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Practical correlations for the thermal resistance of vertical enclosed airspaces for building applications

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ABSTRACT

Many parts of the building envelope contain enclosed airspaces. 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. The 2009 ASHRAE Handbook of Fundamentals (Chapter 26) provides a table that contains the *R*-values for an enclosed airspace. The ASHRAE table is extensively used by modelers, architects and building designers in the design of building enclosures. This table provides *R*-values for enclosed airspaces for different values of the thickness of the airspace, effective emittance, mean airspace temperature, and temperature differences across the airspace. The effect of the airspace aspect ratio (height/thickness of airspace) on the *R*-value is not included in the ASHRAE table. However, in a recent study on the *R*-value of reflective insulations using a numerical simulation model, it was shown that the aspect ratio of the airspace can affect the *R*-value of the enclosed airspace. The numerical simulation model used in this study had been benchmarked against experimental data obtained using two standard test methods: ASTM C-518 and ASTM C-1363.

In this paper, a numerical simulation study was conducted, that was based on previous work focused on enclosed airspaces, to investigate the effect of the aspect ratio on the *R*-value of vertical enclosed airspaces of different thicknesses and having a wide range of values for effective emittance, mean temperature, and temperature differences across the airspace. The *R*-values predicted from numerical simulation are compared with those provided in the ASHRAE table. Considerations were also given to investigating the potential increase in *R*-values of enclosed airspaces when a thin sheet is placed vertically in the middle of the airspace and whose surfaces have different values of emissivity. Finally, practical correlations are developed for determining the *R*-values of an enclosed airspace for future use by modelers, architects and building designers. The simplicity of these correlations suggests that these could be included in the ASHRAE Handbook of Fundamentals.

1. Introduction

The design of building envelope roof 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 [1,2]. A straightforward means of reducing building operating costs is to limit heat transmission and thus energy loss through the building envelope. This evidently can be achieved by increasing the thermal resistance (*R*-value) of the building envelope. Reflective Insulation (RI) products are widely used in both space as well as terrestrial applications, for example, in building construction. For applications in building construction, and in accordance with installation guidelines of the Reflective Insulation Manufacturers Association International (RIMA-I) [3], RI products have at least one reflective surface facing an airspace. As well, RI products are typically being used in conjunction with mass insulation products, such as glass fiber, expanded polystyrene foam (EPS), and other similar insulation products. Reflective Insulation products can be installed in wall cavities, between ceiling and floor joists, to provide radiant energy barriers, and in metallic buildings that cannot readily accommodate loose-fill or batt-type insulations. Furthermore, 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 [4].

An enclosed airspace contributes to the overall thermal resistance of a system whether or not a product having a reflective surface is installed in the system. However, it is known that the

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presence of a reflective surface augments the thermal resistance of that airspace [5–13]. The contribution of the reflective insulation on the thermal performance (*R*-values and energy savings) of above-grade, and above- and below-grade wall systems having a Furred-Airspace Assembly (FAA) have been investigated for which the results are available in a number of publications [7,9–13]. In the wall systems described in these studies, a low emissivity foil material was installed within the furred-airspace assembly.

The thermal resistances (*R*-values) of enclosed airspaces were calculated by many investigators (e.g. see [14–17]) for various orientations of airspaces and reflective boundaries by using heat transfer coefficient data that was published by Robinson et al. [15–17]. The heat transfer coefficient data were obtained from measurements of panels of different thicknesses (0.625–3.375 in (15.9–85.7 mm)) using the test method described in ASTM 236-53 [18]. In those studies, the steady-state heat transmission rates were corrected for the heat transfer occurring along parallel paths between the 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.

Generally, the value for the effective heat conductance, *U*-value (the reciprocal of the *R*-value), of an enclosed space (e.g. airspace) between two parallel planes depends on the physical properties of the gas, the temperature and emissivity of all the surfaces of the space, temperature differences across the space, the dimensions of the space, the direction of heat transfer through the space and the orientation of the space. The *U*-value accounts for the contribution of heat transfer in the enclosed space due to heat transfer by conduction, convection and radiation.

