

THERMAL EFFECTS OF BUILDING'S EXTERNAL SURFACES IN CITY

—Characteristics of Heat Flux into and out of External Wall Surfaces

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ABSTRACT: This study examined the thermal effects of building's external wall surfaces, using observational data of spatial-temporal distribution of surface temperature, air temperature, and heat flux into and out of external surface. Results indicate that external wall surface temperature and nearby air temperature vary with the change of orientation, height and season. In general, the external wall surface temperature is lower near the ground, and is higher near the roof, than nearby air temperature. But north wall surface temperature is mostly lower than nearby air temperature at the same height; south wall surface temperature during the daytime in December, and west wall surface temperature all day in August, is respectively higher than nearby air temperature. The heat fluxes into and out of external wall surfaces show the differences that exist in the various orientations, heights and seasons. In December, south wall surface at the lower sites emits heat and north wall surface at the higher sites absorbs heat. In April, all external wall surfaces, emit heat near the ground and absorb heat near the roof. In August, west wall surface all day emits heat, and other wall surfaces just show the commensurate behavior with that in April.

KEY WORDS: external wall surface; thermal effect; heat flux intensity; spatial-temporal distribution

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1 INTRODUCTION

With the recent modernization and urbanization of China, urban areas have greatly increased, and giant buildings, especially those taller than 100m, have been dominant in cities, which have resulted in the great increase in the proportion of building's external surface to total urban area. The differences of thermal properties mainly induced by solar radiation between building's external surfaces are obvious for different exposures, which can inevitably influence the distributions of air temperature nearby, even the vertical distributions of urban climate environment.

In China the density and height of buildings are rapidly increasing due to limited vehicles, which intensifies the interactions of buildings and climatic environment and creates the notable differences of thermal-physical characteristics from foreign residential quarters. The rapid pace of people's controls on buildings therefore

demands knowledge of correlation of buildings and urban climatic environment, especially thermal effects, in order to exploit reasonable planning and design of architecture and achieve preferable urban development.

In the field of architecture, there has already been much work relating the effect of air temperature on external surface temperature and then on indoor air temperature (BÀNHIDI, 1985; CHEN, 1991; GIVONI, 1979). YOSHIDA *et al.* (1990), NARITA (1992), PARK (1987) have discussed the thermal characteristics of building and ambient environment, including their interactions. Research on urban climate indicated that surface temperature, heat capacity and lapse rate were evidently dissimilar at different urban surfaces (NUNEZ and OKE, 1976, 1977, 1980; KOBAYASHI, 1979). Measurements obtained by TAKAHASHI and FUKUOKA (1994) and ZHANG (1995) showed that in urban area the roof surface was the second thermal active surface, which is different from the ground.

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In China there are numerous comparable measurements from other localities, such as Changchun, Shanghai, Zhengzhou and Guangzhou. These observations showed the distribution of solar radiation on different orientations of wall surfaces (SUN and FU, 1999; ZHU, 1987; ZUO, 1991). Analyzing the observations of radiation balance, air temperature and wind velocity at the different urban surfaces, ZHANG *et al.* (ZHANG and LI, 1997; ZHANG *et al.*, 1997, 1998) pointed out that those elements at the roof surface whose area occupied a considerably larger share of urban area, were different between the city and countryside, which influenced the heat exchange of buildings and ambient environment.

The thermal effects of building's external wall surfaces on urban thermal environment and on the vertical characteristics of urban climate cannot be ignored. Therefore, further research is necessary to confirm the fact whether the building's external wall surface is a new active thermal surface in the urban area or not, but thermal characteristics of external wall surface are less well known and still require detailed investigation.

This research is concerned with the heat flux intensity of building's external wall surface and its thermal effect in Kunming City, Yunnan Province, China, and is undertaken by analyzing observations of external surface temperature, air temperature and heat flux. It is hoped that this research may provide the spatial-temporal distribution and seasonal variations of thermal characteristics of building's external wall surfaces.

