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Theoretical and experimental research on the additional thermal resistance of a built-in curtain on a glazed window

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ABSTRACT

To reduce the heat loss at night and prevent room overheating in the summer, almost all outside glazed windows are installed with a built-in curtain. However, given the abnormal structure and complex heat transfer process of the built-in curtain, the existing heat load calculation method is generally employed only to consider the heat transfer coefficient of the glazed window, and the thermal resistance of the built-in curtain is ignored. At present, a perfect theoretical analysis model and accurate data for the curtain thermal resistance are still lacking. Therefore, a reasonable, simplified physical model of the built-in curtain is proposed in this paper, and the flow and heat transfer characteristics of the simplified model are analyzed. In addition, the model gives comparatively full consideration to the influence of the fold on the curtain thermal resistance. A method for the calculation of the additional thermal resistance of the curtain is presented. The additional thermal resistance values and the optimal installation thickness for various types of curtains are obtained by analysis and calculation. The results show that the range of the optimal installation is from 0.05 to 0.08 m. The minimal and maximal percentages of the curtains additional thermal resistance to the total thermal resistance of the window are 25.9% and 73.8%, respectively. The ranges of the percentage for single curtain and double curtains are 25–60% and 45–75%, respectively. Finally, the rationality of the simplified model and the accuracy of the calculation results are verified through experiments.

1. Introduction

Although a large, south facing, transparent structure can increase the solar radiation in daylight in the winter, it also contributes the primary component of a room's heat load at night [1,2]. To simultaneously satisfy the requirements of heat gain in the daylight and heating insulation at night, installing a built-in curtain is quite important. However, given the abnormal structure and the complex heat transfer process of a built-in curtain, the existing heat load calculation method generally only considers the heat transfer coefficient of the glazed window and ignores the additional thermal resistance of the built-in curtain [3]. Therefore, there are a number of errors in the existing transparent structure heat load calculation method.

Many researchers have attempted to study the thermal performance of built-in curtains [4–10]. Chen [11] presented an estimated value of the curtain thermal resistance and concluded that the single layer glass window heat transfer coefficient could decrease by 25% when a built-in curtain is installed and that the double layer glass window heat transfer coefficient could decrease by 15%. However, this estimation does not specify the forms of the curtain and the window.

Fang and Ge [12] and Fang [13] studied the heat transfer coefficient of the outside window with the curtain by means of experiments. The formula for the curtain thermal resistance is obtained under the condition that the upper and lower sections of the curtain are closed and under the relaxed conditions. The relationship between the closed curtain thermal resistance and the relaxed curtain thermal resistance is also given. The research of the ASHRAE Handbook [14] and Reilly et al. [15] has shown that the curtain thermal resistance is related to the indoor and outdoor air temperatures, the internal and external surface temperatures of the curtain, and the temperature of the curtain itself. Chen [16] proposed a formula to calculate the air layer thermal resistance. To make the calculation more convenient, the thermal convection and radiation of the limited space are handled as a heat conduction process. However, this study considers a closed air layer, and it is thus impossible to define the flow state from the formula.

Verde [17] introduced a closed air layer heat transfer coefficient formula that covers the air layer between the air convection and

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Nomenclature

a	thermal diffusion coefficient (m^2/s).
C_0	black body radiation coefficient ($W/(m^2\,K^4)$)
d_1	thickness of the first curtain (m)
d_2	thickness of the second curtain (m)
d_g	thickness of the window glass (m)
F	effective area of the window (m^2)
Gr	Grashof number
g	gravitational acceleration (m/s^2)
H	height of the curtain (m)
K_w	total heat transfer coefficient of the window ($W/(m^2\,K)$)
n	ratio of expanded area to folded area
Nu	Nusselt number
Pr	Prandtl number
R_0	sum of the window glass thermal resistance and the outside surface thermal resistance ($(m^2\,K)/W$)
R_c	internal surface thermal resistance of the curtain ($(m^2\,K)/W$)
R_g	thermal resistance of the window itself ($(m^2\,K)/W$)
R_1	thermal resistance of the first curtain ($(m^2\,K)/W$)
R_2	thermal resistance of the second curtain ($(m^2\,K)/W$)
R_{I}	thermal resistance of the first air layer ($(m^2\,K)/W$)
R_{II}	thermal resistance of the second air layer ($(m^2\,K)/W$)
t_a	indoor air temperature (°C)
T_{am}	average radiation temperature of the other internal surfaces (K)
t_c	internal surface temperature of the curtain (°C)
t_w	outdoor air temperature (°C)
t_1	air temperature of the first layer (°C)
t_2	air temperature of the second layer (°C)
t_1'	one surface temperature of the first layer (°C)
t_1''	another surface temperature of the first layer (°C)
t_2'	one surface temperature of the second layer (°C)
t_2''	another surface temperature of the second layer (°C)

