in order to investigate the thermal performance of horizontal enclosed airspaces that are subjected to an upward heat flow condition with different T_{avg} and ΔT . The objectives of this study are to conduct numerical simulations in order to:

- Investigate the potential increase in the R-value of an enclosed airspace when a thin sheet having an emissivity ranging between 0.0 to 0.9 is placed horizontally in the middle of the airspace.

- Investigate the effect of the aspect ratio (A_R) on the R-value of horizontal enclosed airspaces of different thicknesses ($\delta = 13, 20, 40$ and 90 mm) for a wide range of effective emittance values ($\epsilon_{\text{eff}} = 0 - 0.82$).
- Compare the predicted R-values with those given in the ASHRAE table [22] for airspaces having different values for δ , T_{avg} , ΔT , and ϵ_{eff} .
- Develop practical correlations for the R-values of enclosed airspaces covering a wide range of values for A_R , T_{avg} , ΔT , and ϵ_{eff} for subsequent use in currently available energy simulation models (e.g. ESP-r, Energy Plus, DOE).

RESULTS AND DISCUSSIONS

This section presents the results of the numerical simulations that were conducted in order to predict the effective R-values of horizontal enclosed airspaces with an upward heat flow condition for the same parameters listed in ASHRAE table [22]: (a) thickness ($\delta = 13, 20, 40$ and 90 mm), (b) mean temperature ($T_{\text{avg}} = 32.2, 10.0, -17.8$ and -45.6°C), (c) temperature difference across the airspace ($\Delta T = 5.6, 11.1$ and 16.7°C), and (d) effective emittance ($\epsilon_{\text{eff}} = 0 - 0.82$). For a given value of δ , the numerical simulations were conducted at different lengths of airspace (H) in order to quantify the effect of the airspace aspect ratio ($A_R = H/\delta$) on the R-values of the airspace. The purpose of considering different values for H was to permit the development of practical correlations for determining R-values that cover most expected building applications having horizontal enclosed airspaces. Examples of these applications include planar horizontal skylights, and Furred-Airspace Assemblies (FAA) attached to thermal insulation (bonded by Low Emissivity Material, LEM) in flat roofing systems having furring of different center-to-center spacing.

Figure 1a shows a schematic of a horizontal enclosed airspace in which only one horizontal surface of the airspace has a low value of emissivity (ϵ_1), and all other surfaces have a high value of emissivity (ϵ_2). Most construction materials have an emissivity of 0.9 [22]. In this study, the numerical simulations were conducted for different values of ϵ_1 (ranging from $0 - 0.9$) and ϵ_2 was taken equal to 0.9 . According to Eq. (1), a wide range of values of the effective emittance, ϵ_{eff} (ranging from $0 - 0.82$) were considered. The value of ϵ_{eff} of 0.82 represents the case when all surfaces of the enclosed airspace have an emissivity of 0.9 (i.e. no LEM installed on the surfaces of the enclosed airspace).

For an enclosed airspace with $H = 12$ in (304.8 mm), numerical simulations were also conducted in order to investigate the potential increase in R-values of the enclosed airspace when a thin sheet (0.1 mm thick) whose surfaces have a low emissivity (ϵ_1), is placed horizontally in the middle of the airspace (see Figure 1b). The thin sheet divides the enclosed airspace into two cavities of equal thickness. It was assumed that no cross airflow occurs between the two cavities. The simulations were conducted for a wide range of values for δ , ϵ_1 , ϵ_2 , T_{avg} , and ΔT . In this paper, the simulation case for which there is no thin sheet material in the airspace is referred to as “1-Cavity” (Figure 1a), whereas “2-Cavities” refers to the case with a thin sheet in middle of the airspace (Figure 1b). The results obtained are discussed next.

Comparisons between Simulation Cases “1-Cavity” and “2-Cavities”

Figure 2 and Figure 5 show the temperature contours derived from the simulation of an enclosed airspace ($H = 12$ in (304.8 mm)) for values of δ of 90 mm and 40 mm, respectively; the simulation cases relate to the “1-Cavity” and “2-Cavities” when $T_{\text{avg}} = 10^\circ\text{C}$, $\Delta T = 16.7^\circ\text{C}$ ($T_H =$

18.35°C and $T_C = 1.65$ °C), $\varepsilon_1 = 0.05$, and $\varepsilon_2 = 0.9$. The corresponding vertical and horizontal air velocities are shown, respectively, in Figure 3 and Figure 4 for $\delta = 90$ mm, and in Figure 6 and Figure 7 for $\delta = 40$ mm.

In both cases (i.e. “1-Cavity” and “2-Cavities”) it is evident that owing to the temperature differential across the enclosed airspace, a buoyancy-driven flow has developed within the airspace. As well, for the two simulation cases it is observed that multi-cellular airflow having a number of convection loops was developed within the enclosed airspaces. For $\delta = 90$ mm, two convection loops were developed for the case of “1-Cavity” (Figure 2a – Figure 4a), whereas for the “2-Cavities” case, four convection loops were developed in each cavity (Figure 2b – Figure 4b). For both simulation cases, a smaller airspace thickness resulted in a greater number of convection loops. For the case of “1-Cavity” (Figure 5a – Figure 7a), it can be seen that 8 convection loops were developed in an enclosed airspace having $\delta = 40$ mm as compared to only 2 convection loops in an enclosed airspace of $\delta = 90$ mm (Figure 2a – Figure 4a). For the case of “2-Cavities”, however, 14 convection loops were developed in each cavity in the enclosed airspace of $\delta = 40$ mm (Figure 5b – Figure 7b) as compared to only 4 convection loops in the enclosed airspace of $\delta = 90$ mm (Figure 2b – Figure 4b).