2 DATA AND METHOD

2.1 General Situation of Study Area

In Kunming City of Yunnan Province, located in an area of low latitude (25°04'02"N, 102°42'00"E) and high altitude (1892m), four seasons in the urban area are not distinguishable easily, but the difference between dry season (November–April) and rainy season (May–October) is distinct, which is induced by the unique geographical location and atmospheric circumstance. The total solar radiation is strongest, commensurate with that in Lhasa, in the end of dry season, and weakest in rainy season, equal to that in Guangzhou. The urban area of Kunming covered 148km² with a population of 2 108 100 (YSB, 2001). With the increase of building's density and area due to rapid urbanization, the structures and properties of urban underlying surfaces become more complicated.

2.2 Study Sites and Data Sources

Study sites were established at the rooftop, external wall

surfaces, covered with mosaic in four orientations (north, east, west and south), of an office house of four stories and 15.1m, and at nearby concrete ground and 0.05 m-tall grass, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Kunming, China.

External wall surface temperatures (505-infrared radiation thermometer, made in Japan MINOLTA Company) in four orientations and air temperatures (TR-72 recording psychrometer, made in Japan T and D Company) 0.5m far from the former were measured at the height of 0, 0.5, 1.5, 6, 10, 14m, respectively. Another observing program on the rooftop, ground and grass includes: surface temperature (505-infrared radiation thermometer, made in Japan MINOLTA Company), air temperature at the height of 0.5m and 1.5 m (TR-72 recording psychrometer, made in Japan T and D Company), wind speed and wind direction (FV-1 anemometer, made in Changchun Meteorological Instrument Institute, China), and cloudiness. These meteorological elements were investigated at an interval of one hour except for air temperature recorded every four minutes.

The data were derived from a period of December 25–27, 1999 (lack the observation value of west wall surface), August 3–12, 2000, and April 20–24, 2001. Cloudiness is expressed as values of 0–10, where 0 indicates no clouds and 10 indicates overcast skies. Fig. 1 shows the time series of average cloudiness in December, April and August in Kunming. The weather is clear in December and April, and cloudy in August, which stands for the general situation in the corresponding season in Kunming.

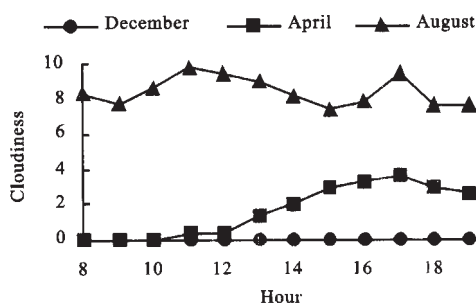


Fig. 1 Temporal variation of low clouds

2.3 Computation of Heat Flux into and out of External Wall Surface

Many theoretical and numerical studies have investigated the heat exchange between building's external wall surface and ambient atmosphere. Considering convection and radiation, heat flux intensity can be determined (CHEN, 1991):

$$Q = a_r(T_s - T) \quad (1)$$

where Q represents total heat flux intensity (W/m^2) a_f is the coefficient of heat exchange ($20.9\text{W}/(\text{m}^2 \cdot ^\circ\text{C})$ for building's external wall surface), T_s is external wall surface temperature, and T is air temperature. $Q > 0$ shows the heat flux out of external surface, and $Q < 0$ indicates the heat flux into external surface.

3 RESULTS AND ANALYSIS

3.1 Characteristics of External Wall Surface Temperature and Nearby Air Temperature

3.1.1 Spatial-temporal distribution of external wall surface temperature

The spatial-temporal distribution of external wall surface temperature is shown in Fig. 2. In general, external wall surface temperatures are higher, in April or August than in December, during the daytime than during the nighttime, and near the ground than near the roof.

