

Research on Summer Thermal Environment of Dwelling with Courtyard

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Abstract: Chinese historical experience of constructing buildings merits attention. As the main and typical kind of Chinese traditional residential building, the dwelling with courtyard is "cool in summer". However, less research on the thermal performance of dwelling with courtyard has been available in public literature. In this paper, based on the systematic analysis on various related elements, the physical and mathematical model of the air temperature distribution is set up. It is proved by the fieldwork measurement and computer simulation that the shielding effect of the aisle, side house and the long-narrow structure are the main reasons for the low temperature in courtyard.

Keywords: courtyard, solar radiation, shielding, dynamic process

1. INTRODUCTION

Dwelling with courtyard is a kind of typical Chinese traditional residential building. Some researchers including famous architects draw a similar conclusion by a long-time investigation and study^[1]: in the respects of site choosing, elevation facing, plane design, space assembly, material selection and construction dealing, the dwelling with yard illustrates well the thought and its application of adapting to and protecting the nature and keeping the building environment simple, friendly and economical^[2]. To gain good thermal performance of the yard is a hot topic these years. It is very necessary to study the practice of the traditional residential building by modern techniques to improve the thermal environment and save the energy consumption of air conditioning currently^[3].

2. MODEL OF AIR TEMPERATURE DISTRIBUTION IN THE COURTYARD^{[4][5]}

2.1 Thermobalance equations of the internal wall of the courtyard

Assume that there is no phase change in the envelope and heat transfer of the vapor diffusion is ignored. For any internal envelope, thermobalance equation is:

$$Q_{cj}(\tau) + Q_{rj}(\tau) - Q_{sj}(\tau) + Q_{Nj}(\tau) = 0$$

$$(j = 1, 2, \dots, N) \quad (1)$$

where,

(1) $Q_{cj}(\tau)$ — heat transfer by convection of j surface and the air inside the courtyard

$$Q_{cj}(\tau) = h_{cj}(\tau)[t_j(\tau) - t_i(\tau)]F_i \quad (2)$$

(2) $Q_{rj}(\tau)$ — heat exchange by radiation of j surface and the other surface of the courtyard

$$Q_{rj}(\tau) = \sum \varepsilon_{ji} \sigma [(t_j + 273.15)^4(\tau) - (t_i + 273.15)^4(\tau)] \psi_{ji} F_j \quad (3)$$

ε_{ji} — equivalent radiation heat transfer emissivity of surface j to i , as to a envelope surface

$$\varepsilon_{ji} = \varepsilon_j \cdot \varepsilon_i$$

σ — Stefan-Boltzmann constant.

ψ_{ji} — angle factor of j and i surface at time τ .

According to the general method of building thermophysics, the above non-linear equations are changed linearly as follows:

$$Q_{rj}(\tau) = \sum h_{rj} [t_j(\tau) - t_i(\tau)] F_i \quad (4)$$

h_{rj} — equivalent coefficient of radiant heat transfer between j and i surfaces.

(3) $Q_{sj}(\tau)$ — solar radiation that j surface receives, which only exists in the acceptance of solar radiation^[6].

With the variety of solar altitude the sun shines at west wall, ground, and east wall in turn. The variety of shined site and width of the facula by h is shown in Tab.1.

(4) $Q_{Nj}(\tau)$ — heat transfer between internal surface and air outside courtyard through envelope.

Table 1: The variation of solar radiation intensity in courtyard with different solar altitude

h	Shinning site	Width of the facula L
$\arctan \frac{h_2}{h_1} \sim \arctan \frac{h_3}{l_1 + l_2}$	West wall	$l_2 \tanh$
$\arctan \frac{h_3}{l_1 + l_2} \sim \arctan \frac{h_3}{l_1}$	West wall ground	$l_3 - t_1 \tanh$ $l_2 + l_1 - h_3 \coth$
$\arctan \frac{h_3}{l_1} \sim \arctan \frac{h_3}{l_1}$	Ground	l_2
$\arctan \frac{h_3}{l_1} \sim \arctan \frac{h_3}{l_1 + l_2}$	Ground east wall	$l_2 + l_1 - h_3 \coth$ $l_3 - t_1 \tanh$
$\arctan \frac{h_3}{l_1 + l_2} \sim \arctan \frac{h_2}{l_1}$	East wall	$l_2 \tanh$

