Time Lags and Decrement Factors under Air-Conditioned and Free-Floating conditions for Multi-Layer Materials

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ABSTRACT

Time lags and decrement factors for multi-layer materials without air gaps under air-conditioned and free floating conditions were obtained using the response factor and finite volume methods. The definitions under free floating conditions, which are independent of the external environmental conditions, are proposed for the first time. A special version of the finite volume method was employed in which the surfaces of materials were used as computational nodes and temperatures and heat fluxes on surfaces as primitive (state) variables. While the time lag is defined as a phase shift, the decrement factor is defined as the ratio of the amplitude of the temporal evolution of the temperature on the inner surface of the multi-layer material to that of the sol-air temperature or the outer surface temperature. To verify this analytical method, the time lags and decrement factors calculated by the response factor method were compared with the published results. The analytical expressions for the time lag and decrement factor of multi-layer materials under free-floating conditions were then obtained. Recommendations are made for choosing a proper definition for the time lag and decrement factor.

KEYWORDS

Response factor method; time lag; decrement factor; thermal capacitance; thermal resistance; thermal performance simulation.

INTRODUCTION

Alford et al. (1939) derived an analytical solution for the inside surface temperature of a homogeneous material under air-conditioned circumstances. Their definition of the decrement factor was the total thermal resistance of the material multiplied by the ratio of the amplitude of the inside surface heat flux to the amplitude of the outside sol-air temperature. The phase lag of the inner surface was defined with respect to the phase of the outside sol-air temperature. Accordingly, the phase lag and decrement factor from Alford et al. (1939) are dependent on the following parameters: thermal capacitance (product of the density and the thermal capacity coefficient), thermal conductivity, thickness, convective heat transfer coefficients on both surfaces of the material layer and the angular frequency. Mackey and Wright (1944, 1946) similarly developed mathematical expressions for homogeneous walls or roofs and composite walls and roofs. They defined the decrement factor as the ratio of the amplitude of the temperature at the inside surface of the building material to the amplitude of the outside sol-air temperature. The lag angle of the inner wall temperature was also defined corresponding to the sol-air temperature.

Yumrutas et al. (2007) presented a study on the estimation of total equivalent temperature values for multi-layer walls by complex finite Fourier transformation (CFFT). They defined the time lag as the phase shift between the inside and outside surfaces of the building material. They used the thermal properties of the multi-layer materials reported by Mackey and Wright (1946) and calculated their time lag and decrement factors. Comparison of results from Yumrutas et al. (2007) and Mackey and Wright (1946) shows some discrepancies. It is, however, not known whether the discrepancies are due to the difference in definition of the time lag or that of the decrement factor.

The objective of the present paper is to shed some light on the underlying reasons behind the above-mentioned discrepancy. Using the response factor and finite volume methods the application of the time lag and decrement factor are extended to any multi-layer material.. The new methodology is then employed to derive relevant mathematical expressions for the time lags and decrement factors of multi-layer materials under free-floating conditions (i.e. not air-conditioned).

MATHEMATICAL EXPRESSIONS

Assumptions on the free floating condition

Assuming that the zone (room) air temperature is uniform in the zone and the six room surface

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temperatures are identical, the governing equation for the room air energy balance reads,

$$\frac{\partial(\rho_a C_{pa} V T_{rm})}{\partial t} = 6Ah_{rs}(T_{rs} - T_{rm}) + \dot{q} \tag{1}$$

in which $\rho_a C_{pa}$ is the thermal capacitance of the air, and V is the air volume in the zone, T_{rm} is the temperature for the room air, h_{rs} is the convective heat transfer coefficient for the room internal surfaces, A is the area of the room internal surface and $\dot{q}$ is the energy source from other sources. If the left side of Eq. (1) is ignored considering that the thermal capacitance of air is almost 10^{-3} of that of typical solid materials, and further assuming $\dot{q}$ = 0, it can be derived from Eq. (1) that,

$$T_{rs} = T_{rm} \tag{2}$$

Because the temperature of the surrounding walls is identical, thermal radiation among the internal wall is zero. Moreover, the convective heat transfer is also zero due to Eq. (2). Thus, the heat flux at the internal room surface can be assumed as zero:

$$\dot{q}_{rs} = 0 \tag{3}$$

This is called the adiabatic condition as applied to the room internal surfaces.