The values of the maximum vertical velocities (u_y) and maximum horizontal velocities (u_x) taken from Figure 3 and Figure 4 for an airspace of $\delta = 90$ mm and from Figure 6 and Figure 7 for an airspace of $\delta = 40$ mm are summarized in Table 1 for the “1-Cavity” and “2-Cavities” simulation cases. These values indicate that the air velocity in the “1-Cavity” case is greater than that in the “2-Cavities” case. For example, for $\delta = 90$ mm, the maximum vertical velocity and maximum horizontal velocity in the case of “1-Cavity” are 1.7 and 2.1 times that for the case of “2-Cavities”. For $\delta = 40$ mm, however, these values in the case of “1-Cavity” are 2.7 and 2.6 times that for the case of “2-Cavities”. For the “1-Cavity” and “2-Cavities” cases, there are a number of parameters that have interactive and coupled effects on R-values of enclosed airspaces, namely:

- Heat transfer by conduction. Due to heat transfer by conduction in the absence of heat transfer by convection and radiation, the thermal resistance for the “1-Cavity” and “2-Cavities” cases would be approximately the same.
- Strength of convection currents. Stronger convection currents (i.e. airflow with higher velocity) in the enclosed airspace occur in the case of “1-Cavity” as compared to the “2-Cavities” case (see Figure 3, Figure 4, Figure 6 and Figure 7, and Table 1). For the same value of δ in the absence of heat transfer by radiation and conduction, and for the same number of convection loops per unit length of the airspace, stronger convection currents would result in higher thermal conductance (i.e. lower thermal resistance) of the enclosed airspace. Consequently, a greater reduction in the R-value of an enclosed airspace would occur in the case of “1-Cavity” as compared to the “2-Cavities” case if they both had the same number of convection loops per unit length.
- Number of convection loops. A greater number of convection loops per unit length of the enclosed airspace would enhance its thermal conductance, resulting in lower R-value. In previous studies [14 and 17], it was shown that a greater number of convection loops resulted in lower R-value. Also, as will be shown later in this study, for the same δ , ε_{eff} , T_{avg} , and ΔT , a greater number of convection loops per unit length of the airspace results in lower R-value. As such, in the absence of heat transfer by conduction and radiation, and for the same value of the air velocity in the airspace, a greater reduction in the R-value would occur in the case of “2-Cavity” (4 and 14 convection loops in each cavity for

$\delta = 90$ and 40 mm, respectively) as compared to the case of “1-Cavity” (2 and 8 convection loops for $\delta = 90$ and 40 mm, respectively).

- Heat transfer by radiation. For a given T_{avg} , and ΔT , and given the installation of a thin horizontal sheet whose surfaces have a low value of emissivity (ϵ_1) in the middle of the enclosed airspace, the temperature differential across the upper and lower cavities is reduced ($\sim 0.5 \Delta T$, see Figure 2 and Figure 5). As such, in the absence of heat transfer by convection and conduction, the rate of heat transfer by radiation through the enclosed airspace in the case of “2-Cavities” would be lower than in the case of “1-Cavity”, resulting in higher resistance for the former as compared to the latter.

For the same values of H , δ , ϵ_{eff} , T_{avg} , and ΔT , the interactive and coupled effects of the different parameters described above resulted in higher R-values for the enclosed airspace in the case of “2-Cavities” as compared to the “1-Cavity” case (see Figure 8 through Figure 11). Thus, we can conclude that for the “2-Cavities” case, the positive impact of reduced temperature differential across the cavities and weaker convection currents outweighs the negative impact of the increased number of convections loops.

For an enclosed airspace of thickness $\delta = 13, 20, 40$ and 90 mm ($H = 12$ in (304.8 mm)) at different values of ϵ_{eff} , T_{avg} and ΔT , comparisons between the R-values for the “1-Cavity” and “2-Cavities” cases are shown in Figure 8 through Figure 11. As discussed above, these figures show that the R-values for the “2-Cavities” simulation case are higher than that of the “1-Cavity” case. Table 2 shows the increase in the R-value due to the incorporation of a thin sheet horizontally in the middle of the enclosed airspace (see Figure 1b) and having an emissivity = ϵ_1 on both sides of the thin sheet at $\epsilon_{eff} = 0.03$ and 0.82 . As shown in this table, depending on the values of T_{avg} and ΔT , the percentage increase in the R-value for $\epsilon_{eff} = 0.03$ changes: (a) from 8.3% to 153.8% for $\delta = 13$ mm, (b) from 94.5% to 204.9% for $\delta = 20$ mm, (c) from 95.5% to 143.3% for $\delta = 40$ mm, and (d) from 83.3% to 95.9% for $\delta = 90$ mm (Table 2). Similarly, for $\epsilon_{eff} = 0.82$, the percentage increase in the R-value changes: (a) from 53.3% to 130.9% for $\delta = 13$ mm, (b) from 94.6% to 144.8% for $\delta = 20$ mm, (c) from 97.1% to 114.8% for $\delta = 40$ mm, and (d) from 84.0% to 89.5% for $\delta = 90$ mm (Table 2).

In summary, the R-value could be tripled if a thin horizontal sheet is installed in the middle of the horizontal enclosed airspace when subjected to an upward heat flow condition. In previous studies, it was shown that the R-value could be doubled due to installing a thin sheet vertically in the middle of the vertical enclosed airspace [30] and in the middle of horizontal enclosed airspace with downward heat flow [31]. The results presented in this section could be important for future applications when a thin reflecting foil is placed in the middle of the airspace of planar horizontal skylights, and Furred-Airspace Assemblies (FAA) attached to thermal insulation in flat roofing systems so as to enhance the energy performance of these systems.

Comparison between the Predicted and ASHRAE R-values

For single cavity in horizontal airspace of length of 12 in (304.8 mm), Table 3 shows comparisons between the predicted R-values and the ASHRAE R-values [22] for different values of thickness ($\delta = 13, 20, 40$, and 90 mm), mean temperature ($T_{avg} = 32.2, 10.0, -17.8$ and -45.6°C), temperature difference across the airspace ($\Delta T = 5.6, 11.1$ and 16.7°C), effective emittance ($\epsilon_{eff} = 0.03, 0.05, 0.2, 0.5$ and 0.82). The positive values in this table represent the case when the R-values given in ASHRAE table were greater than the predicted R-values. Whereas the negative values represent the case when the ASHRAE R-values were lower than

the predicted R-values. For $\delta = 13$ mm, Table 3 shows that the maximum deviations between the ASHRAE and predicted R-values were +21.9 % and -20.3%. For $\delta = 20$ mm, 40 mm and 90 mm, the maximum deviations between the ASHRAE and predicted R-values were +19.0%, +18.9% and -16.8%, respectively. The same data is plotted for various airspace thickness in Figure 12a-g ($\delta = 13$ mm), Figure 13a-g ($\delta = 20$ mm), Figure 14a-g ($\delta = 40$ mm), and Figure 15a-g ($\delta = 90$ mm). The following observations were made from the results shown in Table 3 and these figures:

- For all values of δ , T_{avg} and ΔT , the predicted R-values were mainly in good agreement with the R-values of the ASHRAE table for a high value of ϵ_{eff} of 0.82.
- For $\delta = 13$ mm, $T_{avg} = 32.2^\circ\text{C}$ & $\Delta T = 5.6^\circ\text{C}$ and $T_{avg} = -17.8^\circ\text{C}$ & $\Delta T = 5.6^\circ\text{C}$ the predicted and ASHRAE R-values were mainly in good agreement for all values of ϵ_{eff} . (Figure 12a,e). For low values of ϵ_{eff} (≤ 0.5), the ASHRAE R-values were higher than the predicted R-values for the pairs of $T_{avg} = 10.0^\circ\text{C}$ & $\Delta T = 16.7^\circ\text{C}$, $T_{avg} = -17.8^\circ\text{C}$ & $\Delta T = 11.1^\circ\text{C}$, $T_{avg} = -45.6^\circ\text{C}$ & $\Delta T = 11.1^\circ\text{C}$, and $T_{avg} = -45.6^\circ\text{C}$ & $\Delta T = 5.6^\circ\text{C}$ (Figure 12b,d,f,g), however, ASHRAE R-values were lower than the predicted R-value for the pair of $T_{avg} = 10^\circ\text{C}$ & $\Delta T = 5.6^\circ\text{C}$ (Figure 12c).
- For $\delta = 20$ mm, the predicted and ASHRAE R-values were mainly in good agreement for all values of ϵ_{eff} at $T_{avg} = 32.2^\circ\text{C}$ & $\Delta T = 5.6^\circ\text{C}$ (Figure 13a). For the other values of T_{avg} & ΔT , the ASHRAE R-values were higher than the predicted R-values (Figure 13b-g).
- For $\delta = 40$ mm and low ϵ_{eff} (< 0.5), the ASHRAE R-values were mainly in good agreement for T_{avg} & ΔT shown in Figure 14e,f but higher than the predicted R-values for other values of T_{avg} & ΔT shown in Figure 14a-d,g.
- For $\delta = 90$ mm and all values of T_{avg} & ΔT , the ASHRAE R-values were in good agreement with the predicted R-values for enclosed airspace of length of $\sim 24 - 36$ in ($\sim 610 - 914$ mm) (see Figure 15a-g).

Dependence of the R-value on the Aspect Ratio (A_R)

In previous studies, the dependence of the R-value on the aspect ratio of the vertical enclosed airspaces [30] and horizontal airspaces with downward heat flow [31] were investigated. Depending on the thickness of the airspace and the operating conditions, the results of that study showed that the aspect ratio can have a significant effect on the R-value. In this study for horizontal enclosed airspaces of different thickness ($\delta = 13, 20, 40$ and 90 mm) and subjected to upward heat flow, numerical simulations were conducted at $T_{avg} = 32.2, 10.0, -17.8$ and -45.6°C , $\Delta T = 5.6, 11.1$ and 16.7°C , and $\epsilon_{eff} = 0 - 0.82$ in order to investigate the effect of the aspect ratio on the R-values. For a given airspace thickness, numerical simulations were conducted for different lengths (H) ranging from 8 in (203.2 mm) to 36 in (914.4 mm). The obtained R-values are shown in Figure 12a-g ($\delta = 13$ mm), Figure 13a-g ($\delta = 20$ mm), Figure 14a-g ($\delta = 40$ mm), and Figure 15a-g ($\delta = 90$ mm). For the purpose of comparison, these figures also show the ASHRAE R-values, which are independent on the length of the airspace [22]. As shown in these figures, because the predicted R-values for enclosed airspaces of different thicknesses having lengths of $H = 24$ in (609.6 mm) and 36 in (914.4 mm) were quite close, no numerical simulations were conducted at H greater than 36 in.

Due to the temperature differential across the horizontal enclosed airspace and the upward heat flow condition, a buoyancy-driven flow was developed within the airspace, resulting in multi-cellular airflows with a number of convection loops within the enclosed airspace (e.g. see Figure 2 through Figure 7). As discussed earlier, both the number of convection loops and airflow velocity in the enclosed airspace affect the R-value. The greater the number of convection loops

per unit length for a given air velocity would result in an increase in the thermal conductance of the airspace (i.e. reduction in thermal resistance). For the airspace having the greatest thickness ($\delta = 90$ mm), the number of convection loops predicted in the airspaces of $H = 8$ in (203.2 mm), 12 in (304.8 mm), 16 in (406.4 mm), 24 in (609.4 mm) and 36 in (914.4 mm) were, respectively, 2, 2, 4, 6 and 10 loops, and the air velocities in these airspaces were approximately the same. The corresponding number of convection loops per unit length in inches (N_L) was, respectively, 0.25, 0.17, 0.25, 0.25 and 0.28.

As shown in Figure 15 ($\delta = 90$ mm), because the airspace of $H = 12$ in (304.8 mm) had the lowest N_L (0.17) and the airspace having $H = 36$ in (914.4 mm) had the largest N_L (0.28), the former airspace resulted in the highest R-value, whereas the latter airspace resulted in the lowest R-value. As the airspace thickness decreases, the number of the convection loops per unit length for airspaces of different lengths becomes approximately the same. Consequently, the effect of airspace length (or the aspect ratio, $A_R = H/\delta$) on the R-value decreases by decreasing the airspace thickness. For the airspace of the smallest thickness ($\delta = 13$ mm), Figure 12 shows that the airspace length has an insignificant effect on the R-value. For example, for airspace of various δ at $T_{avg} = -45.6^\circ\text{C}$ and $\Delta T = 11.1^\circ\text{C}$, the different values of A_R resulted in a maximum change in the R-values by <1% (Figure 12f, $\delta = 20$ mm), 4% (Figure 13f, $\delta = 20$ mm), 9% (Figure 14f, $\delta = 40$ mm), and 16% (Figure 15f, $\delta = 40$ mm). It is important to point out that for vertical enclosed airspace [30], the results showed that A_R has a significant effect on the R-values (e.g. up to ~85% for an effective emittance of 0.03).

In summary, this study has shown that the effect of the aspect ratio on the R-value of horizontal enclosed airspaces subjected to an upward heat flow condition is not as significant as that found for vertical enclosed airspaces as provided in a previous study (see reference [30] for more details).

