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A STUDY ON THE CHARACTERISTICS OF INTERNAL AND EXTERNAL WALL SURFACE TEMPERATURE IN THE URBAN AREA

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ABSTRACT: Internal and external wall surface temperatures (T_{ws}) in April, August and December in Kunming, a city in low latitude plateau, were investigated. Results showed that the T_{ws} in April were of the highest among the three, followed by August and December. The T_{ws} differences among walls with different orientation were higher in April and December when the weather tends to be sunny, and lower in August with more cloudy days in the time. In April and August, T_{ws} of E-wall was the highest, followed by S- and N-wall. But in December T_{ws} of S-wall might be sometimes higher than E one. Diurnal range of internal T_{ws} was usually smaller than that of the external, with also a time lag for the occurrence of its maximum and minimum. The results can serve as a basis for further research on building microclimate and urban architecture designs. It also gives suggestions for similar studies in other areas.

Key words: wall; internal and external surface; surface temperature; heat flux

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1 INTRODUCTION

With the development of society, requirements on life quality have been steadily increasing, and household buildings are an important part. The fending structure of such architectural bodies act to separate the indoors space from the outdoors so that immediate effect of climatic elements such as outdoor air temperature, humidity, wind, solar radiation, rain and snow can be eased or stopped[1]. Surface area of architectural buildings has taken up large percentage of the total urban surface area, as the development of cities is fastening the pace of urbanization and buildings grow taller and taller in ever-increasing density[2]. Temperature varies substantially according to the orientation of wall surfaces and affects the urban climate in a way that it no longer goes neglected. The issue is also important for efforts to keep buildings warm or prevent them being heated, which relates to the design of thermodynamic engineering, air-conditioning, rational partitioning of housing cells as well as indoor micro-climate research.

In the arena of architecture, the effect of environment on living condition has well been studied and discussed[1, 3, 4] and thermodynamic condition and variation of the surface of buildings have been well documented abroad, but mostly in developed countries in the middle and high latitudes of the subtropical and extra-tropical zones. Similarly, work in this aspect is only on Shanghai, Beijing and Xi'an[4, 7, 8]. For the low-latitude, plateau region in western China, Zhang et al.[9 –13] make preliminary attempts to study the effects of urban buildings on solar radiation and temperature in indoor and outdoor surroundings. Mainly with three select months of observations of inner and outer wall surfaces facing different directions in the buildings of Kunming, the current work comprehensively compares and analyzes the characteristics and variation patterns of

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temperature on the surfaces of inner and outer building walls and transportation of heat flux and provides scientific foundations for more study on urban climate and rational architectural design in cities locating in low-latitude plateau.

2 METHODS

Standing with the urban district of Kunming, the office building of the Kunming Branch, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences (with the front facing south, four floors) was used in the observation, which took place in two of its offices, one in the south and the other in the north sides of the eastern wing of the building (to be referred to as "southern room" and "northern room", respectively). Being 3.2 m from floor to ceiling, both of the rooms have eastern, southern and northern walls. Yellowish orange mosaics are decorated on the outer surface of the walls, which are 0.33 m in thickness. Being in the southern and northern wall surfaces, the windows are equipped with single-sheet glass, taking up about 40% or the total wall area. Facing each other, the southern and northern rooms are separated by a corridor. Six sites of observation were set up at the central points of the inner wall surfaces in the direction of east (E), west (W), south (S), north (N), ceiling and floor, with the azimuth for individual indoor sites of observation takes as reference point the place where the center of each surface locates. There are 12 sites of observation in the rooms, in addition to three observation sites at the centers of outer wall surfaces to E, S and N outside the office building (with the azimuth referred to the same orientation of each of relevant outer walls). With data that cover the same period for both inner and outer walls in the E and S directions (southern room) and E and N directions (northern room), the work compares and analyzes the distribution characteristics, variation patterns and temporal and spatial difference of temperature on the surface of buildings.

Surface temperature was the element measured (with COMPAC3 infrared radiation thermographs made by Minolta Ltd, Japan). The observation was conducted over periods of December 25 – 27, 1999, August 3 – 12, 2000 and April 20 – 22, 2001, at the intervals of 1 hr. For the weather condition during the observation, it was generally fine in December and April, and cloudy in August, which is typical of what the weather is like for the Kunming area over the time of the year.