Time lag and decrement factor with respect to outside wall surface temperature

Starting from a one-dimensional energy balance equation for a homogeneous material, as shown by Luo et al. (2006), the temperature and heat flux solutions can be expressed as,

$$\begin{aligned} T(x,t) &= A + Bx + \sum_{i=1}^{N} \left(A_i e^{\sqrt{j\omega_i/\alpha}\,x} + B_i e^{-\sqrt{j\omega_i/\alpha}\,x}\right) e^{j\omega_i t} \\ &= A + Bx + \sum_{i=1}^{N} T_i(x) e^{j\omega_i t} \end{aligned} \tag{4}$$

$$\begin{aligned} Q(x,t) &= -kB - \sum_{i=1}^{N} k\sqrt{j\omega_i/\alpha}\left(A_i e^{\sqrt{j\omega_i/\alpha}\,x} - B_i e^{-\sqrt{j\omega_i/\alpha}\,x}\right) e^{j\omega_i t} \\ &= -kB + \sum_{i=1}^{N} Q_i(x) e^{j\omega_i t} \end{aligned} \tag{5}$$

In which T is the temperature, x the distance from the left wall surface as illustrated in Fig. 1, t the time variable, ω_i the angular frequency, α the thermal diffusivity coefficient ($k/\rho C_p$), Q the heat flux, and A, B, A_i and B_i are arbitrary constants determined by initial/boundary conditions. $T_i(x)$ and $Q_i(x)$ are also the coefficients of the complex Fourier expansions for temperature and heat flux, respectively. T, Q, T_i, Q_i, A, B, A_i and B_i are all complex numbers and j is the unit imaginary part of the complex numbers.

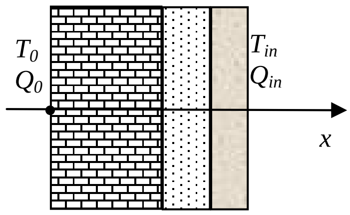

Fig. 1 The configuration of a multi-layer wall.

Assuming $H = \sqrt{j\omega_i/\alpha}\,L$ and $R = L/k$, the relationship between the temperature and heat flux coefficients on the left (x = 0) and right wall surfaces (x = L) for a homogeneous material layer can be obtained from Walsh and Delsante (1983),

$$\begin{pmatrix} T_L \\ Q_L \end{pmatrix} = \begin{pmatrix} \cosh(H) & -R\sinh(H)/H \\ -H\sinh(H)/R & \cosh(H) \end{pmatrix} \begin{pmatrix} T_0 \\ Q_0 \end{pmatrix} \tag{6}$$

For a multi-layer material, the temperature and heat flux coefficients of the inside surface (the right wall surface) can be related to those of the outside surface using the following expression,

$$\begin{pmatrix} T_{in} \\ Q_{in} \end{pmatrix} = A_N A_{N-1} \dots A_1 \begin{pmatrix} T_0 \\ Q_0 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} T_0 \\ Q_0 \end{pmatrix} \tag{7}$$

Note that the matrix components a_{11}, a_{12}, a_{21} and a_{22} are all complex numbers.