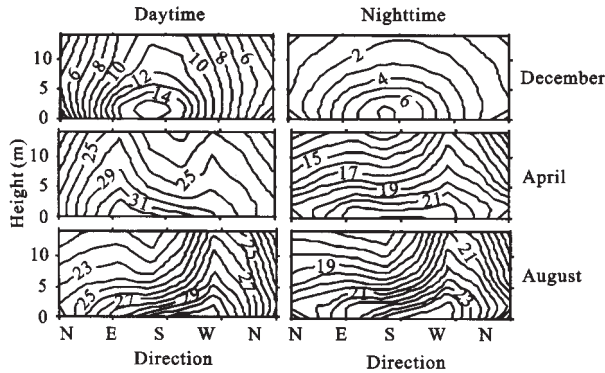


Fig. 2 Average external surface temperature ($^\circ\text{C}$)

At the same height, in December, external surface temperature is highest on south wall due to lower solar elevation and longer sunshine duration, and is lowest on north wall. In April, because daily extraterrestrial irradiation on the vertical wall surfaces in Kunming in summer is stronger on east (west) wall than on south (north) wall (Fig. 3) due to higher solar elevation and longer sunshine duration, external surface temperature is higher, on east and west wall during the daytime, on west wall during the nighttime, than that on the other surfaces. In August, the distributions of external surface temperatures are mostly similar, influenced by cloudy weather. The external surface temperature is highest on west wall due to slightly stronger daily extraterrestrial irradiation, and lowest on north wall.

3.1.2 Spatial-temporal distribution of air temperatures

Fig. 4 shows the spatial-temporal distribution of air temperature 0.5m far from external wall surface at the same height. Air temperatures are higher, in April or

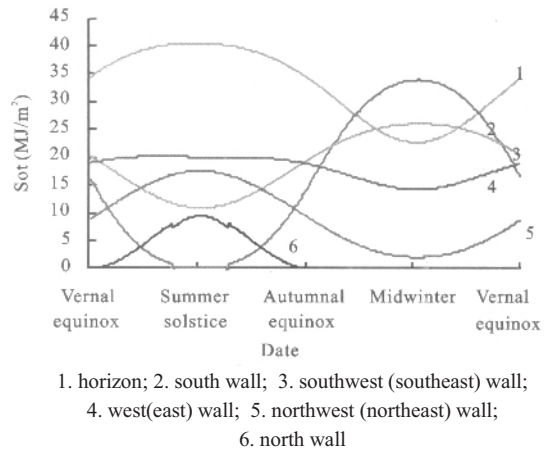


Fig. 3 Annual variation of daily extraterrestrial irradiation on the 8-azimuth vertical wall surfaces in the city of Kunming

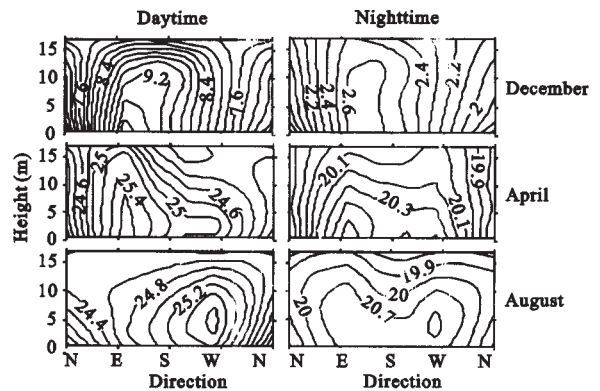


Fig. 4 Average air temperature near external surface ($^\circ\text{C}$)

August than in December, during the daytime than during the nighttime, and near the ground than near the roof.