Practical Correlations for the R-values

The results of the R-values that were presented in the previous section for an enclosed airspace of thicknesses 13, 20, 40, and 90 mm, and as provided in Figure 12h through Figure 15h were used to develop practical correlations for the R-values. Similar to the previous study for vertical enclosed airspace [30], to help ensure a broad application of these correlations, two types of correlations were considered for a horizontal enclosed airspace subjected to an upward heat flow condition, namely:

- I. For given set of values for T_{avg} and ΔT , as are provided in the ASHRAE table [22], a correlation was developed for each value of thickness, δ , to obtain the corresponding R-value in (ft²hr°F/BTU) as a function of the aspect ratio ($A_R = H/\delta$) and effective emittance (ϵ_{eff}). This correlation is given in the following form:

$$R - value = R_c(T_{avg}) + a_0 A_R^{\alpha_1} + a \epsilon_{eff}^\beta \sum_{i=1}^4 g_i A_R^i + A_R^{\alpha_2} \sum_{i=1}^4 b_i \epsilon_{eff}^i, \quad (2)$$

where the coefficients $a_0, a, \alpha_1, \alpha_2, \beta, b_1, b_2, b_3, b_4, g_1, g_2, g_3$, and g_4 in Eq. (2) are listed in Table 4 for different values of δ . In this equation, $R_c(T_{avg})$ is the R-value in (ft²hr°F/BTU) of the enclosed airspace due to heat transfer by conduction only, which is given as [30, 31]:

$$R_c(T_{avg}) = \delta / \lambda(T_{avg}), \quad (3)$$

where,

$$\lambda(T_{avg}) = \sum_{i=0}^4 f_i T_{avg}^i, f_0 = -0.00227583562, f_1 = 1.15480022 \times 10^{-4}, \quad (4)$$

$$f_2 = -7.90252856 \times 10^{-8}, f_3 = 4.11702505 \times 10^{-11}, f_4 = -7.43864331 \times 10^{-15}$$

Note that $\lambda(T_{avg})$ in Eq. (4) is the average thermal conductivity of air in (W/mK), which is evaluated at the mean temperature of the airspace, T_{avg} in (K). It is important to point out that the calculated value of $R_c(T_{avg})$ from Eq. (3) and (4) must be converted to (ft²hr°F/BTU) in order to be used in Eq. (2).

II. A comprehensive correlation was developed for each value of δ to obtain the R-value in (ft²hr°F/BTU) as a function of all parameters (i.e. T_{avg} , ΔT , A_R and ϵ_{eff}). This correlation is given in the following form:

$$R - value = R_c(T_{avg}) + a_0 A_R^{\alpha_1} T_{avg}^{a_1} (\Delta T)^{c_1} + a \epsilon_{eff}^{\beta} T_{avg}^{a_2} (\Delta T)^{c_2} \sum_{i=1}^4 g_i A_R^i + A_R^{\alpha_2} T_{avg}^{a_3} (\Delta T)^{c_3} \sum_{i=1}^4 b_i \epsilon_{eff}^i \quad (5)$$

In Eq. (5), $R_c(T_{avg})$ is given by Eq. (3) and (4) and the units must be in (ft²hr°F/BTU), whereas the units of T_{avg} and ΔT must be in (K). The other coefficients in Eq. (5) ($a_0, a, b_1, b_2, b_3, b_4, \alpha_1, \alpha_2, \beta, a_1, a_2, a_3, c_1, c_2, c_3, g_1, g_2, g_3$, and g_4) are listed in Table 5. In order to develop an accurate correlation, these coefficients were obtained for different ranges of the effective emittance (ϵ_{eff}).

Close examinations for the correlations given by Eq. (2) and Eq. (5) reveal that the first term on the RHS of Eq. (2) and Eq. (5) represents the R-value due to heat transfer by conduction only. The second term on the RHS of these equations represents the reduction in R-value due to heat transfer by convection only. The last two terms on the RHS of these equations represent the reduction in R-value due to heat transfer by radiation only at different values of ϵ_{eff} .

For a given thickness of horizontal enclosed airspace with an upward heat flow condition, the predicted R-values obtained using the numerical simulation model and shown in Figure 12 through Figure 15 were compared with those obtained using the correlations given in Eq. (2) and Eq. (5). These comparisons are provided in Figure 16 ($\delta = 13$ mm), Figure 17 ($\delta = 20$ mm), Figure 18 ($\delta = 40$ mm), and Figure 19 ($\delta = 90$ mm). As shown in these figures, the calculated R-values using the correlation given by Eq. (2) are in good agreement with the predicted R-values (within approximately $\pm 2\%$ and $\pm 3\%$, see Figure 16a to Figure 19a). Furthermore, the calculated R-values using the correlation given by Eq. (5) are also in good agreement with the predicted R-values (within approximately $\pm 3\%$ and $\pm 4\%$, see Figure 16b to Figure 19b).

It is important to point out that the ranges of the aspect ratios (A_R) that were used to develop the correlations given by Eq. (2) and Eq. (5) corresponded to airspaces of different lengths ranging from $H = 8$ in (203.2 mm) up to 36 in (914.4 mm). These ranges are: $A_R = 15.6$ to 46.9 for $\delta = 13$ mm, $A_R = 10.2$ to 30.5 for $\delta = 20$ mm, $A_R = 5.1$ to 22.9 for $\delta = 40$ mm, and $A_R = 2.3$ to 10.2 for

$\delta = 90$ mm. As such, for a given value of δ , these correlations are applicable only within these ranges of A_R . As indicated earlier, for a given airspace thickness, the predicted R-values for $H = 24$ in (609.6 mm) were approximately the same as that for $H = 36$ in (914.4 mm). Consequently, for an application that has a horizontal enclosed airspace of length greater than 24 in, A_R could be determined based on $H = 24$ in (609.6 mm) so as to use the correlations given by Eq. (2) and Eq. (5) for determining the R-value.

SUMMARY AND CONCLUSIONS

Previous studies undertaken to determine the R-values of vertical enclosed airspaces [30] and horizontal enclosed airspaces with downward heat flow condition [31] were extended in the present study to investigate the thermal performance of horizontal enclosed airspaces that were subjected to an upward heat flow condition. In the first part of this paper, numerical simulations were conducted to predict the thermal resistance (R-value) of horizontal enclosed airspaces of different dimensions and effective emittance, and subjected to different mean temperatures and temperature differences. The predicted R-values were compared with the R-values given in the ASHRAE table [22] for different conditions. For an airspace of length of 12 in (304.8 mm), the results showed that the absolute percentages of the maximum deviations between the predicted and ASHRAE R-values were 21.9, 19.0, 18.9 and 16.8%, respectively, for an airspace thickness of 13, 20, 40 and 90 mm. The dependence of the R-value on the aspect ratio of the enclosed airspace was also investigated for different conditions. The results showed that the effect of the aspect ratio on the R-value of horizontal enclosed airspaces is not as significant as for vertical enclosed airspaces as was provided in the previous study [30].