In the absence of heat transfer by radiation, the contribution of heat transfer due to convection in an enclosed space is normally given in terms of the Nusselt number, Nu ($\mathrm{Nu} = h\delta/\lambda$, where h is convective heat transfer coefficient, δ is the thickness of the space, and λ is the thermal conductivity of the fluid filling the space). According to many authors [19,20], the convective heat transfer coefficient for an enclosed space can be given as:

$$\mathrm{Nu} = h\delta/\lambda = a(\mathrm{Gr}\cdot\mathrm{Pr})^b A_\mathrm{R}^c = a(\mathrm{Ra})^b A_\mathrm{R}^c, \text{ and } \mathrm{Gr} = g\beta\rho^2\delta^3\Delta T/\mu^2. \tag{1}$$

where the coefficients a, b and c in Eq. (1) are dimensionless constants, derived from experiments, A_R is the aspect ratio of the enclosed space (A_R = height (H)/thickness (δ)), Gr is the Grashoff number, Ra is the Raleigh number ($\mathrm{Ra} = \mathrm{Gr} \times \mathrm{Pr}$), and Pr is the Prandtl number. In order to derive the coefficients a, b and c (Eq. (1)), from which the heat transfer coefficient, h, due to the convective component of heat transfer can be determined, the emissivity of all surfaces that bound the enclosed space must be zero (i.e. purely reflective surfaces). However, it is not possible in practice, to use materials having zero emissivity when conducting such experiments. Hence, to derive the coefficients a, b and c of Eq. (1) from experiments, as mentioned previously, the rate of radiative heat transfer across the enclosed space would be subtracted from the total rate of heat transfer across the space.

A number of correlations for the value of Nu in the form of the relationship given in Eq. (1) and for different ranges of values of Ra, A_R and Pr are provided in several studies as described in the IEA Annex XII report [19]. Some of these correlations showed the dependence of the Nu on the aspect ratio of the enclosed space (A_R). As such, it is anticipated that the effective thermal conductance or the effective thermal resistance of the enclosed space would be affected by the aspect ratio of the space, as will be shown later in this study.

Yarbrough [4] developed a one-dimensional, steady-state model, called "REFLECT" to provide *R*-values of reflective assemblies and 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. The model was used to calculate the *R*-values using the heat transfer coefficients derived by Robinson [15–17] 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 of the enclosed airspace [4].

The 2009 ASHRAE Handbook of Fundamentals (Chapter 26) [14] 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. [15–17]. These values were obtained by combining the convective and radiative components of heat transfer from which the total thermal resistance value for an enclosed airspace was provided for airspaces of different thickness (δ = 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 (ΔT = 5.6, 11.1 and 16.7 °C), effective emittance (ε_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 [14]:

$$1/\varepsilon_\mathrm{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1, \tag{2}$$

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

The ASHRAE table [14] is being used extensively by modelers, architects and building designers. 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 [14].

2. Model descriptions and benchmarking

The NRC's hygrothermal model "hygIRC-C" was used in this study to predict the *R*-values of vertical enclosed airspaces having different ε_eff and subjected to wide ranges of T_avg and ΔT. This model solves simultaneously the 2D and 3D moisture transport equation, the energy equation, the surface-to-surface radiation equation (e.g. the surface-to-surface radiation in the enclosed airspace, an example is provided in Fig. 1) and the air transport equation in the various material layers. The air transport equation is the Navier–Stokes equation for the airspace layers (e.g. air cavities), and the Darcy equation (Darcy Number, DN $<10^{-6}$) and Brinkman equation (DN $>10^{-6}$) for the porous material layers. The present model was benchmarked [27] against the hygIRC-2D model previously developed at NRC [28,29], and against experimental results from the evaluation of a number of different wall assemblies. A full description of the present model is available in previous publications (see references [1,2,6–13,24–27]).

In building applications that are similar to this study, the present model was benchmarked against thermal performance data for a wall assembly featuring a reflective insulation product. The data was obtained using a Guarded Hot Gox (GHB) (in accordance with ASTM C-1363 test method [21]) for a full-scale (8 ft × 8 ft) above-grade wall system. This wall featured 2 × 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.