Evaluation and use of airspaces for thermal resistance in buildings

H H Saber¹,³ and D W Yarbrough²

¹Prince Saud bin Thuniyan Research Center and Mechanical Engineering Department at Jubail University College, Royal Commission of Jubail and Yanbu, Jubail Industrial City, Kingdom of Saudi Arabia, saberh@ucj.edu.sa
²Vice President, R&D Services, Inc., Watertown, TN, USA, dave@rdservices.com
³Corresponding author, saberh@ucj.edu.sa

Abstract. The thermal resistance (R-value) of airspaces depends on the emittance of surfaces around the airspace, dimensions, heat-flow direction, and the temperatures of bounding surfaces. Assessing the energy performance of building envelope components and fenestration systems requires accurate results for the R-values of any enclosed spaces. The evaluation of reflective insulation R-values has evolved to include use of computational fluid dynamics and surface-to-surface radiation to quantify convective and radiation contributions to the heat transfer across airspaces of all types. This paper compares an advanced and validated computational tool for calculating enclosed airspace R-values with the widely-used ISO 6946 and airspace R-values in the ASHRAE Handbook-Fundamentals. The tool evaluates construction defects, air-infiltration impact, and dimensional aspect ratios that 1-D methods do not address. The differences between the methods that are currently being used to evaluate the R-value and the advantages of the advanced method for evaluation of reflective insulation applications are discussed.

1. Introduction

The use of all types of thermal insulations to reduce the energy used for heating and cooling is an important part of current efforts to achieve zero energy buildings. Thermal insulation products with low thermal emittance surfaces that have been studied and utilized for over 100 years to reduce thermal radiation across airspaces are an example [1]. The resulting product type, called reflective insulation, utilizes the low thermal conductivity of air [2], reduced radiative transport, and in some cases reduced convection to provide high thermal resistance. The thermal resistance provided by airspaces, especially reflective airspaces, gained recognition in the mid-20th century due to publication of thermal test results from the U.S. National Bureau of Standards (NBS) [3]. The NBS results provided a basis for calculating the thermal resistance of airspaces. Early and subsequent editions of the ASHRAE Handbook of Fundamentals contained selected data from the NBS database [4-5]. The database for the thermal resistances of airspaces was extended by additional data published in 1990-1991 [6-7] and the evaluation of reflective airspaces have been also represented at the international level, for example, by ISO 6946 [8].

The data sets used for evaluating the thermal resistance of airspaces described above have limitations. The test data are representative of parallel isothermal surfaces with five heat-flow directions represented [5], the data were obtained with a single airspace aspect ratio with a few exceptions in the 1991 data from Tye and Desjarlais [6], and the number of independent variable assignments needed to obtain a thermal resistance (R-value) discourages interpolation. The development of computational fluid dynamics models and ever-increasing computational speed has made the simulation of heat transfer by
calculate heat transfer with all modes of heat transfer represented allows results to be obtained as a function of heat-flow direction, aspect ratio, boundary conditions, and all of the previously considered independent variables [9-10, 14]. In addition, the computational program that has been developed and validated was recently configured to estimate the impact of air infiltration, wind washing, airflow between adjacent reflective airspaces, imperfection installation of low emittance foils/sheets, and non-rectangular shapes of enclosed airspaces on the overall thermal resistance of the airspaces, subjected to various operating conditions. These capabilities remove many of the limitations of previous techniques for evaluating the thermal performance of enclosed reflective airspaces.

2. Numerical Model

Most recently, the model that is used in this study was extensively used to develop a user-friendly evaluation and design tool for enclosed airspaces called “Reflective Airspace Tool” that can be used by modelers, architects and building engineers to determine the R-values for enclosed airspaces of various designs when they are subjected to different operating conditions. In November of 2020, the full capabilities and features of this tool were presented to the Reflective Insulation Manufacturers Association International (RIMA-I [11]). Briefly, the model solves simultaneously the 2D and 3D moisture transport equation, energy equation, surface-to-surface radiation equation (e.g., surface-to-surface radiation in enclosed airspace, and as well surface-to-surface and surface-to-ambient radiation for the case of open airspace such as that in radiant barriers) and air transport equation in the various material layers of building components (walls, roofs, windows, curtain walls and skylight devices). The air transport equation is the Navier-Stokes equation for the airspace (e.g., air cavity), and Darcy equation (for Darcy Number, DN ≤ 10$^6$) and Brinkman equation (for DN > 10$^6$) for the porous material layers.