In the study below, the numerals of surface temperature are the mean for each day during the observation.

3 RESULTS AND ANALYSIS

3.1 *Diurnal variation of temperature on the wall surface*

3.1.1 DIURNAL VARIATION OF TEMPERATURE ON THE OUTER WALL SURFACE

Studying the temporal variation of surface temperature on the outer walls of the building over the months (Fig.1), we learn that it is fine throughout December in Kuming with lower angle of solar altitude and thus weaker radiation than other times of the year; the temperature at the outer wall surface has such large diurnal variation that it can drop substantially during the night and is sometimes as low as below 0°C. In April, the city is in the late period of dry season that enjoys cloudless sky and stronger solar radiation that, in combination with other radiation being reflected from other surface, the temperature on the outer surface of the office building is relatively high. In August, Kunming steps into its raining season when there are more clouds, making the surface temperature lower than in April on the outer wall.

In the months of interest, nighttime surface temperature is similar and with small difference between individual wall orientations. Temperature falls gradually after sunset and reaches the diurnal minimum 5 to 7 hours before sunrise.

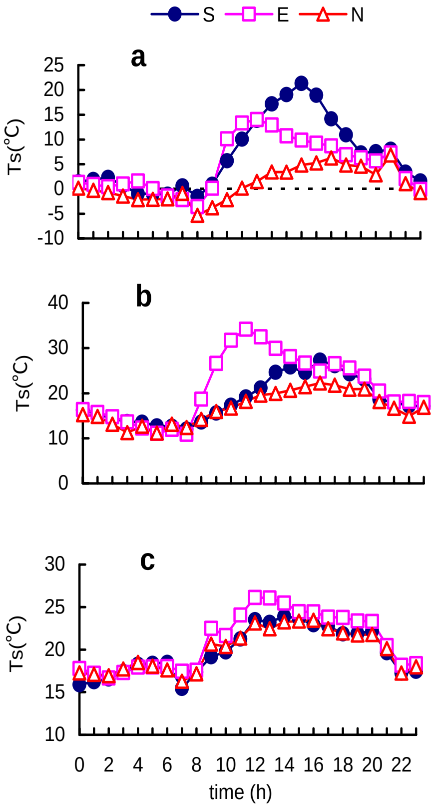

Fig.1 Diurnal variation of temperature on the outer surface of the walls. a. Dec., b. Apr., c. Aug.

During the daytime, surface temperature is all higher than at night for all sites of observation, though with large difference in variation tendency due to the effect of the angle of solar altitude. Subject to direction insolation right after sunrise, the outer walls at the E and S directions have a rapid increase of surface temperature, especially so on the E walls, which receive sunshine from much earlier time on. In fact, it peaks the diurnal range around 11:00. in all those months while it warms up slowly on the N-facing walls and touches the highest diurnal point after 16:00, which is lower than the outer walls towards E and S regardless of day or night.

It is interesting to note that late sunrise and low angle of solar altitude in December (winter) results in rapid increase of surface temperature on the S outer walls; its longer exposure to sunlight causes larger rise of surface temperature than on the E walls, reaching the maximum (21.3°C) at 15:00, nearly 7.3°C higher than its counterpart for the E walls (14.0°C); it remains higher than the latter all through to 02:00. In April and August, when the angle of solar altitude stays relatively high, the solar radiation amount reaching the S outer wall (normal to the surface) is smaller than the one reaching the E one, with surface temperature being lower during the day and at night and having the maximum about two hours late, than the latter.

3.1.2 DIURNAL VARIATION OF TEMPERATURE ON THE INNER WALL SURFACE

First, let’s examine the variation of temperature on the inner surface of the southern room walls over individual months (Fig.2). Consistent with the outer wall surface, the inner wall surface also hits the minimum in December, second lowest in August and maximum in April.

Looking at the azimuth, it is known that the surface temperature follows a similar pattern of change in the three months on the surface of E and S walls. With the lapse of time, temperature reduces gradually until reaching the minimum of the day between 10:00 and 11:00.

