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Decay rates and time lags of heat conduction in building construction under field conditions

Peng Changhai[1,2] Wu Zhishen[1] Chen Zhenqian[1] Li Min[1]

([1] International Institute for Urban Systems Engineering, Southeast University, Nanjing 210096, China)

([2] Key Laboratory of Urban and Architectural Heritage Conservation of Ministry of Education, Southeast University, Nanjing 210096, China)

Abstract: The field measurements of decay rates and time lags of heat conduction in a building construction taken in Nanjing during the summer of 2001 are presented. The decay rates and time lags are calculated according to the frequency responses of the heat absorbed by the room's internal surfaces, inside surface temperature, indoor air temperature and outdoor synthetic temperature. The measured results match very well with the theoretical results of the zeroth and the first order values of the decay rates and time lags of heat conduction in the building construction, but the difference between the measured values and the theoretical values for the second order is too great to be accepted. It is therefore difficult to accurately test the second order value. However, it is still advisable to complete the analysis using the zeroth- and the first-orders values of the decay rates and time lags of heat conduction in building construction under field conditions, because in these cases the decay rates of heat conduction reach twenty which meets the requirements of engineering plans.

Key words: decay rates; time lags; heat conduction; building construction; field

The experimental determination of decay rates and time lags of walls always presents a practical problem in the field of thermal analysis as well as for energy savings. In past years, experiments were done in the laboratory by using prototypes of walls. In particular, according to careful directives, prototypes were designed and built, which met both the international standards[1-6] and the North American standards[7-8]. Then, these samples were used to measure the surface temperatures and the heat flux of walls under steady-state conditions.

It should be noted that in particular cases, the experimental determination of the thermal characteristics of walls should be made in a laboratory. However, it is difficult in some cases because the walls are from an actual building. In these cases, it is desirable and useful to evaluate the decay rates and time lags. In doing this, we cannot only markedly reduce costs, but also completely eliminate uncertainties due to the use of prototypes which are inevitably different from the practical elements under consideration[9].

In this paper, according to the standards of ISO 9869[10], we measured the field thermal physical characteristics of a room in Nanjing during the summer of 2001 by using the heat-flow meter technique. The frequency responses of heat conduction in the building construction under field conditions are analyzed. The calculation of the frequency responses of heat conduction in the building construction under field conditions is recommended because of the reduced differences between the measured and the theoretical values.

1 Test Chamber and Measuring Points

The test chamber, which has a reinforced concrete frame of 4.8 m × 3.6 m × 2.6 m, is the top-floor room of an apartment situated in a new residential development district in Nanjing. It consists of a flat roof, a western external wall, a northern internal wall, an eastern internal wall and a southern external wall which has a double-glazed window of 1.8 m × 1.8 m to reduce heat transfer. The layout of this construction is shown in Fig. 1. This room is equipped with an air-conditioning unit which keeps the indoor temperature and humidity at pre-set levels during the work periods under consideration. It is also instrumented with resistance thermometers for the measurement of the indoor air temperature and the thermal resistance. Heat flux sensors are applied to the walls and the roof to measure the temperature and the heat flux.

The outdoor temperatures are recorded in real time by means of three pyranometers, a pyrheliometer, and a small meteorograph station. Experimental data are recorded by DT-800, a data acquisition system placed in the test chamber. And then these data are transferred to a computer in the auxiliary room where a cooling unit is housed.

In order to obtain sufficient data, we arrange 30 thermopairs and 6 heat flux meters in the room. Two thermopairs are set up on the northern wall and two on the eastern wall. Four thermopairs are glued onto the inner surface of the southern wall and two on the external surface of the southern wall. At the window, two heat flux meters are glued onto the inner and external surfaces, respectively. Six thermopairs and three heat flux meters are set up on the western wall which is one of the important measurement areas. The ceiling and the roof have five thermopairs and one heat flux meter. The floor has one thermopair. More details can be found in Fig. 2.

2 Measurement Results

Measurement was continuously carried out during the summer of 2001. Fortunately, the weather on July 21st to July 25th was ideal because of continuous clear sky, high temperature, and strong solar radiation. We select the results on July 24th as the typical meteorological date for analysis according to the standards of ISO 9869[10]. The outside air tem-

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Biography: Peng Changhai (1970—), male, doctor, associate professor, pengchanghai1@yahoo.com.cn.

