PREDICT THE OUTDOOR THERMAL ENVIRONMENT AND THERMAL COMFORT IN ANNUAL TIME SCALE

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ABSTRACT

A comfortable outdoor thermal environment is very important for pedestrian's health and safety. However, in the traditional design method, usually only several typical hours are considered. Although these typical hours can be reproduced well, considering the complicated outdoor environment and the varied weather condition, the simulation result is not capable of reproducing the overall thermal condition of a season. Therefore, the concept of annual prediction is proposed. However, the calculation amount is huge so that some simplification is necessary. A simplification for wind environment simulation is proposed and a homemade CFD code is developed to fulfil the annual prediction of wind environment. Furthermore, the most time consuming radiation simulation is simplified based on the simulation system SPOTE so that the calculation time is shortened greatly so that the annul prediction is possible. To evaluate the annual outdoor thermal comfort, the concept of „best clothes insulation' is proposed. A comfortable outdoor environment is defined as an environment in which pedestrians can reach comfortable state by adjusting the clothes insulation in a reasonable region. The best clothes insulation is defined as that can make people feel most comfortable in the specific environment. Based on this definition, some annual thermal comfort indices are proposed. A design plan of a living district is simulated and evaluated, and the results of some typical hours and the entire year are studied. The comparison shows that the results of annual prediction are more helpful for improving the design plan.

INTRODUCTION

In recent years, industrialization and urbanization have affected weather condition significantly, which is well known as global warming effect. The global warming tends to cause more severe weather conditions, which endanger pedestrians' health and comfort. The urban planning designers and researchers have been working on developing different measures in order to improve the outdoor thermal environment. One of the best and quickest methods is using numerical simulation to assist designing and planning.

Due to previous studies, a carefully modelled simulation can give a satisfactory prediction of the outdoor thermal environment at a specific hour. However, there are many factors affecting the outdoor thermal environment are time dependent, which makes the outdoor environment much more complicated. Therefore, it is difficult to evaluate the outdoor thermal environment by a single hour simulation because of the complexity of outdoor climate.

With the development of computer science, it is possible to execute very complicated and time-consuming simulations. In this paper, we aim to develop a simulation system which can predict the outdoor thermal environment and thermal comfort in annual time scale and also some evaluation indices so that the influence of time dependent variables can also be considered.

METHODOLOGY

In our study, SPOTE (Simulation Platform for Outdoor Thermal Environment) validated by a filed measurement in the summer of 2002(Ma et al., 2012; Lin et al., 2008) is used to predict the outdoor thermal environment. SPOTE consists of an air model, a vegetation model, an underlying surface model and a general radiation calculation model, and could deal with the coupled calculation of radiation, convection, conduction and air flow when the plants exist.

Some adjustments to the program structure and some simplifications are made to make SPOTE capable of annual prediction, details are described as follows.

Simplification of wind model

Considering both the accuracy and the efficiency, 2-equation RANS model is the best choice in real case application. The Durbin turbulence model is one of the best 2-equation models (Mochida et al., 2008; Durbin 1996), therefore, in present paper Durbin turbulence model is adopted to predict the outdoor wind environment. However, the calculation amount is still unacceptable for prediction of every hour in a year.

Two assumptions are made to make the simulation executable: (1) The wind amplification factor (Blocken et al., 2004), which is defined as the ratio of local wind velocity at the building site to that at the meteorological site, is assumed to be constant under a certain wind direction. (2) The buoyancy effect is neglected so that the simulation of wind environment and heat transfer can be decoupled. It should be mentioned that these two assumptions do lead to some simulation errors under the circumstance of both intensive radiation and weak ventilation, but will make the simulation executable and help continuing the research. In another way, the extreme weather condition of both intensive radiation and weak ventilation is actually not very frequent, e.g. in TMY data of Beijing there are only 262 extreme hours (with a radiation intensity higher than 500W/m2 and wind velocity lower than 1m/s) in a year, thus the frequency of big errors is low in practice.

Under these assumptions, the incoming wind is divided into 16 directions which are restricted to the TMY data we use, and then the wind amplification factor of each direction is calculated by CFD. The hourly wind environment can be simply calculated by multiplying the amplification factor and the incoming wind velocity together so that the prediction can be finished in an acceptable time.

With the distribution of wind environment, the air temperature can be calculated by solving only the energy transportation equation with much less time.