Greek symbols

α_a	internal surface heat transfer coefficient of the glass window without a curtain ($W/(m^2\,K)$)
α_w	window exterior surface heat transfer coefficient ($W/(m^2\,K)$)
α_c	coefficient of the convective heat transfer of the curtain internal surface ($W/(m^2\,K)$)
α_r	coefficient of the radiation heat transfer of the curtain internal surface ($W/(m^2\,K)$)
α_c'	convective heat transfer coefficient of the air layer surface ($W/(m^2\,K)$)
α_r'	radiation heat transfer coefficient of the air layer surface ($W/(m^2\,K)$)
β	expansion coefficient (1/K)
δ	curtain air layer average thickness (m)
δ_d	corresponding air layer average thickness of the laminar and turbulent parting (m)
δ_o	optimal curtain air layer thickness (m)
δ_1	average thickness of the first air layer (between the glass and the first curtain) (m)
δ_2	average thickness of the second air layer (between the two curtains) (m)
λ	air thermal conductivity ($W/(m\,K)$)
λ_1	heat conductivity coefficient of the first curtain ($W/(m\,K)$)
λ_2	heat conductivity coefficient of the second curtain ($W/(m\,K)$)
λ_g	thermal conductivity coefficient of the window glass ($W/(m\,K)$)
ν	coefficient of kinematic viscosity (m^2/s)
ε	air layer surface system emissivity

Subscripts

a	indoor air
w	outdoor air
c	convection
r	radiation
g	glass
o	optimal
I	the first air layer
II	the second air layer

heat conduction processes but ignores the influence of the air layer surface radiation heat transfer. The above research is generally in accordance with the enclosed air layer and does not consider the influence of the curtain fold on the thermal resistance.

In this paper, the flow and heat transfer characteristics of the built-in curtain are studied firstly, and a calculation method for the additional thermal resistance of the built-in curtain is proposed. Second, the additional thermal resistance values and the optimal install thickness of commonly used types of curtains are obtained. Finally, the rationality of the simplified model and the accuracy of the calculation results are verified by experiments. The research results provide the theoretical basis for the heat transfer of the window and its installation position.

2. The simplified physical model

Given the additional thermal resistance of the curtain as the corrected result of the window thermal resistance, a quasi steady state calculation method is adopted. The basic assumptions are the following:

(i) The influence of the temperature change on the curtain thermal resistance is ignored.
(ii) It is believed that the curtain maintains an approximately vertical position, and the vertical fold of the curtain is ignored.
(iii) The horizontal fold of the curtain is not ignored.
(iv) The additional thermal resistance of the curtain is constant.

The simplified physical model of a single layer glass window with double curtains is shown in Fig. 1. The thermal network model is shown in Fig. 2.

The terms t_a and t_w are the indoor and outdoor air temperatures respectively in °C, δ_1 and δ_2 are the average thicknesses of the first air layer (between the glass and the first curtain) and the second air layer (between the two curtains) respectively in m; t_1 and t_2 are the air temperature of the first and second layer, respectively (°C); t_1' and t_1'' are the two surface temperatures of the first layer in °C; t_2' and t_2'' are the two surface temperatures of the second layer in °C; And t_c is the internal surface temperature of the curtain in °C. All of the R values are the various thermal resistances in $(m^2\,K)/W$.

R_0 is the sum of the window glass thermal resistance and the outside surface thermal resistance in $(m^2\,K)/W$ given by the following equation:

$$R_0 = R_g - \frac{1}{\alpha_a} \tag{1}$$