In the second part of this paper, considerations were given to investigate the potential increase in the R-value of the enclosed airspace when a thin sheet having different values of emissivity on both sides was placed horizontally in the middle of the airspace. The results showed that, depending on the value of the effective emittance and the thickness of the airspace, the R-value could be tripled by incorporating this thin sheet along the middle of the enclosed airspace.

In the last part of this paper, two practical correlations were developed to determine the R-values of horizontal enclosed airspaces of different thicknesses (δ), and for a wide range of values for various parameters, including: (a) aspect ratio (A_R), (b) temperature difference across the airspace (ΔT), (c) mean temperature (T_{avg}), and, (d) effective emittance (ϵ_{eff}). These correlations are provided by Eq. (2) and Eq. (5). For a given T_{avg} and ΔT that are given in the ASHRAE table [22], the calculated R-values using the correlation given by Eq. (2) are in good agreement with the predicted R-values (within approximately $\pm 2\% - \pm 3\%$). Furthermore, for a given T_{avg} , ΔT , A_R and ϵ_{eff} , the calculated R-values using the correlation given by Eq. (5) are also in good agreement with the predicted R-values (within approximately $\pm 3\% - \pm 4\%$).

It is of practical importance in the design of building envelopes to determine the R-value of enclosed airspaces of different orientations and directions of heat flow, and having different values of effective emittance under varying climatic conditions as the results of the design may help avoid selecting oversized heating or cooling equipment. The practical correlations that were developed in this study for horizontal enclosed airspaces with an upward heat flow condition, and those developed in the previous studies for vertical enclosed airspaces [30] and horizontal enclosed airspaces with downward heat flow condition [31] can be used by architects, modellers and building designers to determine the R-values of enclosed airspaces having varying aspect ratios and values of effective emittance, and subjected to a wide range of mean temperatures and temperature differences across the airspace. These correlations can also be

readily implemented in currently available energy simulation models (e.g. ESP-r, Energy Plus, DOE, etc). Similar practical correlations for determining the R-values of sloped roof systems having enclosed airspaces of different orientations and directions of heat flow will be reported in future publications.

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Table 1. Maximum vertical and horizontal velocities of the air in the cases of “1-Cavity” and “2-Cavities” when $T_{avg} = 10^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$, $\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.9$, $\delta = 13 \text{ mm}$, $H = 12 \text{ in}$ (304.8 mm)

δ (mm)	Maximum Upward Velocity (u_y) / Maximum Downward Velocity (u_y) (mm/s)			Maximum Right Velocity (u_x) / Maximum Left Velocity (u_x) (mm/s)		
	“1-Cavity”	“2-Cavities”	$u_{y, \text{ 1-Cavity}} /$ $u_{y, \text{ 2-Cavities}}$	“1-Cavity”	“2-Cavities”	$u_{x, \text{ 1-Cavity}} /$ $u_{x, \text{ 2-Cavities}}$
90	90.7 / -116.7	63.6 / -62.7	~ 1.7	130 / -130	61.4 / -61.5	~ 2.1
40	84.5 / -85.2	30.9 / -30.8	~ 2.7	75.4 / -75.4	28.9 / -28.9	~ 2.6

Table 2. Percentage increase in R-value between “2-Cavities” and “1-Cavity” simulation cases for given value of $\epsilon_{\text{eff}} = 0.03$ and 0.82 ($H = 12$ in (304.8 mm))

Thickness of Airspace, δ (mm)	Increase (%) in R-value between “2-Cavities” and “1-Cavity” Simulation Cases for Given Value of ϵ_{eff}		Governing Simulation Conditions and Related Figures
	$\epsilon_{\text{eff}} = 0.03$	$\epsilon_{\text{eff}} = 0.82^*$	
$\delta = 13$ mm	9.1%	57.5%	$T_{\text{avg}} = 32.2^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 8a)
	102.8%	100.0%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 16.7^\circ\text{C}$ (Figure 8b)
	8.3%	53.3%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 8c)
	109.4%	103.5%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 8d)
	48.7%	69.6%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 8e)
	153.8%	130.9%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 8f)
	97.3%	96.7%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 8g)
$\delta = 20$ mm	94.5%	94.6%	$T_{\text{avg}} = 32.2^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 9a)
	200.0%	136.4%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 16.7^\circ\text{C}$ (Figure 9b)
	120.2%	104.7%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 9c)
	204.9%	144.1%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 9d)
	154.1%	121.0%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 9e)
	147.6%	134.5%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 9f)
	191.9%	144.8%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 9g)
$\delta = 40$ mm	143.3%	114.8%	$T_{\text{avg}} = 32.2^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 10a)
	102.1%	100.5%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 16.7^\circ\text{C}$ (Figure 10b)
	113.7%	105.9%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 10c)
	107.3%	103.3%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 10d)
	95.7%	97.5%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 10e)
	95.5%	97.1%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 10f)
	99.6%	99.5%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 10g)
$\delta = 90$ mm	95.9%	89.5%	$T_{\text{avg}} = 32.2^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 11a)
	90.2%	87.4%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 16.7^\circ\text{C}$ (Figure 11b)
	92.2%	88.1%	$T_{\text{avg}} = 10.0^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 11c)
	87.0%	85.9%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 11d)
	89.4%	86.4%	$T_{\text{avg}} = -17.8^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 11e)
	83.8%	84.0%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 11.1^\circ\text{C}$ (Figure 11f)
	83.3%	84.3%	$T_{\text{avg}} = -45.6^\circ\text{C}$, $\Delta T = 5.6^\circ\text{C}$ (Figure 11g)

*0.82 means that all surfaces of the airspace have emissivity of 0.9

Table 3. Comparison between the predicted R-values for an enclosed horizontal airspace and the R-values given in the ASHRAE table [22] for all values of δ , T_{avg} , ΔT , and ϵ_{eff}