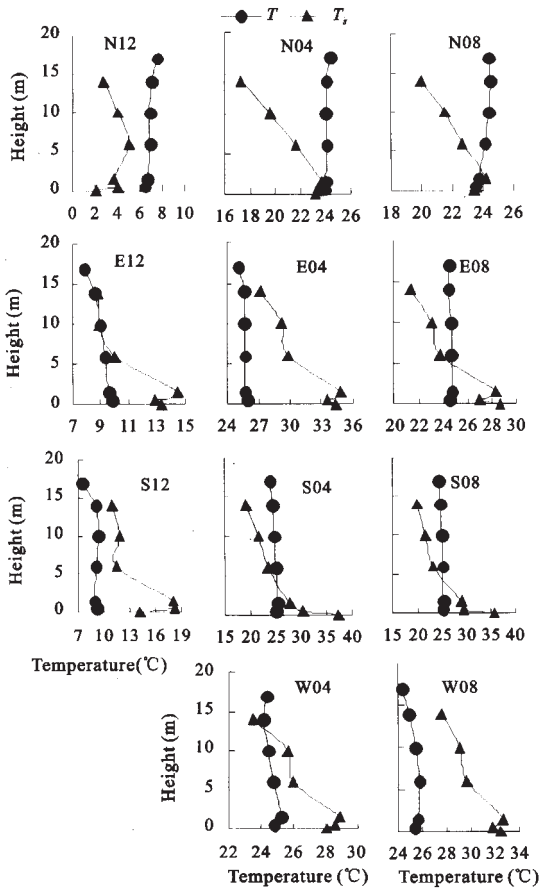
At the same height, in December, during the daytime, the maximum of air temperature is at the lower height for east wall, at the higher height for south wall, and the minimum is for north wall; during the nighttime, air temperatures are higher for east and south walls than for other walls. In April, air temperature is highest for east wall and lowest for north wall, all day. In August, air temperature is highest for west wall (at the height of 4m) and lowest for north wall.

3.2 Vertical Comparison of External Wall Surface Temperature and Air Temperature

The vertical distribution of mean external wall surface temperature and air temperature at the same height during the daytime (8:00 a.m.–6:00 p.m. Beijing standard time in December, and 8:00 a.m.–7:00 p.m. Beijing standard time in April and August) are showed in Fig. 5. For north wall, in the three seasons, air temperature

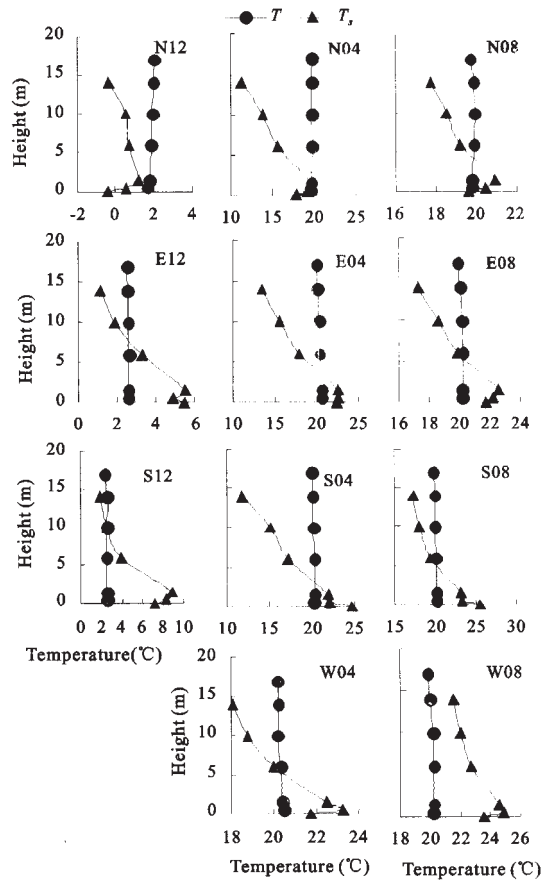
is higher than wall surface temperature, and the difference is smaller near the ground than near the roof. For east wall, in December and April, air temperature is mostly lower than surface temperature, and the difference is more distinct at bottom than at top; in August, air temperature is lower near the ground, and is higher near the roof, than surface temperature. For south wall, in December, air temperature is lower than surface temperature, and the difference is notable near the ground; in April and August, air temperature is lower at the lower sites, and is higher at the higher sites, than surface temperature. As for west wall, in general, air temperature is lower than surface temperature.

obvious difference at top; in August, air temperature is lower at the lower sites, and is higher at the higher sites, than surface temperature. For east wall, air temperature is lower at the lower sites, and is higher at the higher sites, than surface temperature, in the three seasons. For south wall, air temperature is lower at the lower sites, and is higher at the higher sites, than surface temperature; the difference is notable near the roof in April and near the ground in December, and is commensurate at the same height in August. As for west wall, in April, air temperature is lower than surface temperature at the lower sites. In August, air temperature is lower than surface temperature at the same vertical height.