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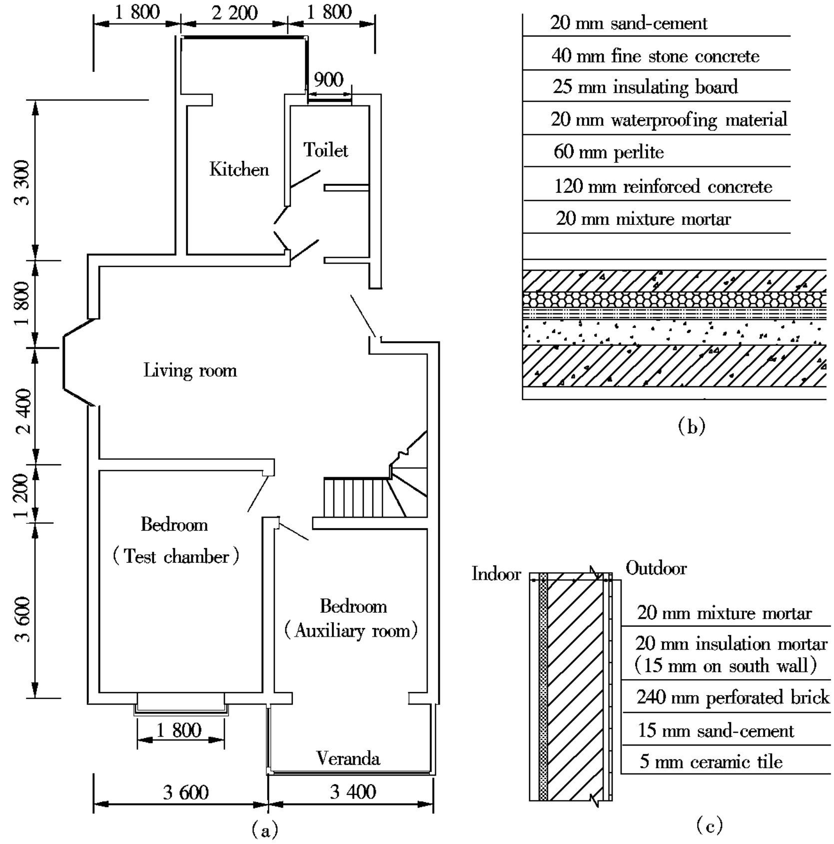
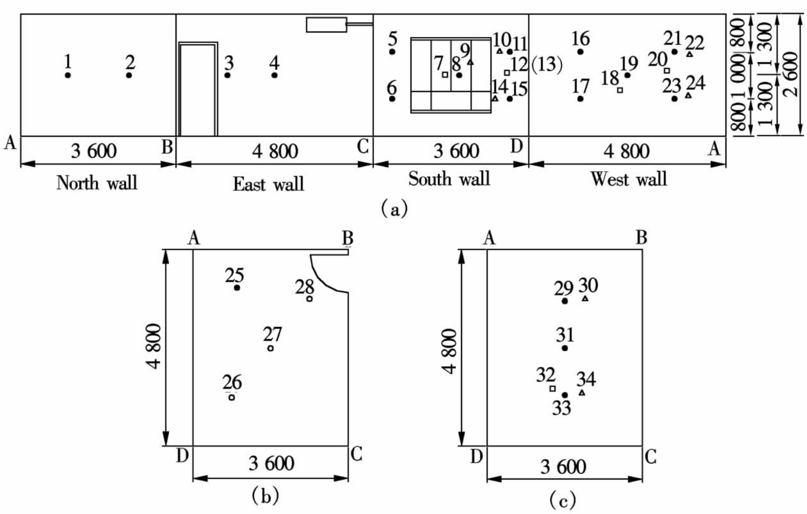


Fig. 1 Layout and structure of test chamber. (a) Layout (unit: mm); (b) Roof structure; (c) Wall structure



1, 2—Inside surface temperature of northern wall; 3, 4—Inside surface temperature of eastern wall; 5, 6—Inside surface temperature of southern wall; 7—Inside surface heat flow rate of southern window; 8—Inside surface temperature of southern window; 9—Outside surface temperature of southern window; 10—Outside surface temperature of southern wall; 11—Inside surface temperature of southern wall; 12—Inside surface heat flow rate of southern wall; 13—Outside surface heat flow rate of southern wall; 14—Outside surface temperature of southern wall; 15—Inside surface temperature of southern wall; 16, 17—Inside surface temperature of western wall; 18—Inside surface heat flow rate of western wall; 19—Inside surface temperature of western wall; 20—Inside surface heat flow rate of western wall; 21—Inside surface temperature of western wall; 22—Outside surface temperature of western wall; 23—Inside surface temperature of western wall; 24—Outside surface temperature of western wall; 25—Inside surface temperature of floor; 26, 27, 28—Indoor air temperature of room; 29—Inside surface temperature of ceiling; 30—Outside surface temperature of roof; 31—Inside surface temperature of ceiling; 32—Inside surface heat flow rate of ceiling; 33—Inside surface temperature of ceiling; 34—Outside surface temperature of roof