In previous studies, the model has been benchmarked against thermal performance data for a wall assembly containing a reflective insulation product [13]. The data were obtained using a guarded hot box for a full-scale wall system. The results showed that the R-value predicted by the model was within 1.2 % of the measured R-value. The model also was benchmarked against test data for reflective insulation products that were obtained using a heat flow meter. The heat fluxes predicted by the model were within ± 1.0% of measured heat fluxes [9, 12]. For a wide range of simulation parameters, the model is used in this study to demonstrate the increase in the R-value as a result of dividing an enclosed airspace of different aspect ratios, $A_R$ ($A_R = \text{Length (H)}/\text{Thickness (δ)}$) into two enclosed airspace of equal thickness. The model predictions for the R-values of enclosed airspaces were compared in this study with those from the HRP 32 data of single-and double-airspaces [3] as well as those calculated using the ISO 6946 [8].

3. Results and Discussions

This section presents thermal performance data for three cases: (a) vertical airspaces ($θ = 90°$) with heat-flow horizontal to represent building components such as walls, windows and curtain walls with reflective insulation (RI), (b) horizontal airspaces ($θ = 0°$) with heat-flow up to represent building components such as flat roofs or skylights with RI during the cold season, and (c) horizontal airspaces ($θ = 0°$) with heat-flow down to represent building components such as flat roofs or flat skylights with RI during the hot season. The results in this paper were obtained for enclosed airspaces ($δ = 89$ mm thick) of different aspect ratios and effective emittance ($ε_{eff} = 0$ to 0.82) with warm-side temperature ($T_{hi}$) of 32.2°C (90°F) and cool-side temperature ($T_{li}$) of 15.6°C (60°F) (i.e., temperature difference across the airspace ($ΔT$) of 16.6°C (30°F) and mean temperature of airspace of ($T_{avg}$) of 23.9°C (75°F)). In addition, results are provided in this paper for the cases (a), (b) and (c) listed above after splitting the airspace ($δ = 89$ mm) into two airspaces of equal thickness ($δ = 45.5$ mm), by installing a thin sheet with emittances sides ranging from 0 to 0.9 on both sides.

Unlike other available methods for determining the R-values of enclosed airspaces such as ISO 6946 [8] and ASHRAE [4-5, 15], the heat transfer by radiation from framing that bounds the airspace is accounted for by the present model. The emittance of all non-reflective surfaces bounded the airspace...
was taken to be equal to 0.9 [5]. Throughout this paper, unless otherwise specified, the case before splitting the airspace is called “single-airspace”, whereas the case after splitting the airspace is called “double-airspaces”. The present R-values are compared with those obtained using ISO 6946 [8] and those based on the data that is contained in Housing Research Paper (HRP) 32 [3] and calculated using correlations from Yam et al. [16]. It is important to point out that the details of the temperature and airflow distributions as well as the shapes and number of convection loops inside the enclosed airspaces are not provided in this paper due to the limitations in the number of pages.

3.1. Vertical airspaces with heat-flow horizontal

For single-airspace of 406 mm long, Figure 1a shows comparisons of the present R-values with end effect (solid line i.e., with heat transfer by radiation at the two airspace ends) and without end effect (dash line, i.e., without heat transfer by radiation at the two airspace ends) with those obtained using ISO 6946 [8] and HRP 32 [3]. As shown in this figure, both ISO 6946 and HRP 32 R-values are approximately the same, which are in good agreements with the present R-values for the case of large effective emittance ($\varepsilon_{\text{eff}} \geq 0.35$). However, the ISO 6946 and HRP 32 R-values are in closest agreements with the present R-values for single-airspaces of 610 mm long (i.e., $A_\varepsilon = 6.9$, see Figure 2). Neglecting the end effect has resulted in higher R-value than that with end effect for the low range of effective emittance ($\varepsilon_{\text{eff}} < 0.2$). For example, at $\varepsilon_{\text{eff}}$ of 0.05, the R-value with end effect (0.414 m$^2$K/W) was overestimated by 5% in relation to the case of no end effect (0.437 m$^2$K/W). Figure 1b shows comparison between the present R-values with the HRP 32 R-values [3, 16] for double-airspaces of 406 mm long. Similar to single-airspace, the present R-values are in good agreements with HRP 32 R-value for $\varepsilon_{\text{eff}} \geq 0.35$. For $\varepsilon_{\text{eff}}$ of 0.05 and 0.1, the HRP 32 R-values are 25% and 20% higher than the present R-values. On the other hand, both present and HRP 32 R-values are in closest agreements for the full range of effective emittance of double-airspaces that are 1,524 mm long ($A_\varepsilon = 34.3$, see Figure 3).