During the daytime, the surface temperature on both the E and S walls is lower than at night, though in a way that is varying over the time of year. In December, the late sunrise and low angle of solar altitude, longer exposure to sunshine in the southern room, passage of sunlight through the window glass into room around midday and reflection by the floor to the E wall are responsible for the rapid rise of temperature on its surface through 12:00 and beyond when it is warmer than the S wall and the acquisition of the diurnal maximum at 17:00 (15.6°C). Temperature on the S wall surface also shows a rising tendency but it doesn’t surpass the E wall until 19:00 and tops the diurnal cycle at 21:00 (15.4°C). In April and August, however, both the E and S wall surfaces show rising trends of temperature during the daytime and the maximum also occurs at a later time on the S wall (22:00 – 24:00) than the E wall (21:00), but the S wall surface is cooler than the E wall over the entire diurnal range, which is unlike December. Their difference

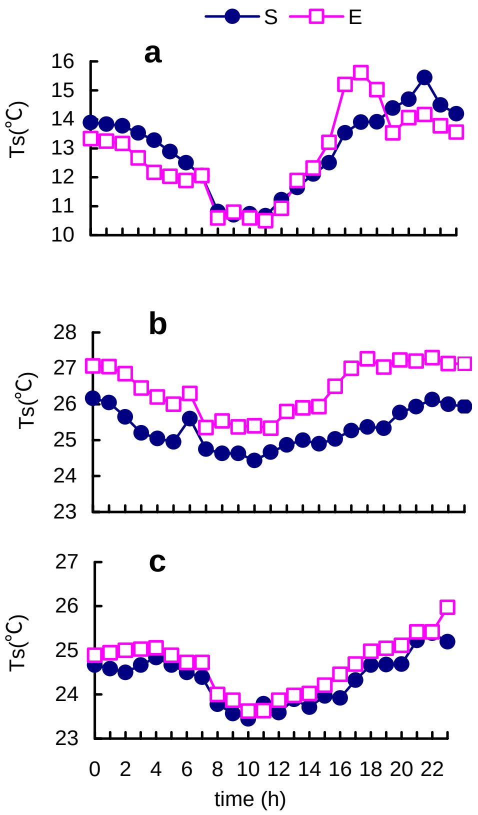

Fig.2 Diurnal variation of temperature on the inner wall surface of the southern room. a. Dec., b. Apr., c. Aug.

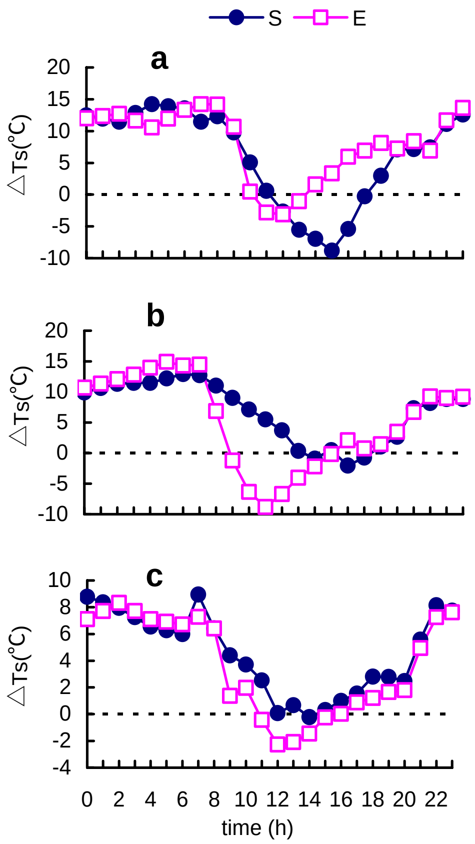

Fig.3 Same as Fig.2 but for the difference between the inner and outer wall surfaces.

is smaller in August than in April.

The case of the northern room (figure omitted) is similar to that of the southern room in that the inner wall surface temperature is the lowest in December and highest in April with August in between. The surface temperature is relatively low during the day (09:00 – 16:00) but relatively high at night. The difference is what follows next. Over the three months of observation, there are similar changes on the surfaces of the E and N walls in that temperature decreases gradually over time at night and reaches the minimum between 07:00 and 11:00 and it increase gradually during the day to reach the maximum between 21:00 and 22:00. Additionally, the magnitude and variation range of temperature over the three months are generally greater on the surface of the E wall surface than that of the N one, with the difference between the two larger in December and April than in August.