Fig. 2 Layout of measuring points (unit: mm). (a) Developed façades; (b) Floor; (c) Ceiling or roof

perature and solar radiant illumination on July 24th are shown in Figs. 3 (a) and (b), respectively. The outside and inside surface temperatures of the room are shown in Figs. 3 (c) and (d), respectively. The heat flow rates on the inner surfaces of the southern wall, the western wall and the ceiling are illustrated in Figs. 3 (e) and (f). Tab. 1 reports the indoor air temperature, outdoor synthetic temperature and inside surface temperature on July 24th, 2001.

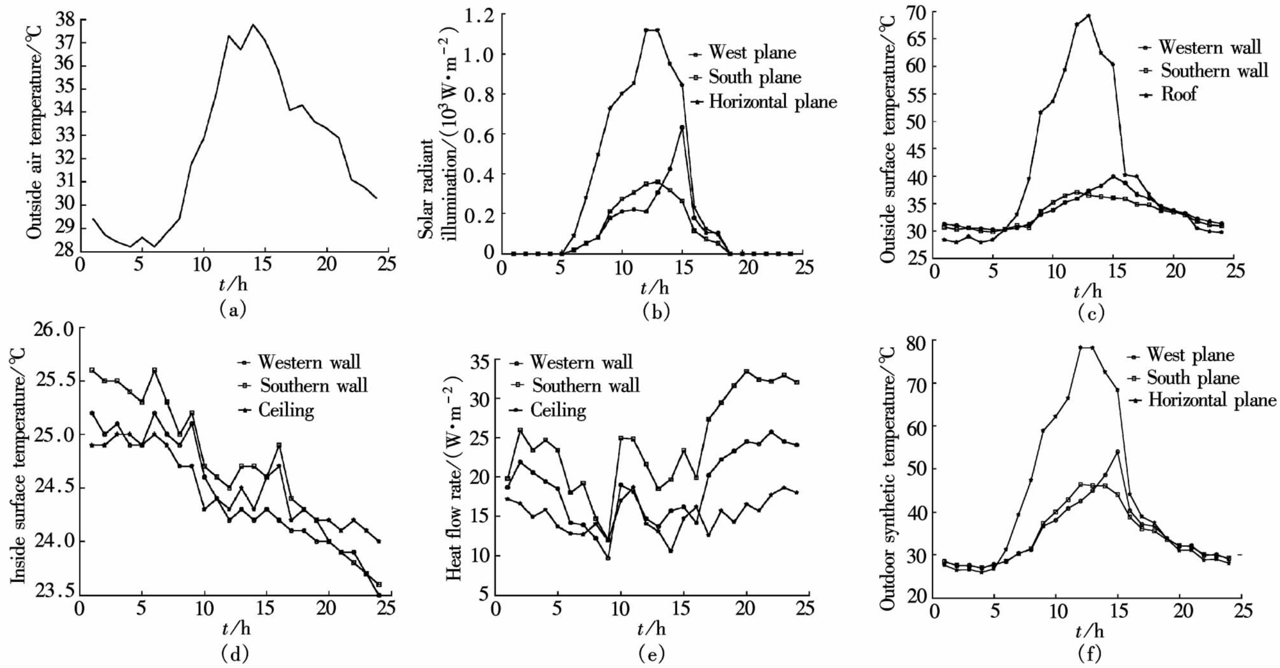


Fig. 3 Meteorological parameters on July 24th, 2001. (a) Outside air temperature; (b) Solar radiant illumination; (c) Outside surface temperature; (d) Inside surface temperature; (e) Heat flow rate on inner surface; (f) Outdoor synthetic temperature

Tab. 1 The temperatures of the room on July 24th, 2001 ℃

Indoor air temperature		Outdoor synthetic temperature			Inside surface temperature		
		West plane	South plane	Horizontal plane	Western Wall	Southern wall	Ceiling
Maximum	25.0	54.0	46.4	78.2	25.2	25.6	25.1
Minimum	20.5	26.9	27.2	26.0	23.5	23.6	24.0
Mean	22.5	35.0	34.6	43.3	24.4	24.7	24.5