3.2. Horizontal airspaces with heat-flow down

Figure 1c compares the present R-values with and without end effect with the ISO 6946 [8] and HRP 32 [3] R-values for single-airspace of 406 mm long. This figure shows that both ISO 6946 and HRP 32 R-values are approximately the same, which are in good agreements with the present R-values for the range of $\varepsilon_{\text{eff}} \geq 0.1$. At $\varepsilon_{\text{eff}}$ of 0.05, both ISO 6946 HRP 32 R-values are higher than the present R-value by 15%. However, Figure 4 shows that the ISO 6946 and HRP 32 R-values are in closest agreements with present R-values for single-airspaces 610 mm or 914 mm long ($A_\varepsilon = 6.9$ or 10.3). For double-airspaces, Figure 1d shows comparisons between the present R-values and HRP 32 R-values. As shown in this figure, both present and HRP 32 R-values were in good agreements for $\varepsilon_{\text{eff}} \geq 0.1$; whereas the HRP 32 R-value was 9% higher than the present R-value at $\varepsilon_{\text{eff}}$ of 0.05. However, Figure 5 shows that both present and HRP 32 R-values are approximately the same for the whole range of effective emittance of double-airspaces 1,524 mm long.

Similar to airspaces with heat-flow horizontal ($\theta = 90^\circ$), neglecting the end effect in airspaces with heat-flow down ($\theta = 0^\circ$) has resulted in higher R-value than that with end effect for the low range of effective emittance ($\varepsilon_{\text{eff}} < 0.3$). At $\varepsilon_{\text{eff}}$ of 0.05 for single-airspaces, Figure 1c shows that the R-value with end effect (1.180 m$^2$K/W) was overestimated by 31% in relation to the case of no end effect (1.710 m$^2$K/W). At this value of $\varepsilon_{\text{eff}}$ for double-airspaces (0.05), the R-value with end effect (1.928 m$^2$K/W) was overestimated by 15% in relation to the case of no end effect (2.265 m$^2$K/W, Figure 1d).

3.3. Horizontal airspaces with heat-flow up

For single-airspace 406 mm long, Figure 1e shows comparisons of the present R-values with and without end effect with the ISO 6946 [8] and HRP 32 [3] R-values. This figure shows that both ISO 6946 and HRP 32 R-values are approximately the same at $\varepsilon_{\text{eff}}$ of 0.5 and 0.82. However, at $\varepsilon_{\text{eff}}$ of 0.05, 0.1 and 0.35, respectively, the HRP-32 R-values were 15%, 13% and 9% higher than ISO 6946; whereas the HRP-32 R-values were in good agreements with the present R-values (within 4%, 2% and -3%, respectively).
For the full range of the effective emittance, Figure 6 shows that the HRP 32 R-values were in good agreement with the present R-values for airspaces of 406 mm and 1,219 mm long ($A_R = 4.6$ and 13.7). Figure 1f shows comparisons between the present R-values and HRP 32 R-values for the double-airspaces of 406 mm long. As shown in this figure, both present and HRP 32 R-values were in good agreements for $\varepsilon_{\text{eff}} \geq 0.5$. At $\varepsilon_{\text{eff}}$ of 0.05, 0.1 and 0.35, respectively, the HRP 32 R-values were 22%, 19% and 9% higher than the present R-value. However, Figure 7 shows that the HRP 32 R-values were in closest agreements with the present R-values for the enclosed airspace of 1,524 mm long ($A_R = 34.3$).
at which the highest deviation between the HRP 32 and the present R-values (13%) occurred at $\varepsilon_{\text{eff}}$ of 0.05.