3.2 *Temperature difference between the inner and outer wall surfaces*

Values of temperature difference between the inner and outer wall surfaces are calculated for the two rooms and diurnal variation characteristics are analyzed.

3.2.1 DIURNAL VARIATION OF TEMPERATURE DIFFERENCE BETWEEN THE INNER AND OUTER WALL SURFACES

Fig.3 gives diurnal variation of temperature difference between the inner and outer wall surfaces in the months, which shows that the difference is larger in December and April, which is usually fine, than in August, which is usually cloudy.

At night, the difference is generally the same for the azimuths of E and S of the southern room in the three months. As it is getting late in the course of the day, there is a large positive difference of temperature that hits the maximum between 02:00 and 07:00, with the inner surface warmer than the outer one and heat transporting from the former towards the latter.

During the day, the trend of variation is quite large inside the southern room. After sunrise in the morning, temperature increases rapidly on the outer surface of the wall due to direction sunlight, diminishing the positive difference between the inner and outer surfaces of the E and S walls. The effect is especially clear with the E wall that receives sunlight from a much earlier time on the outer surface so that the inner-outer difference is close to zero around 10:00, which is earlier than the S wall, in all the three months. A negative temperature difference appears afterwards and reaches the maximum around 12:00, indicating heat transportation from the warmer outer surface towards the inner surface. The maximum is the largest in April (–8.8°C), followed by December (–3.1°C) and August (–2.3°C), which is the smallest of all. The temperature difference then continues to decline in the negative zone and tends to approach to zero again between 14:00 and 16:00 before turning positive in increasing value till nighttime when heat begins to transport, once again, from the inner surface to the outer surface.

The difference occurs in December. As the S wall exposes to long hours of strong, direct solar radiation, the positive difference rapidly decreases between the inner and outer surfaces of the E and S walls. The difference starts to appear at 11:00 after approaching zero and reaches the minimum at 15:00 (–8.8°C), with a longer period of negative temperature difference and much larger maximum than the E wall; during the day heat transports from the warmer outer surface to the inner surface in most of the time. In April and August, positive temperature difference also decreases after sunrise between the inner and outer surfaces of the S wall and falls to its minimum around 14:00 (close to zero) before climbing again to its maximum in early morning. The difference is generally positive throughout the day and night for the S wall surface in April and August and heat always goes from the inner to the outer surface. In addition, in the three months the inner versus outer surface difference changes in numerical value and extent more significantly on the E wall than on the S wall, which shows the effect of azimuth on the surface temperature.

The case of the northern room (figure omitted) is similar to the southern one. The difference is also larger in December and April than in August and shows similar trend of variation with azimuth (E and N) in the three months — there is large positive temperature differences, heat transports from the inner to the outer wall and positive temperature differences reach the maximum between 02:00 and 08:00. During the day, the difference between the E and N wall surfaces is relatively large, with the E wall having larger numerical value and extent than the N wall in the three months. After sunrise, however, positive temperature difference between the inner and outer surface of the E wall decreases rapidly and approaches zero and becomes negative around 10:00, being minimum around 11:00, which is most prominent in April (–9.2°C), followed by December (–6.5°C) and August (–1.8°C), indicating the outward transport of heat. With the rapid decrease of the outer surface temperature, the negative temperature difference is getting smaller so that the E wall keeps a high positive inner/outer surface temperature difference that transports heat outward from the inner surface. Showing a slowly decreasing trend, the positive temperature difference between the inner and outer surface of the N wall remains positive after sunrise, for it receives the shortest sunshine on the outer surface throughout the year. A minimum appears at 16:00, lagging behind the E wall, with heat always transporting from the inner surface to the outer one.

From the analysis above, it is known that temperature falls dramatically on the outer surface of the walls at night, making it much cooler than the inner surface and driving heat outward;

temperature increases rapidly on the outer surface as it is being heated by the sun after sunrise and gets warmer than the inner surface, transporting heat inwards; temperature falls rapidly on the outer surface after sunset, transporting heat again outwards.