12, 04 and 08 represent the month; N stands for the north wall, E for east wall, S for south wall, and W for west wall
Fig. 5 Vertical distribution of external surface temperatures (T_s) and air temperatures (T) in the daytime

The vertical distribution of mean external surface temperature and air temperature at the same height during the nighttime (7:00 p.m.–7:00 a.m. Beijing standard time in December, and 8:00 p.m.–7:00 a.m. Beijing standard time in April and August) are showed in Fig. 6. For north wall, in December and April, air temperature is higher than surface temperature, with most



12, 04 and 08 represent the month; N stands for the north wall, E for east wall, S for south wall, and W for west wall
Fig. 6 Vertical distribution of external surface temperatures and air temperatures in the nighttime

3.3 Characteristics of Heat Flux into and out of External Wall Surface

3.3.1 Spatial-temporal distribution of heat flux intensity

The spatial-temporal distribution of heat flux into and out of external wall surfaces estimated using Equation (1) is presented in Fig. 7.

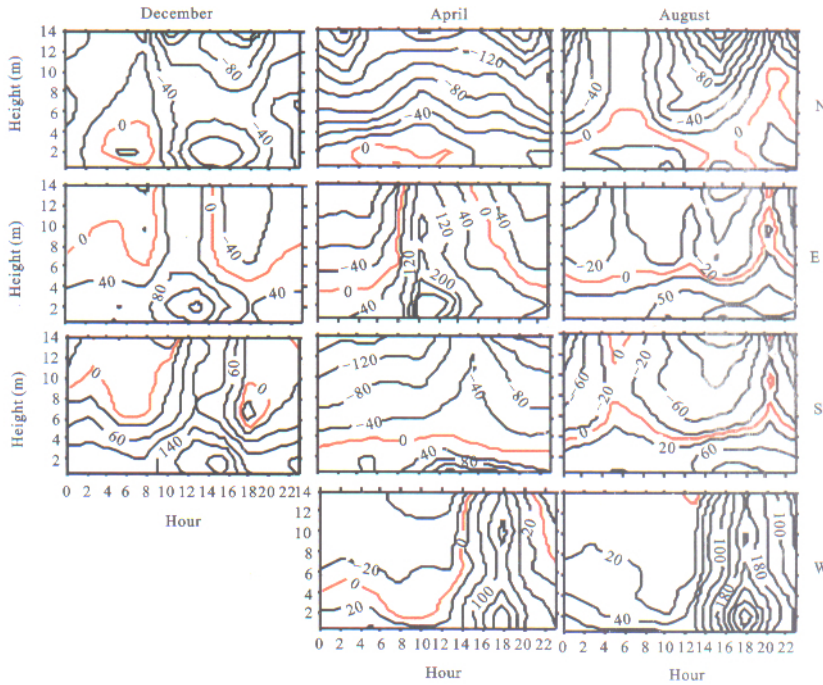


Fig. 7 Spatial-temporal distribution of heat fluxes into and out of external surfaces (w/m^2)

North wall, in December and April, in most time, absorbs heat ($Q < 0$); heat flux intensity is strongest at top (-154.4 W/m^2 in December, -248.8 W/m^2 in April). But the difference of heat flux between daytime and nighttime is more distinct in December than in April. In August, $Q > 0$ near the ground and $Q < 0$ near the roof, but the absolute value of heat flux intensity is smaller near the ground (58.8 W/m^2) than that near the roof (185.3 W/m^2), which indicates that north wall mostly absorbs heat from ambient atmosphere.

East wall, in December and April, in most time of the daytime, emits heat ($Q > 0$); the heat flux intensity is strongest near the ground (226.0 W/m^2 in December, 365.5 W/m^2 in April); at night, east wall emits heat ($Q > 0$) at the lower sites, but just shows the opposite behavior at the higher sites ($Q < 0$). In August, in most time, east wall emits heat ($Q > 0$) at the lower sites and absorbs heat ($Q < 0$) at the higher sites, but the absolute values of them are commensurate.