3 Discussion

Under field conditions in summer, the outdoor solar radiation is so strong and variable that the outdoor temperature is never in a steady state. In contrast, the indoor temperature can be controlled using an air-conditioning unit. It is known that only some of the heat on the outside surface of the building envelopes can be transferred into the building and arrive on the inside surface because of the thermal resistance of building materials. The heat on the outside surface of building envelopes cannot be immediately transferred to the inside due to the thermal storage capacity of heavy construction materials, such as concrete and bricks. The phenomenon of the weakened and delayed heat flow is the so-called frequency responses of heat conduction in building construction, which makes it possible for buildings to keep the indoor temperature relatively constant and comfortable compared with the variations in the outdoor temperature. Thus, it is very important to analyze the frequency responses of heat conduction in the building construction under in situ conditions.

Usually, the thermal performance of building envelopes is computed by the OST which indicates the comprehensive effect resulting from the outdoor air temperature, the solar radiation absorbed by the outer surface of the buildings and the long wave radiation between the buildings and the environment. According to the analyses mentioned above, the OST on July 24th can be expanded by the Fourier function because of its periodicity and convergence. The method for calculating frequency responses is as follows.

First, the Fourier series is analyzed until the second order value for the division of the OST on the horizontal plane is calculated. Then,

$$t_{\mathrm{s,sa}} = 43.3 + 23.080\cos\left(\frac{\pi}{12}\tau - 3.265\right) + 9.350\cos\left(\frac{\pi}{6}\tau - 0.055\right) \tag{1}$$

Because the inside surface temperature on July 24th shows periodicity and convergence, the Fourier series is analyzed to determine it on the ceiling. Then,

$$\theta_{\mathrm{h,i}} = 24.5 + 0.35\cos\left(\frac{\pi}{12}\tau - 1.624\right) + 0.24\cos\left(\frac{\pi}{6}\tau - 2.221\right) \tag{2}$$

Eq. (2) can be converted to a complex function as follows:

$$\theta_{\mathrm{h,i}} = 24.5 + 0.35\exp\left[\left(\frac{\pi}{12}\tau - 1.624\right)\mathrm{i}\right] + 0.24\exp\left[\left(\frac{\pi}{6}\tau - 2.221\right)\mathrm{i}\right] \tag{3}$$

Moreover, the Fourier series is analyzed to determine the indoor air temperature. That is,

$$t_i = 22.5 + 0.48\cos\left(\frac{\pi}{12}\tau - 1.872\right) + 0.05\cos\left(\frac{\pi}{6}\tau - 0.827\right) \quad (4)$$

The frequency responses of heat absorption of the construction in the test chamber are calculated by the thermoelectricity analogy method (TEAM) according to the building's structure which is similar to that described in Ref. [11]. The results are shown in Tab. 2.

Tab. 2 Frequency responses of heat absorbed by room's internal surfaces

Order number	Frequency/Hz	Decay rate			Phase delay/rad		
		Ceiling	Western wall	Southern wall	Ceiling	Western wall	Southern wall
0	0	1.098	1.209	1.227	0	0	0
1	π/12	2.636	1.486	1.559	0.546	0.291	0.293
2	π/6	3.321	1.663	1.742	0.494	0.455	0.437

Therefore, the temperature wave on the inside surface of the construction resulting from the indoor air temperature is

$$t_{hi,i} = \frac{22.5}{1.098} + \frac{0.48}{2.636}\cos\left(\frac{\pi}{12}\tau - 1.872 - 0.546\right) + \frac{0.05}{3.321}\cos\left(\frac{\pi}{6}\tau - 0.827 - 0.494\right) \quad (5)$$

Eq. (5) can be converted to a complex function as follows:

$$t_{hi,i} = 20.5 + 0.18\exp\left[\left(\frac{\pi}{12}\tau - 2.418\right)i\right] + 0.02\exp\left[\left(\frac{\pi}{6}\tau - 1.321\right)i\right] \quad (6)$$

The temperature wave on the inside surface of the construction is the sum of the wave of the OST and the wave of the inside air temperature. Therefore, the temperature wave on the inside surface of the construction resulting from the outdoor synthetic temperature can be calculated as follows.

For the roof, the zeroth order ($\tau = 0$) temperature wave on the ceiling surface resulting from the outdoor synthetic temperature is 24.5 − 20.5 = 4.0.