For free floating cases (i.e. not air-conditioned) Q_{in} = 0.0 and hence,

$$T_{in} = a_{11}T_0 - a_{12}\frac{a_{21}}{a_{22}}T_0 = \frac{a_{11}a_{22} - a_{12}a_{21}}{a_{22}}T_0 \tag{8}$$

Therefore, the time lag and decrement factor of the inner surface with respect to the outer surface are:

$$T_{lag} = \arg\left(\frac{a_{11}a_{22} - a_{12}a_{21}}{a_{22}}\right) \tag{9}$$

$$f_L = \left|\frac{a_{11}a_{22} - a_{12}a_{21}}{a_{22}}\right| \tag{10}$$

For air conditioned cases, the room temperature is assumed to be constant at a set value (T_{rm}). Assuming that $T' = T - T_{rm}$, ignoring the prime, the supplementary equation is $Q_{in} = h_{in}(T_{in} - T_{rm}) = h_{in} T_{in}$, and the coefficients for temperature and heat flux at the inner surface read,

$$T_{in} = a_{11}T_0 + a_{12}\frac{h_{in}a_{11} - a_{21}}{a_{22} - h_{in}a_{12}}T_0 = \frac{a_{11}a_{22} - a_{12}a_{21}}{a_{22} - h_{in}a_{12}}T_0 \tag{11}$$

$$Q_{in} = a_{21}\frac{a_{22} - h_{in}a_{12}}{h_{in}a_{11} - a_{21}}Q_0 + a_{22}Q_0 = \frac{a_{11}a_{22} - a_{12}a_{21}}{h_{in}a_{11} - a_{21}}h_{in}Q_0 \tag{12}$$

Thus, the time lag and decrement factor of the inner surface with respect to the outer surface under air-conditioned cases are:

$$T_{lag} = \arg\left(\frac{a_{11}a_{22} - a_{12}a_{21}}{a_{22} - h_{in}a_{12}}\right) \tag{13}$$

$$f_L = \left|\frac{a_{11}a_{22} - a_{12}a_{21}}{a_{22} - h_{in}a_{12}}\right| \tag{14}$$

Time lag and decrement factor with respect to the sol-air temperature

Ignoring the thermal radiation in the inside wall surface, the heat flux coefficients for inner and outside surfaces are,

$$Q_0 = h_0(T_{a0} - T_0) \tag{15}$$

$$Q_{in} = h_{in}(T_{in} - T_{rm}) \tag{16}$$

in which T_{a0} is the complex Fourier coefficient for the sol-air temperature. Combining Eqs. (7), (15) and (16), the complex Fourier expansion coefficients of the temperature and heat flux at both surfaces (T_0, T_{in}, Q_0, and Q_{in}) can be expressed as,

$$T_0 = \frac{h_0(a_{22} - h_L a_{12})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})} T_{a0} + \frac{h_{in}}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})} T_{rm} \tag{17}$$

$$T_{in} = \frac{h_0(a_{11}a_{22} - a_{12}a_{21})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})} T_{a0} + \frac{h_{in}(a_{11} - h_0 a_{12})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})} T_{rm} \tag{18}$$

$$Q_0 = \left[1.0 - \frac{h_0(a_{22} - h_L a_{12})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})}\right] h_0 T_{a0} - \frac{h_0 h_{in}}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})} T_{rm} \tag{19}$$

$$Q_{in} = \frac{h_{in} h_0(a_{11}a_{22} - a_{12}a_{21})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})} T_{a0} + \left[\frac{h_{in}(a_{11} - h_0 a_{12})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})} - 1.0\right] h_{in} T_{rm} \tag{20}$$

For air-conditioned cases, the room temperature T_{rm} is assumes to be 0.0. According to Eq. (18), the time lag and decrement factor with respect to sol-air temperature are,

$$T_{lag} = \arg\left(\frac{h_0(a_{11}a_{22} - a_{12}a_{21})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})}\right) \tag{21}$$

$$f_L = \left|\frac{h_0(a_{11}a_{22} - a_{12}a_{21})}{h_{in}(a_{11} - h_0 a_{12}) - (a_{21} - h_0 a_{22})}\right| \tag{22}$$

For free-floating cases, Q_{in} = 0.0. Hence, by combining Eq. (7) and (15) the time lag and decrement factor with respect to sol-air temperature take the following forms,

$$T_{lag} = \arg\left(\frac{(a_{11}a_{22} - a_{12}a_{21})h_0}{h_0 a_{22} - a_{21}}\right) \tag{23}$$

$$f_L = \left|\frac{(a_{11}a_{22} - a_{12}a_{21})h_0}{h_0 a_{22} - a_{21}}\right| \tag{24}$$

Time lag and decrement factor for a homogeneous layer

Considering $a_{11}a_{22} - a_{12}a_{21} = 1$ for a homogeneous layer, the time lag and decrement factor can be reduced from the expressions (9-10), (13-14), and (21-24) for the multi-layers as shown below.