Thermal model

The thermal model of SPOTE is based on the energy conservation equation of each surface cell. The impact of the weather conditions to the outdoor thermal environment can be determined by the heat balance of the solid wall. For any solid surface cell i exists the following heat balance equation:

$$S_i+R_i+H_i+C_i+LE_i=0 \tag{1}$$

Where i indicates element i; S_i is the absorbed solar radiation; R_i is the absorbed long-wave radiance from the sky and other surfaces; H_i is the sensible heat exchange between the surface and the surrounding air; C_i is the conductive heat exchange between the surface and the interior walls or deep soil beneath the ground; LE_i is the latent heat exchange between the vegetation and the surrounding air which is not considered in present study.

The view factors between each two surfaces are computed by the ray-tracing/Monte Carlo method. The direct and diffuse solar heat gain after multiple reflection is calculated using the Gebhart's absorption factor (Gebhart 1959) as equation (2) shows. The heat exchange of long-wave radiation is also calculated by Monte Carlo method and Gebhart's method as equation (3) shows.

$$S_i = \alpha_i (E_{Di} + E_{si}) + \sum_{j=1}^{n} B_{ij} (1-\alpha_j)(E_{Dj} + E_{Sj}) \tag{2}$$

$$R_i = \sum_{j=1}^{n} B_{ji} (\varepsilon_j A_j \sigma T_j^4) - \varepsilon_i A_i T_i^4 \tag{3}$$

Where α_i is the absorbance of solar radiation at grid *i*; E_{Di} is the direct solar radiation gain at grid *i*; E_{si} is the sky solar radiation gain at grid *i*; B_{ij} is the Gebhart's absoption factor; ε_i is the absorbance of long wave radiation at grid *i*.

In the present paper, the response factor method (Stephenson et al. 1967; Kusuda 1969) is adopted to solve the building and ground unsteady state heat conduction. When the response factors are achieved, the heat conduction flux can be represented as follows:

$$Q_{Ci}^{n} = A_i \left(\sum_{j=0}^{Ns-1} Y_i^j \cdot T_{bi}^{n-j} - \sum_{j=0}^{Ns-1} X_i^j \cdot T_i^{n-j} \right) \tag{4}$$

Where Q_{Ci}^{n} is the heat conduction flux of surface at time n; T_{bi}^{n-j} is the inside temperature of buildings or the underground temperature at time n-j; T_i^{n-j} is the outside surface temperature at time n-j; Y_i^j is the heat conduction response factor of wall or ground layer; X_i^j is the outside heat intake response factor of wall or ground layer.

More details of the model descriptions in SPOTE and the validation by a filed measurement can be found in previous studies (Ma et al., 2012; Lin et al., 2008).

Coupling of the simulation

Figure 1 shows a demonstration of the coupling process. After inputting some necessary data, the hourly wind environment has already been calculated in wind model. With the air temperature initially set as incoming weather data, the surface temperature can be calculated then used as the boundary condition for calculating air temperature, the iteration can reach convergence in very few steps. Finally, the four main parameters can be calculated.

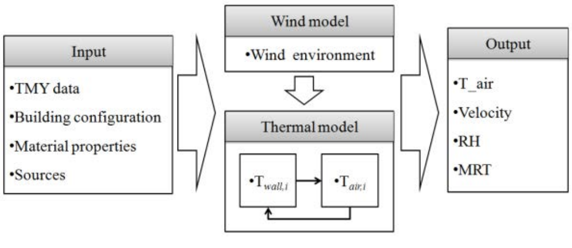


Figure 1 Flowchart of the coupling process

THERMAL COMFORT EVALUATION

“ Comfortable” is a subjective feeling. However, when dealing with the OTE assessment issue, an objective evaluation is essential. In previous studies, several kinds of thermal comfort indexes are proposed and studied, theoretically or experimentally. Among which the physiological equivalent temperature (PET) and the Standard Effective Temperature (SET) have abundant research and validations and are most widely used.

However, the relationship between thermal sensation and PET/SET is not definite due to previous studies. Thermal adaption is one possible explanation that pedestrian's thermal sensation is affected by the surroundings and personal physiological or psychological status. Since no corresponding conclusion has been reached, in this paper we will make an approximation in thermal comfort index issue and focus on the OTE evaluation.

In previous studies, the neutral temperature of SET is observed as around 25℃ (Spagnolo et al., 2003; Shimazaki et al., 2011; Zhai et al., 2009), and the acceptable range is approximately from 20℃ to 30℃. Correspondingly, in our study the acceptable range of SET is also approximately taken as 20℃-30℃.

Besides, there exists another issue that the pedestrians will change their clothes to fit the environment and get a most comfortable feeling. For a certain environment, it is not objective if an unsuitable CLO value is used in SET calculation. Therefore, an optimization of CLO is necessary when calculating SET. In our research, 51 default CLO settings (CLO value from 0.3 to 3.0, clothes color of black, white and gray) are inputted. For each parameter combination (Ta, MRT, V, RH), 51 SET values are calculated respectively and the most comfortable one is chosen as the evaluation of the environment.