Calculating $Q_N(\tau)$ is one of the most difficult problems of dynamic thermal process. For a multi-layer envelope of constant properties and non-phase change, internal temperature field is determined by the following equation^[7]

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} = \frac{1}{a} \frac{\partial t}{\partial \tau} \quad (5)$$

and the related boundary condition equations. Since the boundary condition is multiple owing to the variety of the construction, it is commonly simplified to one-dimensional heat transfer. Therefore, the equation becomes

$$a \frac{\partial^2 t(x, \tau)}{\partial x^2} = \frac{\partial t(x, \tau)}{\partial \tau} \quad (6)$$

Boundary layer condition of outer surface is:

$$\lambda \frac{\partial t}{\partial x} \Big|_{x=0} = a_0 [t(\tau) - t_0(\tau)]$$

Boundary layer condition of multi-layer surface:

$$\lambda_j \frac{\partial t}{\partial x} = \lambda_k \frac{\partial t}{\partial x}$$

There are many solutions of the above equation such as harmonic respond method proposed by A.M. Ilinskiy of former Soviet Union, respond factor method by D.G.Stephenson and G.P.Mitalas, the derived Z transfer function method, and room respond factor method^[5]. For computer analysis, the respond factor is adopted in this paper. By this method, the heat transfer of j internal surface and air outside courtyard through envelope can be written as:

$$Q(\tau)_j = F_1 \sum_{n=0}^N X(n) t_j(\tau - n) - F_1 \sum_{n=0}^N Y(n) t_0$$

$$(\tau - n) + C_j Q_N(\tau - 1) \cdot F_j$$

(7)

$$Q_N = K_j [t_i(\tau) - t(\tau)] \cdot F_j \quad (8)$$

C_j — general ratio of the reaction coefficient of heat transmission and reaction coefficient of heat absorption,

$Q_N(\tau - 1)$ — heat exchange of the air internal and external at the former time, but to the light-weighted envelope,

$$Q_N = K_j [t_i(\tau) - t(\tau)] \cdot F_j \quad (9)$$

2.2 Thermobalance equation of the inner envelope (thermal storage construction) surface

By the dynamic process, the inner envelope is a part of the courtyard thermal process. The influence of the thermal environment is determined by the thermal capacity and the heat exchange performance. However, by the respond factor method, heat exchange by thermal storage of the inner envelope and the surface temperature can be written as:

$$Q_j(\tau) = F_j \sum_{n=0}^N [X(n) - Y(n)]$$

$$t_j(\tau - n) + c_j q_j(\tau - 1) F_j \quad (10)$$

2.3 Calculation of the ground surface temperature

Some observatories in China record the temperature of ground surface and 0.6 m below. Also a few of them record the temperature at 3.2 m below the surface.

The surface temperature of semi-infinite body, like ground, can be written as the cosine function

$$\theta(0, \tau) = \theta_w = A_w \cos \frac{2\pi}{T} \tau \quad (11)$$

θ_w — excess temperature at any time on the surface of semi-infinite body, based on periodical

variety average temperature, $\theta = t - t_m$

A_w — temperature amplitude of the body surface

T — period of the temperature wave

Substitutes temperature with excess temperature $\theta = t - t_m$, and the thermal conductive differential equation becomes

$$\frac{\partial \theta}{\partial \tau} = a \frac{\partial^2 \theta}{\partial x^2} \quad (12)$$

The above two equations depict the ground surface calculation model completely. The air distribution equation could be achieved by the variable separation method,

$$\theta(x, \tau) = A_w e^{-\sqrt{\frac{\pi}{aT}} x} \cos\left(\frac{2\pi}{T} \tau - x \sqrt{\frac{\pi}{aT}}\right) \quad (13)$$

3. NUMERICAL SIMULATION

3.1 Put solar radiant intensity and the air temperature of the courtyard into Fourier progression

Put solar radiant intensity into Fourier progression

$$I = I_0 + \sum_{n=1}^{\infty} \alpha_n \text{EXP}(in\omega\tau) \quad (14)$$

In the above equation, coefficient of Fourier progression is $\alpha_n = A_n \text{EXP}(-i\sigma_n)$

$A_n \cdot \sigma_n$ — amplitude and phase of harmonic variable analysis on period change in climate parameter values in a certain area.