The heat flux into and out of south wall varies rapidly with the change of season. In December, during 8:00–16:00 of the daytime, south wall, receiving longer duration of sunshine than other walls, emits heat ($Q > 0$) and the heat flux intensity is strongest near the ground (350.0 W/m^2); during 17:00–7:00, although $Q < 0$ at the higher sites, its absolute value is very small, which shows that the thermal effect of south wall focuses on heating air. In April, heat flux intensity is nearly not time dependent, but $Q > 0$ below 3m and $Q < 0$ at the

higher sites. In August, in general, $Q > 0$ at the lower sites and $Q < 0$ at the higher sites; about at 6:00 and 20:00, heat flux intensity at the top nears zero.

For west wall, in April and August, during the post-meridian time, both its emit heat ($Q > 0$) and its heat fluxes intensity are strongest at the height of 1.5m and 10m. Although $Q < 0$ at the higher sites in April, its absolute value is very small.

3.3.2 Vertical distribution of heat flux intensity

The vertical distribution of mean heat flux intensity during the daytime is showed in Fig. 8. In December, north wall absorbs heat ($Q < 0$) at all vertical sites. The heat flux out of east wall ($Q > 0$) is strongest at the height of 1.5m (1135.1 W/m^2) and is weakest at the top. The heat flux out of south wall is stronger than that out of east wall at the same height.

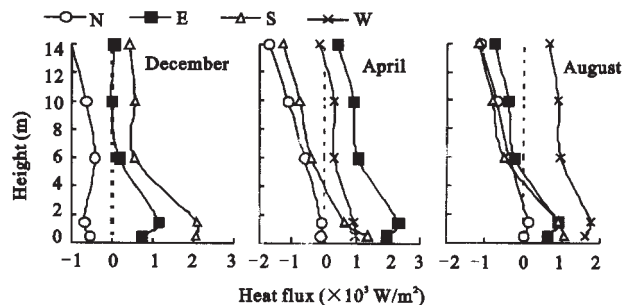


Fig. 8 Vertical distribution of heat fluxes into and out of external surfaces during the daytime

In April, the heat flux into north wall ($Q < 0$) is strongest at the top (-1709.2 W/m^2). The heat flux out of east wall ($Q > 0$) is stronger than that out of other walls at the same height, and its maximum is at the height of 1.5m (2299.2 W/m^2). The heat flux out of south wall is strongest at the height of 0.5m (1356.9 W/m^2), and the heat flux into south wall is strongest at the top (-1269.1 W/m^2). The maximum of heat flux out of west wall is near the ground (957.2 W/m^2).

In August, the behavior of heat flux into north wall is consistent with that in April. Both south and east wall emit heat ($Q > 0$) at the lower sites, and absorb heat ($Q < 0$) at the higher sites. Commensurate with April, west wall always emits heat ($Q > 0$) at the vertical height.

Fig. 9 displays that the vertical distribution of mean heat flux intensity at night. In December, the heat flux into north wall hardly varies with the increase of height. The heat flux out of south wall near the ground is stronger than that out of east wall, and the heat flux into south wall near the roof is weaker than that into east wall. The maximum heat flux intensity is 798.9 W/m^2 for east wall, 1698.4 W/m^2 for south wall, both at the height of 1.5m.

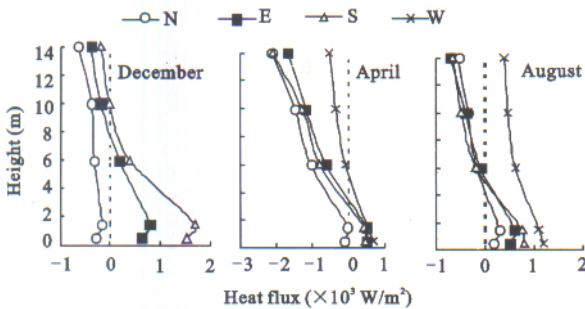


Fig. 9 Vertical distribution of heat fluxes into and out of external surfaces during the nighttime

In April, north wall at all sites, east wall and south wall above the height of 3m, all absorb heat, and the maximum heat flux is near the roof. The heat flux out of west wall is stronger at the lower sites, and weaker at the higher sites, than that out of other walls.