3.2.2 DIURNAL RANGE OF TEMPERATURE DIFFERENCE BETWEEN THE INNER AND OUTER WALL SURFACES

From the diurnal difference of temperature between the inner and outer wall surfaces for the months (Tab.1), it is noted that it is larger in December and April than in August, even in terms of azimuth.

For the outer surface, difference in the diurnal range is large with azimuth, being the maximum on the S wall (22.8°C, five times that for the inner surface of the S wall in the southern room), followed by the E direction and then N direction. In April and August, the diurnal difference is the largest on the outer surface of the E wall, followed by the S and then N directions. Specifically, the diurnal difference is the highest in April for the E wall (23.3°C, 12 times that for the inner surface of the E walls in both rooms). Additionally, it is much larger on the outer surfaces than on the inner one in all the months.

It is known from the diurnal difference for the inner surface that it can be as large as about 5.0°C for the S and E walls in the southern room, which is higher than in the northern room. The diurnal difference for all inner surfaces is about 2.0°C in April and August, showing that small diurnal difference of the inner wall surface is associated with small differences between azimuths.

Tab.1 Diurnal difference of surface temperature between the inner and outer wall in the three months (°C)

Time	Outer surface			Inner surface			
	N	E	S	.S, SR	E, SR	E, NR	N, NR
Dec.	12.2	17.6	22.8	4.8	5.1	2.3	1.6
Apr.	11.1	23.3	15.3	1.7	2.0	2.0	1.8
Aug.	7.2	9.5	8.5	1.9	2.4	1.4	1.1

Note: SR and NR stand for the southern room and northern room, respectively.

4 CHARACTERISTICS OF HEAT FLUX ON THE WALL

The variation of temperature difference between the inner and outer surfaces of the wall is displayed as heat flux through the walls in terms of the magnitude and direction (Fig.3). It is the difference in the direction of heat transportation over sections of the day that keeps temperature from varying too much between the inner and outer surfaces of the wall, i.e. the transportation of heat is adjusting the surface temperature of the walls. Across a number of assumed layers, increased temperature on the shallow layer of the wall and heat is transported to the interior layer in the afternoon; heat, stored in the interior layers of the wall, begins to move to the shallow layer before transporting as a whole to the outer surface of the wall, at night and in the morning. In the course of inward and outward transportation of heat, temperature within the wall is adjusted to make the variation of surface temperature through the wall and that of ambient temperature more in-phase and less different from each other. It modifies the condition of indoor thermal environment that has close relationship with the survival of human being, being significant for the design of architectural buildings and the selection of building materials.

For an architectural expression that relates heat flux through the wall and inner/outer surface temperature difference[1]:

$$Q_{s-s} = A\frac{\lambda}{d}\left(t_2 - t_1\right) \quad (1)$$

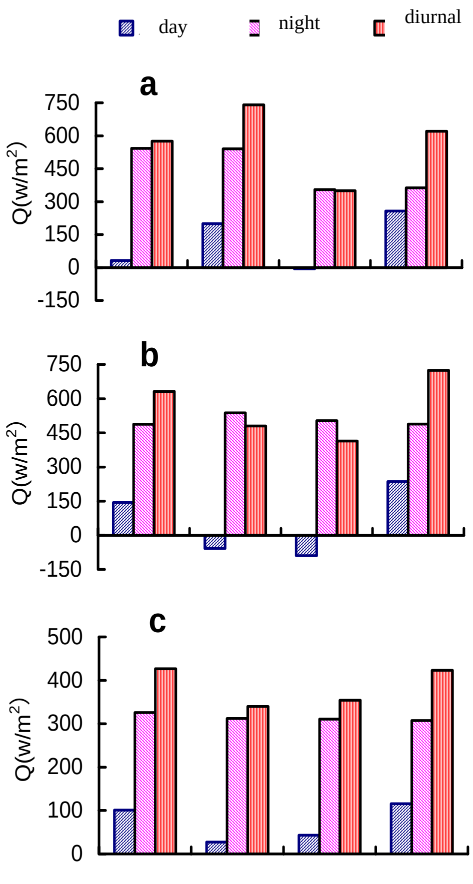

Fig.4 Mean heat flux through walls. a. Dec., b. Apr., c. Aug..

where $Q_{s\text{-}s}$ is the heat flux through the wall from a warm surface to a less warm one (W/m^2), the surface area of the wall is A (m^2), thickness is d (m), the heat conductivity coefficient is λ, and t_2-t_1 is the gradient of temperature (°C).