Similar to airspaces with heat-flow horizontal ($\theta = 90^\circ$), and down ($\theta = 0^\circ$), neglecting the end effect in airspaces with heat-flow up ($\theta = 0^\circ$) has resulted higher R-value than that with end effect for the low range of effective emittance ($\varepsilon_{\text{eff}} < 0.3$). Figure 1e shows that the R-value with end effect (0.343 m$^2$·K/W) for single-airspace at $\varepsilon_{\text{eff}}$ of 0.05 was overestimated by 8% in relation to the case of no end effect (0.372 m$^2$·K/W). Also, Figure 1f shows that at $\varepsilon_{\text{eff}}$ of 0.05 for double-airspaces, the R-value with end effect (0.638 m$^2$·K/W) was overestimated by 4% in relation to the case of no end effect (0.664 m$^2$·K/W).

3.4. Effect of aspect ratio on the R-values
At operating condition of average temperature ($T_{\text{av}}$) of 23.9°C (75°F) and a temperature difference across the airspace ($\Delta T$) of 16.6°C (30°F) (i.e., $T_H = 32.2°C$ (90°F) and $T_i = 15.6°C$ (60°F)), numerical simulations were conducted for single- airspaces (89 mm thick) and double-airspaces (44.5 mm thick each) with heat-flow horizontal ($\theta = 90^\circ$), heat-flow down ($\theta = 0^\circ$) and heat-flow up ($\theta = 0^\circ$) in order to demonstrate the effect of the aspect ratio on the R-values for the full range of effective emittance ($\theta = 0.82$). For single-airspaces these simulations were conducted for a height/length range of 102 mm – 2,438 mm, which represents an aspect ratio range of 1.1 – 27.4. For the double-airspaces, however, the simulations were conducted for only three heights/lengths of 406 mm, 1,524 mm and 2,362 mm, which represents a range of aspect ratio of 9.1 – 53.1 for each airspace. The case of airspace height/length (H) of 406 mm can represent furred-airspace assembly built 406 mm (16 inch) on-center.

3.4.1. Vertical airspaces with heat-flow horizontal
For the full range of effective emittances, Figure 2 shows the effect of the aspect ratio ($A_R$) on the R-values of vertical single-airspace with heat-flow horizontal. The corresponding results for double-airspaces are provided in Figure 3. Note that the effect of the aspect is not accounted for in the available methods for determining the R-values of enclosed airspaces based on ISO 6946 [8] and ASHRAE [4-5]. As shown in Figure 2 and Figure 3, the R-value increases significantly with increasing the aspect ratio (i.e., H) for low effective emittances. For high effective emittances, however, the R-value increases are insignificantly with increasing aspect ratio. The R-value lines for different aspect ratios tend to converge as the effective emittance tends to 0.82. For example, for single-airspaces at low effective emittances of 0.03 or 0.05, respectively, the R-value increases by 97% and 89% with increasing the aspect ratio from 1.1 (H = 102 mm at which R-value = 0.328 and 0.319 m$^2$·K/W, respectively) to 26.6 (H = 2,362 mm at which R-value = 0.646 and 0.602 m$^2$·K/W, respectively). At effective emittance of 0.05, HRP 32 R-value (0.446 m$^2$·K/W [3]) overestimated the R-value by 40% at aspect ratio of 1.1 and underestimated the R-value by 26% at aspect ratio of 26.6 (Figure 2). Similarly, for double-airspace at low effective emittance of 0.03 and 0.05, respectively, Figure 3 shows that the R-value increases by 50% and 46% with increasing the aspect ratio from 2.3 (H = 406 mm at which R-value = 0.912 and 0.870 m$^2$·K/W, respectively) to 53.1 (H = 2,362 mm at which R-value = 1.365 and 1.272 m$^2$·K/W, respectively). At effective emittance of 0.05, HRP 32 R-value (1.088 m$^2$·K/W [3]) overestimated the R-value by 25% at aspect ratio of 2.3 and underestimated the R-value by 14% at aspect ratio of 53.1.