The first order temperature wave ($\tau = 1$) is

$$0.35\exp\left[\left(\frac{\pi}{12}\tau - 1.624\right)i\right] - 0.18\exp\left[\left(\frac{\pi}{12}\tau - 2.418\right)i\right] = 0.171\,9 - 0.192\,4i$$

Its modulus and argument are 0.26 and −0.841 5 rad, respectively.

Similarly, the second order temperature wave ($\tau = 2$) is

$$0.24\exp\left[\left(\frac{\pi}{6}\tau - 2.221\right)i\right] - 0.02\exp\left[\left(\frac{\pi}{6}\tau - 1.321\right)i\right] = -0.044\,3 - 0.223\,8i$$

Its modulus and argument are 0.23 and −1.766 1 rad, respectively. Then,

$$t_{hi,sa} = 4.0 + 0.26\cos\left(\frac{\pi}{12}\tau - 0.841\,5\right) + 0.23\cos\left(\frac{\pi}{6}\tau - 1.766\,1\right)$$

In terms of the decay rates and time lags, the calculations are presented as follows.

For the zeroth order temperature wave, the decay rate is 43.3/4.0 = 10.83, and the time lag is 0 h.

For the first order temperature wave, the decay rate is 23.080/0.26 = 88.77. Its phase delay is −3.265 + 0.841 5 = −2.423 5 (rad). Thus, the corresponding time lag is 2.423 5/(π/12) = 9.26 (h).

Similarly, for the second order temperature wave, the decay rate is 9.350/0.23 = 40.65. Its phase delay is −0.055 + 1.7661 = 1.7111 (rad). Thus, the corresponding time lag is 2π − 1.711 1/(π/6) = 8.73 (h).

Obviously, the decay rate of the second order temperature wave is wrong because its value should be larger than that of the first order value, which is also true for the phase delay and time lag.

Likewise, we can also calculate the frequency responses of the heat conduction of the southern wall and the western wall according to the principles mentioned above. These theoretical and measured values are shown in Tab. 3.

Tab. 3 Theoretical and measured values of frequency responses of heat conduction in building construction

Data	Order number	Frequency/Hz	Decay rate			Time lag/h		
			Roof	Western wall	Southern wall	Roof	Western wall	Southern wall
Theoretical value	0	0	12.57	6.14	5.70	0	0	0
	1	π/12	92.32	29.91	26.08	11.78	10.86	10.59
	2	π/6	412.04	96.62	82.16	8.55	8.06	7.86
Measurement value	0	0	10.83	6.00	5.41	0	0	0
	1	π/12	88.77	27.89	23.88	9.26	10.53	9.08
	2	π/6	40.65	14.40	7.07	8.73	9.69	9.36

4 Conclusion

The field data of decay rates and time lags of heat conduction in a building construction taken in Nanjing during the summer of 2001 are analyzed. It can be seen that the measured results match well with the theoretical results of the zeroth and the first order values of the decay rates and time lags of heat conduction in the building construction. For the second order value, however, the difference between the test values and the theoretical values is too great to be accepted. So, it is difficult to accurately test the second order value. Fortunately, using the zeroth and the first order values to calculate the decay rates and time lags of heat conduction in the building construction under field conditions is still advisable because, in these cases, values can meet the requirements of engineering plans.

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现场条件下建筑结构的热传递衰减倍数与延迟时间

彭昌海[1,2]　吴智深[1]　陈振乾[1]　李　敏[1]

([1] 东南大学城市工程科学技术研究院,南京 210096)

([2] 东南大学城市与建筑遗产保护教育部重点实验室,南京 210096)

摘要:介绍了 2001 年夏天对南京某一建筑围护结构的衰减倍数与延迟时间进行现场测试的情况. 根据房间的内表面吸热频率响应、内表面温度、室内气温和室外综合温度,可计算出建筑围护结构的衰减倍数与延迟时间. 实验结果表明,对于建筑围护结构热传导的衰减倍数与延迟时间,0 阶和 1 阶的现场测试值与理论计算值比较吻合,2 阶值则相差很大,因此很难精确测试出 2 阶值. 然而,现场条件下基于 1 阶以内来分析建筑围护结构的衰减倍数与延迟时间仍然是可行的,因为在计算 1 阶时建筑围护结构的衰减倍数已达到 20,完全可以满足工程要求.

关键词:衰减倍数;延迟时间;热传递;建筑结构;现场

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