δ (mm)	Deviation of ASHRAE R-value from the present R-value of airspace with H = 12 in (304.8 mm) (%)					Governing simulation conditions and related figures for airspace of different lengths
	$\epsilon_{eff} = 0.03$	$\epsilon_{eff} = 0.05$	$\epsilon_{eff} = 0.2$	$\epsilon_{eff} = 0.5$	$\epsilon_{eff} = 0.82$	
13	-13.60	-11.44	-7.97	-10.15	-5.00	$T_{avg} = 32.2^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 12a)
	17.22	15.99	12.45	8.34	3.38	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$ (Figure 12b)
	-20.27	-18.86	-15.85	-10.04	-8.47	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 12c)
	13.01	15.19	13.96	9.37	5.98	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 12d)
	-0.85	-0.92	-1.16	-3.79	-0.61	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 12e)
	21.93	19.35	16.98	15.88	9.54	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 12f)
	14.03	12.65	11.66	9.20	3.66	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 12g)
20	13.97	13.19	7.22	1.97	-0.91	$T_{avg} = 32.2^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 13a)
	19.00	17.89	15.21	6.47	9.45	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$ (Figure 13b)
	16.64	17.54	12.50	4.25	1.54	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 13c)
	16.66	18.95	14.84	6.46	3.39	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 13d)
	18.21	17.90	12.83	8.34	5.29	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 13e)
	16.04	17.60	12.62	8.37	8.87	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 13f)
	18.82	17.56	13.77	12.08	7.43	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 13g)
40	17.58	14.75	8.98	2.68	1.92	$T_{avg} = 32.2^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 14a)
	18.42	17.85	14.14	4.26	1.82	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$ (Figure 14b)
	14.76	13.52	9.30	1.31	1.02	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 14c)
	18.94	17.87	15.46	10.06	3.37	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 14d)
	12.34	9.94	5.56	1.42	0.94	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 14e)
	12.69	14.33	11.69	6.60	4.08	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 14f)
	18.23	17.40	12.88	6.54	3.63	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 14g)
90	4.23	3.20	-2.89	-6.92	-11.16	$T_{avg} = 32.2^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 15a)
	-6.26	-7.84	-8.18	-13.51	-11.68	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$ (Figure 15b)
	0.08	0.11	-5.26	-6.50	-13.58	$T_{avg} = 10.0^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 15c)
	-8.04	-10.27	-9.52	-13.73	-14.97	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 15d)
	-4.14	-5.24	-8.92	-10.17	-11.46	$T_{avg} = -17.8^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 15e)
	-11.68	-12.31	-13.20	-14.84	-16.84	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 11.1^{\circ}\text{C}$ (Figure 15f)
	-7.88	-9.84	-11.51	-13.74	-15.89	$T_{avg} = -45.6^{\circ}\text{C}$, $\Delta T = 5.6^{\circ}\text{C}$ (Figure 15g)

Table 4. List of the correlation coefficients given by Eq. (2) for an enclosed airspace of different thicknesses (δ)