For a free floating case the T_{lag} and f_L with respect to the outer wall surface temperature are,

$$T_{lag} = \arg\left(\frac{1}{\cosh(H)}\right) = \arg tg(tg\sigma \tanh\sigma) \tag{25}$$

$$f_L = \left|\frac{1}{\cosh(H)}\right| = 1.0 / \sqrt{\cos^2\sigma \cosh^2\sigma + \sin^2\sigma \sinh^2\sigma} \tag{26}$$

in which $\sigma = \sqrt{\omega_i / (2\alpha)} L$.

For an air conditioned case with respect to the outer wall surface temperature, T_{lag} and f_L become

$$T_{lag} = \arg\left(\frac{1}{\cosh(H) + h_{in} R \sinh(H)/H}\right) \tag{27}$$

$$f_L = \left|\frac{1}{\cosh(H) + h_{in} R \sinh(H)/H}\right| \tag{28}$$

Similarly, T_{lag} and f_L for a free-floating case with respect to the sol-air temperature can be obtained from,

$$T_{lag} = \arg\left(\frac{h_0}{h_0 \cosh(H) + H \sinh(H)/R}\right) \tag{29}$$

$$f_L = \left|\frac{h_0}{h_0 \cosh(H) + H \sinh(H)/R}\right| \tag{30}$$

And for an air-conditioned case with respect to the sol-air temperature,

$$T_{lag} = \arg\left(\frac{h_0}{\cosh(H)(h_{in} + h_0) + \sinh(H)(h_{in} h_0 R/H + H/R)}\right) \tag{31}$$

$$f_L = \left|\frac{h_0}{\cosh(H)(h_{in} + h_0) + \sinh(H)(h_{in} h_0 R/H + H/R)}\right|. \tag{32}$$

RESULTS AND DISCUSSION

Four different definitions for time lag and decrement factor were derived in the previous section based on sol-air temperature or outer surface temperature under both air-conditioned or free floating conditions. In this section, we first verify the validity of these definitions by comparing their prediction with those reported in the literature and then discuss the differences among the four definitions. Values presented in Table 1 are the thermal properties for the 2- or 3-layer walls used in our calculation.

Shown in the last column in Table 2 is the time lag and decrement factor calculated using Eqs. (21) and (22) with the thermal properties from Table 1 and the angular frequency equating to $\pi/12$ (1/hr). It can be seen that the maximum relative error between the results of the present study and those of Mackey and Wright (1946) is very small (0.35% for the decrement factor and 1.53% for the time lag). Considering the computational difficulties in 1946, Mackey and Wright (1946) can be viewed as reliable. This is further examined by comparing the time lag and decrement factor for two layer walls in Table 3, showing similar good agreement between the current response factor method and Mackey and Wright (1946).

But why are the results reported by Yumrutas et al. (2007) different from those of Mackey and Wright (1946) and the present study? We believe the underlying reason is the different definition of the time lag and decrement factor used in these studies. Using the same thermal properties from Table 1, the time lag and decrement factor with respect to the outer surface temperature for walls subjected to an air-conditioned case can be calculated by Eqs. (13) and (14) (see Table 4). It can be observed that the current results are not consistent with those of Yumrutas et al. (2007) by comparing with Table 2 for wall No. 31-34. This might be caused by different convective heat transfer coefficients by Yumrutas et al. (2007) which were not presented in their corresponding paper.