In August, the heat flux out of south wall near the ground is stronger than that out of north and east wall, and heat flux into east wall near the roof is stronger than that into north and east wall. The heat flux out of west wall is stronger than that out of other walls at the same height.

3.3.3 Spatial distribution of total heat flux

To investigate the thermal effect of each external wall surface on the urban atmosphere, the spatial distribution of total heat flux over the 24-hour period were plotted in

Fig. 10. In December, total heat flux out of external wall surface is the strongest at south wall near the ground (3791.4 W/m^2), which shows south wall surface mostly emit heat, and this effect decreases with the ascending height. Total heat flux into external wall surface is the most distinct at north wall near the roof (-1002.7 W/m^2), indicating the thermal effect of absorbing heat at north wall increases with the ascending height.

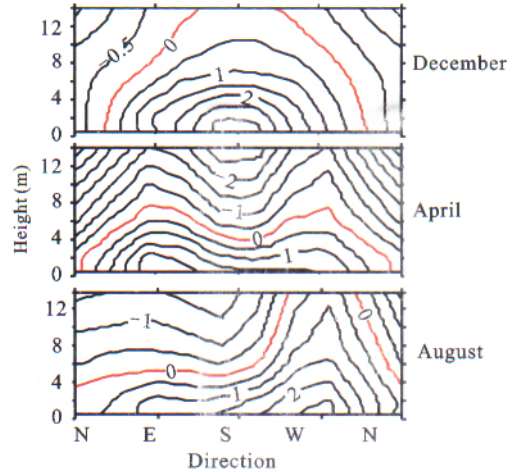


Fig. 10 Total diurnal heat fluxes into and out of external surfaces ($\times 10^3 \text{ W/m}^2$)

In April, the thermal effect is consistent with that in December for north wall, but it shows emitting heat at the lower sites and absorbing heat at the higher sites for other three walls. The maximum of total heat flux out of external wall surface (2798.5 W/m^2) appears at east wall, and at the height of 1.5m. Total heat flux into external wall surface is strongest (-3825.9 W/m^2) at south wall, and at the top.

In August, west wall has the thermal effect of heating air. All other walls emit heat at the lower sites and absorb heat at the higher sites. The maximum of total heat flux out of external wall surface (2858.1 W/m^2) is at west wall, at the height of 1.5m. The strongest total heat flux into external wall surface (-1839.9 W/m^2) is at south wall, near the roof.

4 CONCLUSIONS

Using the meteorological observation data of surface temperatures and nearby air temperatures at the same height for three seasons, this study examined the heat flux into and out of four building's external wall surfaces, and determined the characteristics of their thermal effects, in Kunming City, China.

Following conclusions are drawn from this paper:

(1) Both external wall surface temperature and air temperature show the differences that exist in various orientations, heights and seasons.

(2) The differences between external wall surface temperature and air temperature vary with the increase of height. There are three patterns: air temperature is lower than surface temperature (north wall); air temperature is higher than surface temperature (south wall in December, west wall in August); air temperature is lower at the lower sites, and higher at the higher sites, than surface temperature. The third situation is dominant.

(3) The heat flux into and out of building's external wall surface show the differences that exist in the various orientations, heights and seasons, which indicates the complexity of heat exchange between external wall surface and ambient atmosphere. North wall mostly absorbs heat, increasing in this effect with ascending height; the maximum appears in April. Both south wall in December and west wall in August emit heat, decreasing in this effect with ascending height. In general, external wall surface emit heats at the lower sites, and absorbs heat at the higher sites.

(4) The total diurnal heat fluxes into and out of external wall surfaces present the effect of thermal source near the ground for south wall, and thermal sink near the roof for north wall, in December. It is the thermal source effect for west wall in August, but thermal source effect at the lower sites and thermal sink effect at the higher sites for other three walls, in April and August.

Such thermal characteristics of external wall surfaces inevitably influenced the distribution of urban thermal environment, and they cannot be negligible. It needs to be emphasized here that heat flux into and out of external wall surfaces vary in a complicated manner depending on building's height and external surface materials, and they are also influenced by synoptic condition. More profound and comprehensive discussion based on more observational sites deserves more attention.

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