3.4.2. Horizontal airspaces with heat-flow down
With heat-flow down, Figure 4 and Figure 5 show the effect of the aspect ratio on the R-values of horizontal single-airspace and double-airspaces, respectively. These figures show that the R-value increases significantly with increasing the aspect ratio for the range of low effective emittance ($\varepsilon_{\text{eff}} < 0.2$). However, for the range of high effective emittance ($\varepsilon_{\text{eff}} > 0.3$), unlike the case of heat-flow horizontal, the aspect ratio has approximately no effect on the R-values for the case of heat-flow down, where all R-value lines of different aspect ratios tend to converge as the effective emittance tends to 0.3. Figure 4 shows that for single-airspaces at effective emittance of 0.03 or 0.05, the R-value increases by 124% and 96% with increasing the aspect ratio from 1.1 (H = 102 mm at which R-value = 0.852 and
0.796 m²·K/W, respectively) to 26.6 (H = 2,362 mm at which R-value = 1.906 and 1.560 m²·K/W, respectively). At low effective emittance of 0.05, HRP 32 R-value (1.272 m²·K/W [3]) overestimated the R-value by 60% at aspect ratio of 1.1 and underestimated the R-value by 19% at aspect ratio of 26.6.

Figure 2. Comparisons of R-values of HRP 32 [3], ISO 6946 [8] with present model predictions of various A_R for single-airspace with heat-flow horizontal (θ = 90°).

Figure 3. Comparisons of R-values of HRP 32 [3] with present model predictions of various A_R for double-airspaces with heat-flow horizontal (θ = 90°).

Figure 4. Comparisons of R-values of HRP 32 [3], ISO 6946 [8] with present model predictions of various A_R for single-airspace with heat-flow down (θ = 0°).

Figure 5. Comparisons of R-values of HRP 32 [3] with present model predictions of various A_R for double-airspaces with heat-flow down (θ = 0°).
Figure 6. Comparisons of R-values of HRP 32 [3], ISO 6946 [8] with present model predictions of various $A_R$ for single-airspace with heat-flow up ($\theta = 0^\circ$).

For double-airspace at low effective emittance of 0.03 and 0.05, respectively, Figure 5 shows that the R-value increases by 17% and 14% with increasing the aspect ratio from 2.3 ($H = 406$ mm at which R-value = 2.163 and 1.928 m$^2$K/W, respectively) to 53.1 ($H = 2,362$ mm at which R-value = 2.548 and 2.196 m$^2$K/W, respectively). At effective emittance of 0.05, the HRP 32 R-value (2.108 m$^2$K/W [3]) overestimated the R-value by 9% at aspect ratio of 2.3 and underestimated the R-value by only 4% at aspect ratio of 53.1.

3.4.3. Horizontal airspaces with heat-flow up

With heat-flow up, Figure 6 and Figure 7 show the effect of the aspect ratio on the R-values of horizontal single-airspaces and double-airspaces, respectively. For a 15 aspect ratio values for a single-airspace, Figure 6 shows that the R-value changes significantly with changing the aspect ratio for the full range of the effective emittance ($0 - 0.82$). For a given $\varepsilon_{eff}$ within the low range of effective emittance ($\varepsilon_{eff} < 0.12$), the highest R-value occurred for $A_R$ of 17.1 ($H = 1,524$ mm), whereas the lowest R-value occurred for $A_R$ of 1.7 ($H = 152$ mm). On the other hand, for a given $\varepsilon_{eff}$ within the high range of effective emittance ($\varepsilon_{eff} > 0.3$), the highest R-value occurred for $A_R$ of 1.1 ($H = 102$ mm), whereas the lowest R-value occurred for $A_R$ of 27.4 ($H = 2,438$ mm).

For three values of the aspect ratio for the double-airspaces, Figure 7 shows that the R-value changes with the aspect ratio within the low range of the effective emittance ($\varepsilon_{eff} < 0.3$). In this effective emittance range, the highest R-value occurred for $A_R$ of 34.3 ($H = 1,524$ mm), whereas the lowest R-value occurred for $A_R$ of 9.1 ($H = 406$ mm). However, within the high range of the effective emittance ($\varepsilon_{eff} > 0.3$), the R-values were approximately independent on the aspect ratio, and these values were in good agreements with the HRP 32 R-values [3].