Under the same convective heat transfer coefficients for all materials, the ranking of the construction walls based on the decrement factor is the same for different definitions of the time lag and decrement factor. However, the time lag and decrement factor with respect to the outer surface temperature does not depend on the convective heat transfer coefficient of the outer surface, resulting in a lower sensitive to external environmental conditions (e.g wind speed, etc).

To verify the expression given by Eqs. (21) and (22), solution of the thermal balance equation across the wall is sought by a special finite volume method developed by Luo et al. (2007). The advantage of this method is that only two computational nodes (both surfaces) are needed for most homogeneous layers with $O(L/3)^4$ level of accuracy. For high thermal mass materials, the accuracy can be improved by splitting the single layer into two or more layers. The time lag and decrement factor calculated by the finite volume method are listed in the middle columns in Table 3. The time step is 600 s or 10 minutes, meaning that the possible maximum time delay error could be as high as 600 s or 0.167 hr. It can be observed that the maximum error of the time delay using the finite volume method with respect to the response factor method is 0.123 hr for wall No. 27, less than the time step. As for the decrement factor, the comparison of the results by the finite volume method with those of the response factor is consistently satisfactory. For walls with very high $k\rho Cp$ such as wall 26 and 27, it is necessary to split the single layer into 2-5 layers.

In addition to the comparison for the time lag and decrement factor, the temporal evolvement profiles for the temperature and heat flux at the inner surface are also calculated by the finite voulme method and the response factor method using Eq. (4). Shown in Fig. 2 is the comparison of the inner surface temperature obtained by the finite volume method and the response method. It can be observed that the results of the finite volume method are identical to those by the response factor method. Fig. 3 shows the good agreement for the inner heat flux obtained by the two methods.

For the free-floating situation, According to Eq. (3) the time lag and decrement factor for multi-layer walls can be calculated either by Eqs. (9) and (10) or by Eqs. (23) and (24) depending on the different definitions with respect to the outer surface temperature or the sol-air temperature. All the calculated results are tabulated in Table 4, showing that the decrement factor under free floating conditions is higher than that under air-conditioned environments. The lower decrement factor for walls subjected to air-conditioned environments is due to the constant room air temperature, not due to the thermal properties of the constructing materials.

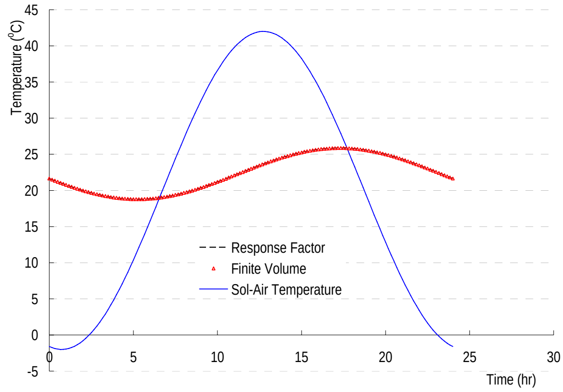

Fig. 2 Comparison of the inner surface temperatures obtained by the response factor method and the finite volume method for wall No. 33 with the sol-air temperature T_{sol} = 20 + 22 cos(ωt-191π/180) ^oC, constant room air temperature set as 23 ^oC, h_0 = 22.8 and h_{in} = 9.405 W/m^{2}K.

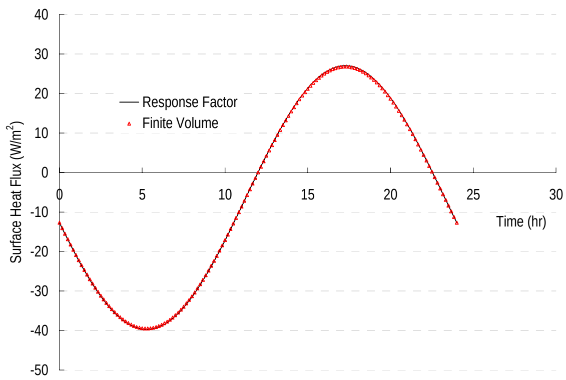

Fig. 3 Comparison of the inner surface heat flux obtained by the response factor method and the finite volume method for wall No. 33 with the sol-air temperature T_{sol} = 20 + 22 cos(ωt-191π/180) ^oC , constant room air temperature set as 23 ^oC, h_0 = 22.8 and h_{in} = 9.405 W/m^{2}K.