The inner/outer temperature difference for the southern and northern walls is used to calculate the heat flux through unit area of wall (A=1 m^2) at individual time and then the sum of heat flux through unit area of wall at individual azimuths of the office building over periods of daytime (08:00 – 19:00), nighttime (20:00 – 07:00) and whole day (00:00 – 23:00) (see Fig.4). It is obvious that the heat flux through the wall is larger at night than during the day. At night, the outer surface cools and sends off heat more rapidly than the inner surface, causing much lower temperature on the latter. Transporting from the inner surface to the outer one, heat has its maximum flux in December through unit area of the S wall in the southern room (543.0 W/m^2) but its minimum flux in August through unit area of the N wall in the northern room (307.3 W/m^2). During the day, temperature rises on both surfaces of the wall and their difference is moderate and so is the heat flux through the wall. With rapid increase of temperature as a result of direction solar rays, the outer surface measures higher temperature than the inner surface around mid-day and enables heat to transport inwards. In the southern room, heat flux is the most significant in April through the E wall (–90.0W/m^2). The combined result is that the diurnal total of heat flux for the three months is pointing outwards from the inner surface, which sees the maximum in December through unit area of the E wall of the southern room (740.2 W/m^2) and the minimum in August through unit area of the same wall of the same room (339.6 W/m^2).

5 CONCLUDING REMARKS

Through comparison and analyses of relevant data of temperature on the surface of inner and outer walls of a building in downtown area of Kunming in different seasons, the work has found that surface temperature is higher on both sides of the wall in April and August than in December; its difference between the inner and outer surfaces facing different azimuths is larger in April and December when it is usually fine than August when it is usually cloudy.

In general, the E outer wall has the largest surface daytime and nighttime temperature in April and August when there are relatively large direct solar radiation and longest possible shining hours, with early sunrise and large angle of altitude. The S direction follows and the N direction is the smallest (for it receives virtually no direction solar rays); differences are larger in mostly fine April than in cloudy August. Due to direct solar rays, the S outer surface is warmer than the N one and even than the E one over sometime in December when the sun sets late and shines at a low angle of altitude. For the appearing time of maximum diurnal surface temperature, the E outer wall is the earliest, followed by the S and then the N ones. As far as the whole office building is concerned, the thermal environment is better on the S wall than on the N one, which is consistent with the findings by Zhou and Shao et al[6 - 8].

As also shown in the study, the inner surface of the E wall is warmer diurnally than that of the S and N wall in either the northern or southern room, with the difference larger in April than in August. The surface temperature is higher on the inner surface of the southern room than that of the northern room, with the difference the most significant in winter (December) when the angle of solar altitude is relatively low (being as large as 4°C or more). In addition, maximum temperature appears earlier on the inner surface of the E wall than that of the S wall in the southern room, with the E and N walls a close match in the northern room.

Combining the results of diurnal variation analysis conducted above, we note that the maximum and minimum temperatures occur later on the inner surface than on the outer surface. The diurnal temperature range is lower on the inner surface than on the outer surface, which is consistent with the results of Givoni[11].

The results above show that the intensity of incoming solar radiation, determined with the month and orientation of the wall, causes large differences in the numerical and temporal distribution of individual wall surface temperature in urban areas, thus resulting in different patterns of temperature on them and differences in indoor surface temperature and thermal condition[9]. Temperatures on wall surfaces are closely related with air temperature indoors. For the Kunming area where there is no household warming system, the surface indoor temperature in winter is between 7.4°C and 15.6°C, reflecting on its ever-green characteristics. As the interface separating indoors and outdoors, walls in architectural buildings store and release heat, playing special thermal roles. The surface temperature varies with location of the city and building material, which inevitably affects the micro-climate of urban buildings. It remains a topic to study in more detail.

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