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Greenhouse Covering Material Overall Heat-transfer Coefficient Determination Using Contour Plots

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Abstract. **Improving greenhouse heat-insulating performance requires covering materials with low overall heat-transfer coefficients. We constructed a contour plot using equations relating this coefficient to longwave radiation absorptance under different outdoor downward longwave radiation levels. It revealed that the coefficient ranged from 4.7 to 7.7 W·m^{-2}·K^{-1}, decreasing with increasing downward longwave radiation and longwave radiation absorptance. This method facilitates rapid estimation of overall heat-transfer coefficients under different downward longwave-radiation levels, based on longwave-radiation absorptance.**

Owing to recent global increases in utility costs, covering materials with good heat-insulating performance must be developed to reduce greenhouse heating-energy consumption in winter. The overall heat-transfer coefficient (in W·m^{-2}·K^{-1}) is used as an indicator of the heat-insulation performance of covering materials. Development of covering materials, including glass and plastic films, with lower overall heat-transfer coefficients will facilitate reductions in greenhouse heating-energy consumption in winter, thus improving energy conservation and supporting decarbonization. In this process, such materials must be rapidly selected from among many material types.

The overall heat transfer coefficient has been evaluated using the hot-box and greenhouse methods (Geoola et al. 2011; Ohashi et al. 2023; Zhang et al. 1996). A hot-box is used to simulate the conditions inside and outside a greenhouse. Heat-balance analysis is then applied to the data obtained using the hot-box method to calculate how much heat passes through the covering material. In the greenhouse method, the greenhouse is heated under the target covering material during nighttime in winter, and heat-balance analysis is used to calculate the overall heat-transfer coefficient of the material. Using both methods, several hours to several days are required to calculate the overall heat-transfer coefficient, making rapid evaluation of heat insulation for multiple sample materials difficult.

We have used the hot-box method to determine the relationship between longwave radiation (4 to 60 μm) absorptance and the overall heat-transfer coefficient of various covering materials under different downward longwave-radiation levels (Ohashi et al. 2023). Details of the study are given subsequently. To estimate this coefficient and evaluate heat-insulation performance simply and intuitively, we developed a contour plot of downward longwave radiation against the longwave radiation absorptance of the covering material. However, because the values measured using the hot-box are sensitive to slight environmental disturbances, they exhibited variability, and the resulting contour plot produced inconsistent estimates and was impractical to apply. For a transparent covering material, both higher longwave-radiation absorptance and higher downward longwave radiation are associated with a lower overall heat-transfer coefficient. However, considering that opposite trends were produced in different parts of the resulting contour plot, it could not easily be used to evaluate heat-insulating performance.

To address this, we aimed to develop a contour plot that facilitates simple estimation of the overall heat-transfer coefficient, using the equations relating longwave radiation absorptance to the overall heat-transfer coefficient for various downward longwave radiation levels developed by Ohashi et al. (2023).

Materials and Methods

We first prepared the equations (Ohashi et al. 2023) relating longwave radiation absorptance to the overall heat-transfer coefficient for various downward longwave radiation levels (212, 237, 256, 276, and 297 W·m^{-2}) (Table 1). These downward longwave radiation levels represent clear to cloudy winter nights. In addition, those equations were created using the following materials: 3 mm glass, 0.1 mm polyolefin, 0.1 mm fluorocarbon resin, 0.05 mm PVC, 0.075 mm polyvinyl acetate, and 0.05 mm polyethylene, which have different longwave radiation absorptance. We assumed that these equations can be used to generate a contour plot to estimate the overall heat-transfer coefficient.

To calculate k (the overall heat-transfer coefficient), we assigned ε (longwave radiation absorptance; Table 1) values from 0.0 to 1.0, in increments of 0.1. As the dataset for contour plotting, we used 55 combinations of d (downward longwave radiation), ε, and k. The final dataset, comprising the d and ε values along with the k values calculated using the equations, was used to generate the contour plots in Surfer mapping software (Golden Software, Golden, CO, USA), using kriging interpolation. The x-axis of the contour plot represents longwave radiation absorptance and the y-axis downward longwave radiation. The overall heat-transfer coefficients are represented by color coding.

Results and Discussion

Obtaining covering materials with lower overall heat-transfer coefficients will reduce greenhouse heating-energy consumption in winter. We therefore developed a simple contour-plot method to estimate this coefficient using equations developed by Ohashi et al. (2023) (Table 1).

On the basis of the contour plot (Fig. 1), the overall heat-transfer coefficients ranged from 4.7 to 7.7 W·m^{-2}·K^{-1}, declining with increasing downward longwave radiation and longwave radiation absorptance. The contour plot exhibited no contradictory results. The contour plot is therefore appropriate for estimating the overall heat-transfer coefficient. To generate the plot, it is necessary to measure longwave radiation absorptance, which takes a few minutes using an emissivity meter (Ohashi et al. 2023, 2024). Using the contour plot, the overall heat-transfer coefficient can thus be rapidly estimated under different downward longwave radiation conditions. In addition, the wind speed above and below the material in the hot box used when creating equations shown in Table 1 was from 0.02 to 0.12 m·s^{-1}, which was almost windless (Ohashi et al. 2024). Therefore, the overall heat transfer coefficient obtained from the contour plot drawn in this study is under almost windless conditions.