In general, the decrement factor and time lag is used to evaluate the thermal performance of a wall and should not change with external environmental conditions. Accordingly, Eqs. (9) and (10) are recommended for calculating the decrement factor and time lag, which only depends on $k_i(\rho Cp)_i$ and R_i, for multi-layer walls under free-floating conditions.

CONCLUSIONS

Time lags and decrement factors for multi-layer walls subjected to air-conditioned and free floating conditions were derived by the response factor and finite volume methods. The time lag and decrement factor by the response factor method agrees well with those obtained by Mackey and Wright (1946) and those by the finite volume method for two- and three-layer walls. The decrement factor and time lag under free floating conditions with respect to outer surface temperature is independent of convective heat transfer coefficients on outer and inner wall surfaces and thus can be viewed as a parameter characterizing the thermal performance of the multi-layer walls.

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REFERENCES

Alford, J. S., Ryan, J. E. & Urban, F. O. (1939) Effect of Heat Storage and Variation in Indoor Temperature and Solar Intensity on Heat Transfer Through Walls. *ASHVE Trans.,* 45**,** 369-396.

Luo, C., B., Moghtaderi, H., Sugo and A., Page (2006) The Verification of Finite Volume Based Thermal Performance Software Using Analytical Solutions and Measurements. *IBPSA Australasia 2006 Conference.* The University of Adelaide, Adelaide, South Australia, Australia.

Luo, C., Moghtaderi, B., Sugo, H. And Page, A. (2007) A new stable finite volume method for predicting thermal performance of a whole building. *Building and Environment,* In Press, Corrected Proof.

Mackey, C. O. & Wright, L. T. (1944) Periodic Heat Flow-Homogeneous Walls or Roofs. *ASHVE Trans.,* 50**,** 293.

Mackey, C. O. & Wright, L. T. (1946) Perodic Heat Flow-Composite Walls or Roofs. *ASHVE Trans.,* 52**,** 283-296.

Walsh, P. J. & Delsante, A. E. (1983) Calculation of the thermal behaviour of multi-zone buildings. *Energy and Buildings,* 5**,** 231-242.

Yumrutas, R., Kaska, O. & Yildirim, E. (2007) Estimation of total equivalent temperature difference values for multilayer walls and flat roofs by using periodic solution. *Building and Environment,* 42**,** 1878-1885.

*Table 1 Thermal properties for 2- or 3-layer walls from Mackey and Wright (1946)**

No. From Mackey and Wright (1946)	Inner layer		Middle (or outer) layer		Outer layer	
	L/k (m^2K/W)	ρCpk ($J^2/(m^4K^2s)$)	*L/k* (m^2K/W)	ρCpk ($J^2/(m^4K^2s)$)	*L/k* (m^2K/W)	ρCpk ($J^2/(m^4K^2s)$)
1 (2-layer)	1.067E-01	6.020E+05	2.201E-01	5.661E+05		
26 (2-layer)	2.134E-01	2.408E+06	8.804E-02	1.416E+07		
27 (2-layer)	2.134E-01	9.632E+06	8.804E-02	1.416E+07		
28 (2-layer)	2.134E-01	2.408E+06	8.804E-02	1.412E+05		
29 (2-layer)	6.402E-01	6.020E+05	4.402E-02	3.543E+06		
31 (3-layer)	1.067E-01	6.020E+05	1.067E-01	6.020E+05	4.402E-02	5.661E+05
32 (3-layer)	4.268E-01	6.020E+05	2.134E-01	6.020E+05	1.101E-01	5.661E+05
33 (3-layer)	1.067E-01	6.020E+05	1.067E-01	6.020E+05	1.101E-01	5.661E+05
34 (3-layer)	1.067E-01	6.020E+05	1.067E-01	6.020E+05	8.804E-02	1.412E+05

Notes: * Original data are in inch-pound (IP) units of measurement.

