HEAT TRANSFER OF EXTERNAL BUILDING ENVELOPES

by

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Three outdoor boundary conditions are considered for heat transfer of external building envelopes. Comparison with other models in open literature reveals significant advantage of the present model, which can be used for optimal design of indoor climate.

Key words: two periodic waves, sol-air temperature, dry-bulb temperature

Introduction

Outdoor boundary condition will greatly affect the thermal transfer of building envelope. In various literature, either dry-bulb temperature [1, 2] or sol-air temperature [3, 4] was adopted, however, either of the boundary conditions can not exactly describe the real problem, resulting in much error in the theoretical prediction of indoor climate. To overcome the problem, a new treatment on the boundary conditions is proposed.

Methodology

In order to illustrate how to suitably incorporate a boundary condition during indoor climate design, we consider a building envelope with 100 mm reinforced concrete structure toward the south with thermal conductivity.

toward the south, with thermal conductivity $\lambda = 1.54$ W/mK, heat transfer coefficient K = 4.48 W/m², thermal diffusivity a = 0.00275 m²/h, direct radiation absorption rate of the structure outer surface $\alpha_{\rm D} = 0.40$, diffuse radiation absorption rate of the structure outer surface $\alpha_{\rm d} = 0.94$, outer surface heat transfer coefficient $h_0 = 23.0$ W/m²K, and inner surface heat transfer coefficient $h_{\rm i} = 8.7$ W/m²K. The temperature inside the structure is constant 18 °C in winter, and constant 28 °C in summer. The

Table 1.	Damping factor	and detention period
for each	order harmonic	wave

Order	Frequency	Damping factor	Detention period	
			rad	h
1	Pi/12	2.25	2.48	9.49
2	Pi/6	3.02	2.02	7.72
3	Pi/4	4.01	1.71	6.51

damping factor and period delay of the reinforced concrete structure for each order harmonic wave, calculated by MATLAB software, are shown in tab. 1.

The damping factor and detention period of structure are only connected with its own material, but have nothing with boundary conditions. How to incorporate the real boundary conditions into indoor climate design becomes a challenging issue on thermal science.

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Three outdoor periodic waves

Take Xi'an city of China for instance. The dry-bulb temperature, normal direct radiation and level diffuse radiation in summer sunny days, and winter sunny days can be obtained, and their average values can be easily calculated. The vertical wall receives solar radiation, which should be conversed to equivalent temperature by the method of thermal equilibrium. The formula can be expressed as:

$$t_s = \frac{\alpha_{\rm D} I_{\rm VD} + \alpha_{\rm d} I_{\rm Vd}}{h_{\rm o}} \tag{1}$$

where I_{VD} and I_{Vd} [Wm⁻²] are the direct radiation and the diffuse radiation received by outer surface of the envelope, respectively, α_D and α_d – the direct radiation absorption rate, and the diffuse radiation absorption rate of the envelope outer surface, separately, and h_0 [Wm⁻²K⁻¹] – the convection heat transfer coefficient at the outer surface of the envelope.

The first three Fourier sine series of outdoor dry-bulb temperature in winter are:

$$t_{\rm a} = 4.06 + 5.02 \sin\left(\frac{\pi}{12}\tau + 3.82\right) + 1.54 \sin\left(\frac{\pi}{6}\tau + 1.04\right) + 0.07 \sin\left(\frac{\pi}{4}\tau + 4.50\right)$$
(2)

The Fourier sine series of solar radiation equivalent temperature in winter is:

$$t_{\rm s} = 2.50 + 4.14\sin\left(\frac{\pi}{12}\,\tau + 4.61\right) + 2.23\sin\left(\frac{\pi}{6}\,\tau + 1.36\right) + 0.53\sin\left(\frac{\pi}{4}\,\tau + 4.38\right) \tag{3}$$

The Fourier sine series of sol-air temperature in winter can be expressed as:

$$t_{\rm as} = 6.56 + 8.46 \sin\left(\frac{\pi}{12}\,\tau + 4.18\right) + 3.72\,\sin\left(\frac{\pi}{6}\,\tau + 1.23\right) + 0.60\,\sin\left(\frac{\pi}{4}\,\tau + 4.39\right) \tag{4}$$

The Fourier sine series of outdoor dry-bulb temperature in summer can be written:

$$t_{\rm a} = 25.6 + 5.3 \sin\left(\frac{\pi}{12}\tau - 2.48\right) \tag{5}$$

The Fourier sine series of outdoor solar radiation equivalent temperature in summer

$$t_{\rm s} = 4.14 + 6.62\sin\left(\frac{\pi}{12}\tau + 4.58\right) + 2.15\sin\left(\frac{\pi}{6}\tau + 1.31\right) + 0.38\sin\left(\frac{\pi}{4}\tau + 1.24\right) \tag{6}$$

The Fourier sine series of outdoor solar radiation equivalent temperature in summer

$$t_{\rm as} = 29.74 + 11.04 \sin\left(\frac{\pi}{12}\,\tau + 1.09\,\right) + 2.15 \sin\left(\frac{\pi}{6}\,\tau + 1.31\,\right) + 0.38 \sin\left(\frac{\pi}{4}\,\tau + 1.24\,\right) \tag{7}$$

Superimposing the two periodic waves eq. (2) and eq. (3) into one wave, it is the same to eq. (4). While superimposing eq. (5) and eq. (6) into one wave, it is the same to eq. (7). It shows that, no matter in winter or in summer, the two superimposed periodic waves before thermal transmission is the same to sol-air temperature but rounding errors. That is to say, the coefficients of the same frequency with different initial phases can add directly.

is:

is:

Results

After decayed and delayed in the structure, the two outdoor periodic waves, sol-air temperature and dry-bulb temperature, inner surface temperatures changed accordingly. Their comparisons are shown in figs. 1(a) and (b) for winter and summer, respectively.



Figure 1. Inner surface temperatures affected by different outdoor conditions; (a) for winter, (b) for summer

Comparison with two periodic waves and sol-air temperature shows that the inner surface temperature affected by dry-bulb temperature is delayed by 1.5 hours in winter and 1.8 hours in summer. The trough of temperature wave affected by dry-bulb temperature is about 1 °C higher than that affected by two periodic waves and sol-air temperature, no matter in winter or in summer. Both in winter and in summer, the inner surface temperatures calculated under sol-air temperature and two periodic waves are also the same. So if sol-air temperature only consists of air temperature and solar radiation equivalent temperature, sol-air temperature is equal to two periodic waves. The waves with the same frequency with different initial phases can add directly after thermal transmission.

Conclusions

This paper compared the method of heat transfer through building envelope under three boundary conditions. By comparing the inner surface temperatures of two periodic waves with dry-bulb temperature, the results show that, no matter in winter or in summer, the mean value and amplitude of the former are both bigger than those of the latter, and the valley of the former appears earlier than the latter. By comparing the two periodic waves with the sol-air temperature, it proves that the coefficients of sine wave with the same frequency but different initial phases can add directly before or after thermal transmission. If the sol-air temperature only consists of air temperature and solar radiation equivalent temperature, the sol-air temperature is the same to the two periodic waves.

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