T_{avg} (°C)	ΔT (K)	a_0	a	α_1	α_2	β	b_1	b_2	b_3	b_4	g_1	g_2	g_3	g_4
$\delta = 13 \text{ mm}$														
32.2	5.6	-1.14948E-01	6.89011E-04	9.96890E-02	6.64057E-03	-9.93882E-02	-6.79857E+00	1.29249E+01	-1.37249E+01	5.85742E+00	-3.14117E+00	1.23603E-01	1.78020E-03	-5.52756E-05
10	16.7	-1.35826E+00	3.92891E-04	4.24658E-02	4.60565E-03	-1.39798E-02	-1.73837E+00	1.83335E+00	-1.32551E+00	4.46705E-01	-3.21246E+00	2.79508E-01	1.39387E-03	-8.12003E-05
10	5.6	-4.02564E-01	7.39826E-04	-3.24379E-01	2.87904E-02	-1.53642E-01	-5.95096E+00	1.04102E+01	-1.05764E+01	4.40964E+00	-2.49218E+00	1.96443E-01	-3.71826E-03	1.32046E-05
-17.8	11.1	-1.69554E+00	-2.65900E-04	3.06698E-03	3.39918E-02	-9.36562E-03	-1.34826E+00	1.18233E+00	-7.48405E-01	2.29272E-01	-3.95940E+00	5.98466E-02	-1.72800E-03	1.65722E-05
-17.8	5.6	-1.07189E+00	-4.43516E-04	3.03728E-03	4.37224E-02	-6.13980E-03	-2.62548E+00	3.11527E+00	-2.47365E+00	8.83556E-01	-4.88236E+00	1.90384E-02	-1.36198E-03	3.21175E-05
-45.6	11.1	-2.13671E+00	-3.34129E-04	4.60671E-03	6.04045E-03	-4.63403E-03	-9.00801E-01	5.68724E-01	-3.09988E-01	9.65291E-02	-2.30056E+00	1.68915E-02	-1.92277E-03	3.78764E-05
-45.6	5.6	-1.76452E+00	-4.53111E-04	3.61300E-03	4.80996E-02	-5.90009E-03	-1.26615E+00	9.01867E-01	-4.37964E-01	9.33137E-02	-2.93362E+00	1.50704E-02	-2.22927E-03	3.97362E-05
$\delta = 20 \text{ mm}$														
32.2	5.6	-2.29085E+00	-1.29992E-02	-3.67492E-02	6.31297E-02	4.61176E-05	-4.11785E+00	7.12991E+00	-7.22908E+00	3.01518E+00	4.13461E-03	1.38859E-02	-4.17185E-04	1.95082E-07
10	16.7	-3.34870E+00	-1.37818E-02	-3.33862E-02	5.66142E-02	-8.49592E-03	-1.56198E+00	1.77251E+00	-1.41233E+00	5.20148E-01	4.01111E-03	1.37374E-02	-2.64757E-04	2.55714E-06
10	5.6	-2.78261E+00	-2.58380E-02	-4.42864E-02	4.78290E-02	8.38079E-03	-3.01938E+00	4.24200E+00	-3.77887E+00	1.46105E+00	4.01064E-03	1.36806E-02	-2.64908E-04	-1.36439E-06
-17.8	11.1	-3.68390E+00	-2.46578E-02	-3.70691E-02	3.19011E-02	-1.84031E-03	-1.43989E+00	1.36447E+00	-9.78362E-01	3.42654E-01	4.01162E-03	1.39216E-02	-2.63617E-04	1.12034E-06
-17.8	5.6	-3.36370E+00	-2.86954E-02	-4.40414E-02	3.76101E-02	6.32812E-04	-2.06818E+00	2.22537E+00	-1.68486E+00	5.95599E-01	4.01155E-03	1.39416E-02	-2.63417E-04	-1.41295E-08
-45.6	11.1	-4.31017E+00	-2.65514E-02	-3.64854E-02	2.63614E-02	-1.58466E-03	-9.59756E-01	6.68459E-01	-4.08229E-01	1.36426E-01	4.01237E-03	1.41085E-02	-2.62651E-04	1.93681E-06
-45.6	5.6	-3.96991E+00	-2.60910E-02	-3.68449E-02	3.19839E-02	-2.34681E-03	-1.37371E+00	1.10427E+00	-7.19189E-01	2.42300E-01	4.01229E-03	1.41046E-02	-2.62638E-04	1.15845E-06
$\delta = 40 \text{ mm}$														
32.2	5.6	-7.46185E+00	8.31344E-02	-3.45633E-03	4.86029E-02	-1.02266E-03	-4.44406E+00	7.55701E+00	-7.50574E+00	3.07774E+00	5.01489E+00	-6.58378E-01	3.52296E-02	-6.53097E-04
10	16.7	-7.90311E+00	5.58244E-02	-7.19861E-04	6.10121E-02	-5.86785E-04	-1.90076E+00	2.24423E+00	-1.78963E+00	6.47958E-01	2.80587E+00	-3.77868E-01	2.05725E-02	-3.83900E-04
10	5.6	-6.76762E+00	1.91182E-02	-6.20789E-04	-4.51353E-03	-5.68818E-03	-4.25660E+00	6.53760E+00	-6.23910E+00	2.53101E+00	-1.79420E+00	3.25752E-01	-2.41648E-02	5.56743E-04
-17.8	11.1	-7.84948E+00	4.34140E-02	-2.01829E-03	7.56807E-02	-1.49927E-04	-1.57512E+00	1.56955E+00	-1.13968E+00	3.96272E-01	-3.57785E+00	4.74581E-01	-2.56524E-02	4.82765E-04
-17.8	5.6	-7.42759E+00	4.15163E-02	-2.00461E-03	-2.07430E-02	-1.44324E-04	-3.12265E+00	3.71854E+00	-3.02226E+00	1.11693E+00	-2.96252E+00	4.34115E-01	-2.72499E-02	5.71652E-04
-45.6	11.1	-6.81602E+00	1.43243E-01	-1.99755E-03	-3.14143E-03	-6.21674E-05	-1.44744E+00	1.11809E+00	-7.00524E-01	2.29336E-01	-6.55844E+00	8.86757E-01	-4.87632E-02	9.22292E-04
-45.6	5.6	-8.88290E+00	1.47586E-02	-5.41251E-03	6.66887E-02	-6.18743E-05	-1.58168E+00	1.33629E+00	-8.59838E-01	2.76825E-01	-4.60298E+00	7.17090E-01	-4.43748E-02	9.09411E-04
$\delta = 90 \text{ mm}$														
32.2	5.6	-1.67430E+01	1.30092E+00	-2.77046E-01	4.99222E-02	5.25843E-04	-6.31057E+00	1.17003E+01	-1.22165E+01	5.15736E+00	-1.14610E+00	-1.05708E-02	1.70871E-02	-1.04441E-03
10	16.7	-1.84297E+01	1.34706E+00	-2.55258E-01	2.97326E-02	1.61293E-04	-3.33287E+00	4.54481E+00	-3.94797E+00	1.49703E+00	-1.16836E+00	-1.06469E-02	1.72445E-02	-1.05302E-03
10	5.6	-1.80164E+01	1.43763E+00	-2.97495E-01	4.26898E-02	3.00060E-04	-5.20079E+00	8.38111E+00	-8.05701E+00	3.24020E+00	-1.18781E+00	-1.05043E-02	1.77754E-02	-1.08889E-03
-17.8	11.1	-2.10117E+01	8.88917E-01	-1.79230E-01	2.44901E-02	1.55726E-04	-2.94502E+00	3.36143E+00	-2.59371E+00	9.15043E-01	-4.32563E-01	-3.50608E-01	6.33569E-02	-3.08806E-03
-17.8	5.6	-2.07793E+01	9.41667E-01	-1.99803E-01	3.29711E-02	2.11666E-04	-3.92443E+00	5.08126E+00	-4.27324E+00	1.58983E+00	-4.37027E-01	-3.55747E-01	6.44437E-02	-3.14436E-03
-45.6	11.1	-2.34461E+01	9.82252E-01	-1.80802E-01	1.18385E-02	9.16033E-05	-2.10543E+00	1.81824E+00	-1.26201E+00	4.61611E-01	-4.29539E-01	-3.65372E-01	6.57948E-02	-3.20404E-03
-45.6	5.6	-2.31234E+01	1.16288E+00	-2.25919E-01	1.72365E-02	1.71131E-04	-2.86447E+00	2.88154E+00	-2.11430E+00	7.43823E-01	-6.34576E-01	-2.98371E-01	5.77959E-02	-2.87339E-03

Table 5. List of the correlation coefficients given by Eq. (5) for an enclosed airspace of different thicknesses (δ)