Table 2 Comparison of the time lag (TL) and decrement factor (DF) for 3-layer walls

No. from Mackey and Wright (1946)	Mackey and Wright (1946) [1]		Yumrutas et al. (2007)[2]		Present [1]	
	TL (hr)	*DF*	*TL* (hr)	*DF*	*TL* (hr)	*DF*
31	3.28	0.2142	4.06	0.25	3.38	0.2149
32	12.2	0.0219	12.84	0.03	12.22	0.0220
33[3]	4.6	0.1612	5.29	0.19	4.53	0.1613
34	3.6	0.1858	4.30	0.21	3.55	0.1863

Notes:
(1) Based on air-conditioned zones with respect to sol-air temperature;
(2) Based on air-conditioned zones with respect to outside surface temperature;
(3) Yumrutas et al. (2007) exchanged the order of 33 and 34;
(4) Convective heat transfer coefficients for outer and inner surface are 22.8 and 9.405 W/m^{2}K.

Table 3 Comparison of the time lag (TL) and decrement factor (DF) for 2- or 3-layer walls by response factor method and finite volume method.

No. From Mackey and Wright (1946)	Mackey and Wright (1946)*		Present paper by finite volume method*		Present paper by response factor method*	
	TL (hr)	*DF*	*TL* (hr)	*DF*	*TL* (hr)	*DF*
1 (2-layer)	4.52	0.1613	4.43	0.1588	4.51	0.1611
26 (2-layer)	15.80	0.0147	15.77	0.0146	15.79	0.0148
27 (2-layer)	24.00	0.0019	23.77	0.0019	23.89	0.0019
28 (2-layer)	8.47	0.0658	8.43	0.0661	8.49	0.0663
29 (2-layer)	12.60	0.0249	12.60	0.0249	12.56	0.0252
31 (3-layer)	3.28	0.2142	3.43	0.2145	3.38	0.2149
32 (3-layer)	12.2	0.0219	12.27	0.0218	12.22	0.0220
33 (3-layer)	4.6	0.1612	4.60	0.1608	4.53	0.1613
34 (3-layer)	3.6	0.1858	3.60	0.1860	3.55	0.1863

Notes: * Based on air-conditioned zones with respect to sol-air temperature.

Table 4 Comparison of the time lag (TL) and decrement factor (DF) for 2- or 3-layer walls by different definitions using the response factor method.

No. From Mackey and Wright (1946)	Air conditioned zones				Free floating zones			
	To sol-air temp		To outer surf. Temp		To sol-air temp		To outer surf. Temp	
	TL (hr)	*DF*	*TL* (hr)	*DF*	*TL* (hr)	*DF*	*TL* (hr)	*DF*
1	4.51	0.1611	3.87	0.1940	6.41	0.3756	5.72	0.4646
26	15.79	0.0148	14.04	0.0332	17.05	0.0235	15.30	0.0527
27	23.89	0.0019	22.13	0.0043	0.65	0.0025	22.88	0.0055
28	8.49	0.0663	8.12	0.0852	9.71	0.1040	9.36	0.1340
29	12.56	0.0252	11.12	0.0352	14.34	0.0563	12.89	0.0788
31	3.38	0.2149	2.76	0.2578	5.15	0.5214	4.35	0.6417
32	12.22	0.0220	11.59	0.0267	13.99	0.0492	13.36	0.0599
33	4.53	0.1613	3.89	0.1946	6.41	0.3750	5.72	0.4645
34	3.55	0.1863	3.16	0.2180	5.45	0.4432	4.95	0.5315