It has been established that the overall heat transfer coefficient is strongly related to longwave radiation absorptance (Ohashi et al. 2023). However, it is also slightly affected by physical properties such as thickness and thermal conductivity. Therefore, the hot-box method should

Table 1. Equations relating longwave radiation absorptance to the heat-transfer coefficient.

d (W·m^{-2})	Equation
212	$k = -2.1907\varepsilon^2 - 0.327\varepsilon + 7.6481$
237	$k = -1.8327\varepsilon^2 - 0.6727\varepsilon + 7.6007$
256	$k = -2.243\varepsilon^2 - 0.0817\varepsilon + 7.279$
276	$k = -1.7623\varepsilon^2 - 0.5816\varepsilon + 7.2107$
297	$k = -1.2413\varepsilon^2 - 0.8493\varepsilon + 6.7915$

d = downward longwave radiation; k = overall heat-transfer coefficient; ε = longwave radiation absorptance (range: 0.0 to 1.0, increments: 0.1). These equations were developed by Ohashi et al. (2023).

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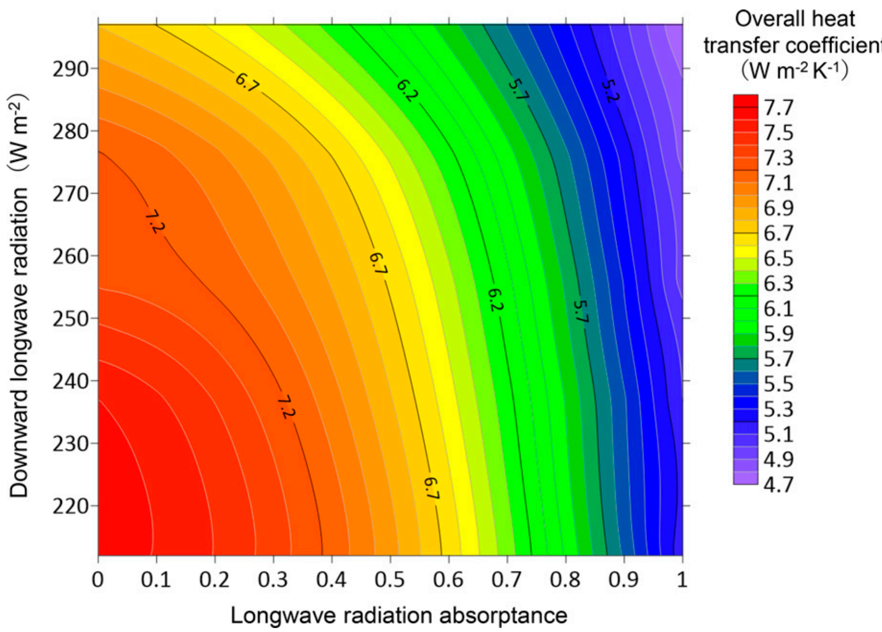

Fig. 1. Relationship between longwave radiation absorptance and overall heat-transfer coefficient under different levels of winter nighttime downward longwave radiation. Kriging interpolation was used.

be used to measure the overall heat transfer coefficient more accurately. Hence, we considered that when the number of samples is small, the hot-box method is suitable to measure the overall heat transfer coefficient, and when the number of samples is large, the simple estimation using the contour plot is ideal in the material development process.

Infrared absorbers, such as glass fillers, are used to improve the heat insulation performance of covering materials (Egami 1990). However, it is time-consuming to determine the appropriate amount of infrared absorber required. The method presented here makes rapid estimation of the overall heat-transfer coefficient of a covering material. This will therefore accelerate the development of covering materials with low overall heat-transfer coefficients. Moreover, the overall heat-transfer coefficient of the covering material directly affects energy consumption during greenhouse heating in winter. The method developed here will therefore help in selecting materials with better heat insulation performance and thus in reducing greenhouse heating energy consumption.

Although the overall heat-transfer coefficients for each covering material are listed in educational textbooks, these tables do not provide the relevant downward longwave radiation conditions. The method presented here thus has educational value because it facilitates an intuitive understanding of how downward longwave radiation and the longwave radiation absorptance of the covering materials affect the overall heat-transfer coefficients.

Using equations relating longwave radiation absorptance to the overall heat-transfer coefficient under different downward longwave radiation conditions, we generated a contour plot that facilitates estimation of the overall heat-transfer coefficient. This will accelerate the development of covering materials with better heat-insulating performance and support decarbonization by improving energy efficiency.

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