4. Concluding remarks

In this paper, numerical simulations were conducted to predict the thermal resistance (R-value) of vertical and horizontal single- and double-airspaces of different aspect ratios for the full range of effective emittance ($0 - 0.82$) when these airspaces were subjected to heat-flow horizontal, up, and down. Consideration was given to the effect on calculated R-values of accounting for the heat transfer.
by radiation at the two ends that represent the surfaces of the framing of the airspaces. The calculated R-values were compared with earlier one-dimensional methods for determining the R-values of enclosed airspaces based on ISO 6946 and HRP 32. The outcome of this paper showed that the aspect ratio of the enclosed airspace has a significant effect on R-value. For airspaces with heat flow horizontal and down, the results show that increasing the aspect ratio results in significant increases in the R-value for the low range of the effective emittances, whereas at high range of effective emittances, the R-value increase is insignificant with increasing the aspect ratio. For single-airspaces with heat-flow up, however, the results show that the R-value changes significantly with change in the aspect ratio for the full range of the effective emittances. As well, for only three values of the aspect ratio for double-airspaces, the results showed that the R-value changes with changing the aspect ratio within the low range of the effective emittance; whereas within the high range of the effective emittance, the R-values are not strongly dependent on the aspect ratio, and these values were in good agreements with the HRP 32 R-values. Finally, this paper showed that depending on the value of the effective emittance, the R-value could be doubled by incorporating a thin sheet with low-e on both sides positioned in the middle of the enclosed airspace perpendicular to the direction of heat flow.

References
[1] Goss WP and Miller RG 1989 Literature review of measurements and predictions of reflective building insulation systems performance: 1900-1986 ASHRAE Transactions 95 (2) 651-664.
[2] Stephan K and Laesecke A 1985 The thermal conductivity of fluid air J. of Physical and Chemical Reference Data 14 (1) 227-234.
[3] Robinson HE and Powell FJ 1956 The thermal insulation value of air spaces Housing Research Paper 32 (HRP 32) National Bureau of Standards Project ME-12, USA.
[4] ASHRAE Handbook of Fundamentals 1972 Design heat transmission coefficients, Chapter 20.
[5] ASHRAE Handbook of Fundamentals 2017 Heat, air, and moisture control in building assemblies-material properties, Chapter 26 -Table 3.
[6] Desjarlais AO and Tye RP 1990 Research and development data to define the thermal performance of reflective materials used to conserve energy in building applications, Oak Ridge National Laboratory Report ORNL/Sub/88-S9825/1.
[7] Desjarlais AO and Yarbrough DW 1991 Prediction of the thermal performance of simple and multi-airspaces reflective insulation materials, Insulation Materials: Testing and Applications, 2nd Volume, ASTM STP 1116, R.S. Graves and D.C. Wysoci, eds., American Society for Testing and Materials, pp. 24-43.
[8] ISO 6946:2017 Building components and building elements-Thermal resistance and thermal transmittance-calculation methods-Annex D-Thermal resistance of airspaces.
[9] Saber HH 2012 Investigations of thermal performance of reflective insulations for different applications Buildings and Environment 55, 32-44.
[10] Saber HH, Maref W and Hajiah AE 2020 Effective R-value of enclosed reflective air spaces for different building applications J. Building Physics 43 (5) 398-427.
[11] RIMA International 2020 Be our zoom guest for Dr. Hamed Saber November 5th. 2020, https://rimainternational.org/news/press-room/09-20-be-our-zoom-guest-for-dr-hamed-saber-november-5th/. Last visited in April 2021.
[12] Saber HH, Maref W, Sherrer G and Swinton MC 2012 Numerical modeling and experimental investigations of thermal performance of reflective insulations J. of Build. Phys. 36(2), 163-177.
[13] Saber HH, Maref W, Swinton MC and St-Onge C 2011 Thermal analysis of above-grade wall assembly with low emissivity materials and furred-airspace Build. & Envir. 46(7), 1403-1414.
[14] Saber HH 2013 Thermal performance of wall assemblies with low emissivity J. of Build. Phys. 36 (3), 308-329.
[15] ASHRAE Handbook of fundamentals 2009 Heat, air, and moisture control in building assemblies material properties, Chapter 26.
[16] Yam KW, Teh KS, Loi P and Yarbrough DW 2020 Reflective insulation assemblies for above-ceiling applications J. of Build. Phys. 44(3), 272-283.