δ (mm)	13			20		40		90	
ϵ_{eff}	< 0.1	$0.1 \leq \epsilon_{\text{eff}} < 0.4$	≥ 0.4	< 0.2	≥ 0.2	< 0.2	≥ 0.2	< 0.2	≥ 0.2
a_0	-1.54709E+01	-1.27448E+03	-6.99114E+03	-5.39206E+01	-1.11420E+03	-1.11273E+03	-1.44727E+03	-1.65421E+03	-3.76451E+03
a	-1.58523E-02	-1.41351E-03	2.56431E-02	4.92331E-01	2.37900E-01	4.76103E+00	1.36580E+02	2.46831E+01	2.67846E+03
b_1	-1.23242E-01	-3.93027E-07	4.39321E-06	-1.59664E-06	1.19199E-03	-4.04396E-06	-1.03094E-03	-3.98228E-06	-8.05988E-02
b_2	2.78167E+00	2.30547E-06	-2.46468E-05	3.06410E-06	-7.49196E-03	1.62515E-05	-3.18010E-02	1.78988E-05	5.56295E-02
b_3	-1.95656E+01	-6.37388E-06	3.17427E-05	-6.62291E-06	1.12642E-02	-9.45214E-05	5.45863E-02	-9.16011E-05	8.33748E-03
b_4	-4.56224E-04	6.41113E-06	-1.36376E-05	9.77292E-06	-5.59415E-03	2.20788E-04	-2.82481E-02	1.99596E-04	-2.29076E-02
α_1	3.46837E-03	5.16797E-03	-5.32747E-03	5.13030E-04	3.95505E-03	5.21809E-04	-8.81731E-04	4.62587E-04	-1.05729E-03
α_2	-3.94220E-02	7.73703E-03	1.69738E-02	-9.10782E-03	6.36155E-03	7.98205E-03	1.20082E-02	-1.43857E-02	-1.30494E-02
β	-3.27987E-03	1.86312E-03	-1.04967E-01	1.17463E-04	3.95704E-05	5.41295E-05	1.93087E-05	1.31956E-04	1.81440E-05
a_1	2.82826E-01	-8.39775E-01	-1.53155E+00	-2.47477E-01	-1.06808E+00	-8.44848E-01	-9.50201E-01	-7.57692E-01	-9.34841E-01
a_2	5.23128E-01	6.79698E-01	2.21720E-01	2.20639E-01	-5.89458E-01	6.88819E-01	-1.76164E+00	3.26700E-04	-1.17960E+00
a_3	1.11580E+02	3.38041E+00	2.33844E+00	2.78709E+00	1.41619E+00	2.62602E+00	1.00785E+00	2.66130E+00	7.48921E-01
c_1	-5.55016E-01	-4.62199E-01	1.46900E-01	-4.86073E-02	8.44660E-02	-5.64897E-02	4.49443E-02	1.11509E-02	1.87348E-02
c_2	-6.35045E-01	-8.83632E-01	-1.31162E+00	-1.23161E-01	-8.23144E-03	-9.80875E-01	-6.01573E-01	-4.65926E-02	-6.40531E-03
c_3	-3.67131E+02	-6.27678E-01	-2.44903E-01	-6.02342E-01	-3.58286E-01	-5.41536E-01	-2.85514E-01	-3.82714E-01	-2.39071E-01
g_1	-4.51829E+01	-6.38997E+01	2.72206E+00	1.71575E+00	4.13459E-03	1.51685E-02	-9.00481E-01	2.22651E-01	5.19953E-01
g_2	2.56185E+00	3.60686E+00	-2.08240E-01	-1.48344E-01	1.38675E-02	-1.97697E-03	-4.67632E-02	-6.74958E-02	-1.63700E-01
g_3	-6.13988E-02	-8.62246E-02	6.19277E-03	5.42525E-03	-4.17684E-04	1.04575E-04	-2.55176E-03	8.26941E-03	2.03727E-02
g_4	5.23501E-04	7.33810E-04	-6.14940E-05	-7.07150E-05	1.46293E-07	-1.91962E-06	1.72097E-04	-3.49517E-04	-8.68099E-04

Figure 1. Schematics of enclosed airspace with and without thin sheet of low emissivity on both sides, placed horizontally in the middle of the airspace

Figure 2. Temperature contours (in °C) in enclosed airspace in the cases of “1-Cavity” and “2-Cavities” when $T_{avg} = 10^\circ\text{C}$, $\Delta T = 16.7^\circ\text{C}$, $\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.9$, $\delta = 90\text{ mm}$, $H = 12\text{ in}$ (304.8 mm)

Note: right contour bar for “1-Cavity” and left contour bar for “2-Cavities”

Figure 3. Vertical velocity contours of the air (in mm/s) in enclosed airspace in the cases of “1-Cavity” and “2-Cavities” when $T_{avg} = 10^\circ\text{C}$, $\Delta T = 16.7^\circ\text{C}$, $\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.9$, $\delta = 90\text{ mm}$, $H = 12\text{ in}$ (304.8 mm)

Figure 4. Horizontal velocity contours of the air (in mm/s) in enclosed airspace in the cases of "1-Cavity" and "2-Cavities" when $T_{avg} = 10^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$, $\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.9$, $\delta = 90$ mm, $H = 12$ in (304.8 mm)

Figure 5. Temperature contours (in $^{\circ}\text{C}$) in enclosed airspace in the cases of "1-Cavity" and "2-Cavities" when $T_{avg} = 10^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$, $\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.9$, $\delta = 40$ mm, $H = 12$ in (304.8 mm)

Figure 6. Vertical velocity contours of the air (in mm/s) in enclosed airspace in the cases of "1-Cavity" and "2-Cavities" when $T_{avg} = 10^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$, $\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.9$, $\delta = 40$ mm, $H = 12$ in (304.8 mm)

Figure 7. Horizontal velocity contours of the air (in mm/s) in enclosed airspace in the cases of "1-Cavity" and "2-Cavities" when $T_{avg} = 10^{\circ}\text{C}$, $\Delta T = 16.7^{\circ}\text{C}$, $\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.9$, $\delta = 40$ mm, $H = 12$ in (304.8 mm)

Figure 8. Dependence of R-value on T_{avg} , ΔT and ϵ_{eff} ($H = 12$ in (304.8 mm) and $\delta = 13$ mm)

Figure 9. Dependence of R-value on T_{avg} , ΔT and ϵ_{eff} ($H = 12$ in (304.8 mm) and $\delta = 20$ mm)

Figure 10. Dependence of R-value on T_{avg} , ΔT and ϵ_{eff} ($H = 12$ in (304.8 mm) and $\delta = 40$ mm)

Figure 11. Dependence of R-value on T_{avg} , ΔT and ϵ_{eff} ($H = 12$ in (304.8 mm) and $\delta = 90$ mm)

Figure 12. Dependence of R-value on T_{avg} , ΔT , ϵ_{eff} and H for airspace of 13 mm thick

Figure 13. Dependence of R-value on T_{avg} , ΔT , ϵ_{eff} and H for airspace of 20 mm thick

Figure 14. Dependence of R-value on T_{avg} , ΔT , ϵ_{eff} and H for airspace of 40 mm thick

Figure 15. Dependence of R-value on T_{avg} , ΔT , ϵ_{eff} and H for airspace of 90 mm thick

Figure 16. Comparison of R-values obtained using the present model and correlation given by (a) Eq. (2) and (b) Eq. (5) for airspace of 13 mm thick

Figure 17. Comparison of R-values obtained using the present model and correlation given by (a) Eq. (2) and (b) Eq. (5) for airspace of 20 mm thick

Figure 18. Comparison of R-values obtained using the present model and correlation given by (a) Eq. (2) and (b) Eq. (5) for airspace of 40 mm thick

Figure 19. Comparison of R-values obtained using the present model and correlation given by (a) Eq. (2) and (b) Eq. (5) for airspace of 90 mm thick