Period is equal to

$$\begin{cases} \frac{2\pi}{\omega} \\ \omega = \frac{2\pi}{24} = \frac{\pi}{12} \end{cases}$$

Considering the internal air temperature is changing periodically at the same frequency, the temperature is put into Fourier progression

$$t = t_0 + \sum_{n=1}^{\infty} t_n \text{EXP}(in\omega\tau)$$

After determining the solar radiation gain and temperatures of air and ground surface, the internal wall temperature could be derived by the iteration of thermobalance equations of the internal wall of the courtyard.

3.2 Compute condition of numerical simulation

Take the actual air condition and the actual inner courtyard the calculating condition. The inner courtyard is simplified to a standard cuboid (the size of the aisle is considered). The actual size is considered in the calculating model, with the boundary conditions is the temperature of the wall, given by the periodical solution of wall temperature and referred to the actual climate properties of Xi'an City on September 8. The ground surface temperature adopts the periodical solution. Solar radiant is taken as a heat source and considered

by hours, while the thermal storage effect ignored. Because the air velocity during the measurement is less than 0.05m/s and irregular, the effect of the wind is not considered in the simulation. For the concerned specific size, the 24-hour air field distribution of the courtyard can be worked out by PHOENICS software by inputting the boundary conditions of each hour. Setting of the probe is coincide with the actual fieldwork measurement. Nomenclature t' in the tables and the diagram is the simulated temperature in the middle of the courtyard. Comparison is done by calculating and fieldwork measurement.

3.3 Comparison of the plane temperature fields

By comparison of the calculated and measured temperatures, we find that the maximum absolute error of the probe point and the calculating point is 1.95°C, the maximum relative error is 6.95%, and the variation of the average temperature is similar to that of the measured one. From the data, it could be seen that difference between calculating point is less than that of the measured probe point. The reason is that the average value of each hour is adopted for calculating the solar radiation in the program. Actually, because of the movement of the facade, the wall temperature is not uniform and air in the vicinity is heated by convection.

3.4 Comparison of the vertical temperature field

By comparison of the calculated and measured temperature point to point, it can be seen that both have the same changing trend. The maximum absolute error of the probe point and the calculating point is 27.5 °C. The maximum relative error is 99.3%. During 11:00 to 16:00, calculated temperature is a little bit higher than that of the measured one. But calculated temperature should be lower than that of the measured one when ignoring the heat gain of people due to the inertia of wall and roof. At the same time, room temperature is lower than that of courtyard temperature, making a part of heat transfers to the room.

4. CONCLUSION

The following conclusions can be drawn from Figure 1 and Figure 2:

(1) The comparison of the temperature of the courtyard t and the outdoor temperature shows the good thermal stabilization of the courtyard. Temperature undulation of the courtyard is much less than that of outdoor's and there is a phase-lag. From the courtyard to the outdoors, amplitude attenuation is from 10.6 °C to 4.7 °C and maximum temperature attenuation from 37.5 °C (appear at 17:00) to 31.3 °C (appear at 19:00), ie. Appearing time of maximum temperature lags 2 hours, whereas that of minimal temperature from 7:00 to 10:00.

(2) It is evident from the comparison curve that the temperature of courtyard can keep relatively low and steady even when the outside is very hot. Maximum temperature difference is 7.3 °C and average temperature difference 2.33 °C.

(3) The shielding effect of the aisle, side house and the long-narrow shape are the main reasons for the low temperature of the yard, which can explain further the

ancient people's reasonable selecting of the courtyard shape. The traditional soil ground and the cyan brick

are good thermal storage material, which play the important role to keep the steady temperature field.

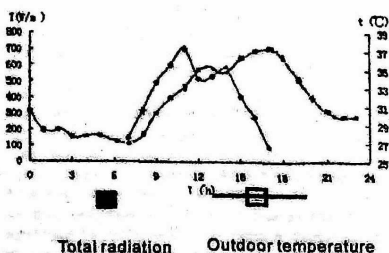


Figure 1: Outdoor temperature conditions

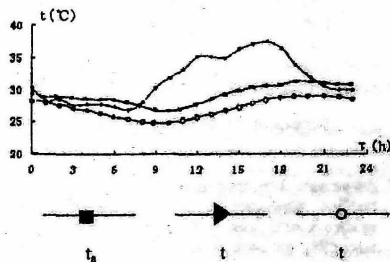


Figure 2: Temperature comparative curve of outdoor and courtyard

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