By calculating the SET value of each hour, it is possible to evaluate the overall thermal comfort level of one lasting period. According to the acceptable range of SET, the percentage of comfortable hours / hot hours / cold hours during a period can be calculated. For example, the percentage of hot hours is defined as follows:

$$HOT\% = \frac{\text{number of hot hours}}{\text{number of total hours}} \tag{2}$$

CASE STUDY

A 100m×100m plane with six 16-floor buildings is studied. The simulation domain and the building model configuration are shown in Figure 2. The simulation was performed in 3D. The thermal environment and the thermal comfort at pedestrian level are compared between each case and the annual prediction.

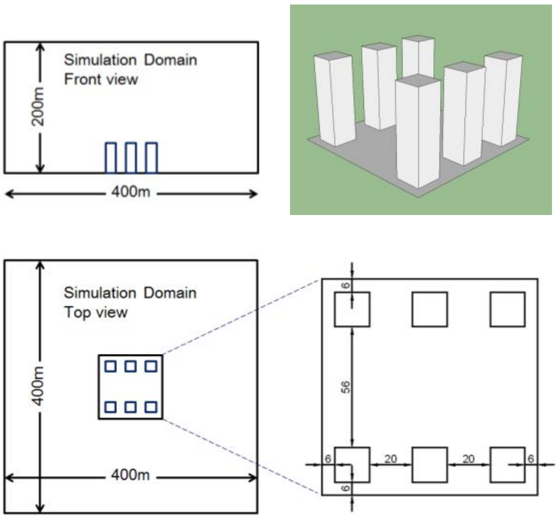


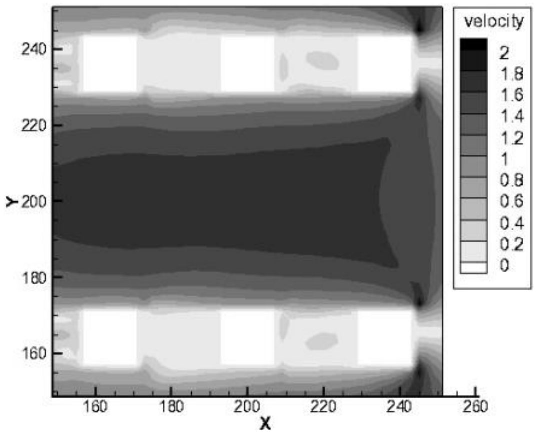
Figure 2 Building model configuration

Results of a typical hour

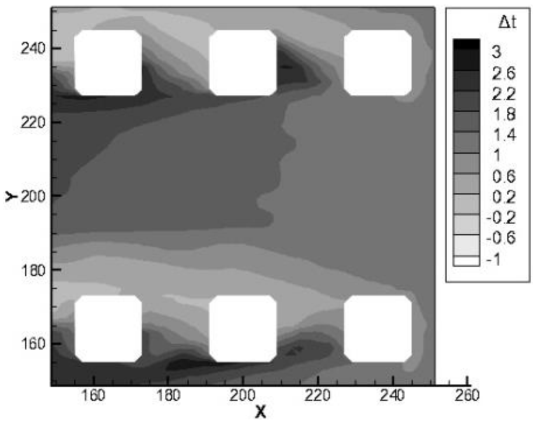
In this section, the day of July 21th is chosen at which the highest temperature is close to that of the whole summer, and the solar radiation is intensive. The predominant wind direction of the day is E and SE which is similar to that of the summer.

Table 1
Weather data of typical hours

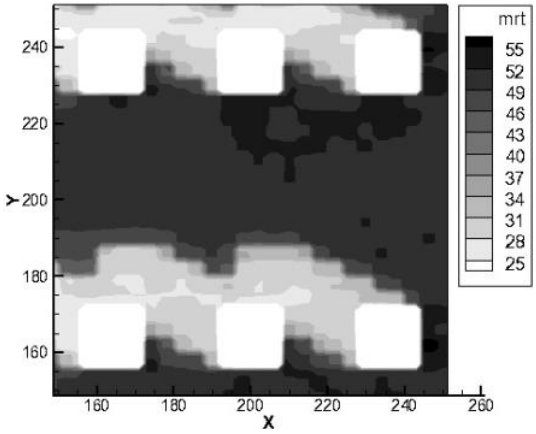
TIME		10:00	15:00
Dry bulb temperature	℃	28.6	32.4
Humidity	g/kg	17.09	17.29
Horizontal diffuse radiation intensity	W/m2	73	40
Normal direct radiation intensity	W/m2	790	685
Inflow wind velocity	m/s	3	3
Inflow wind direction		E	SE



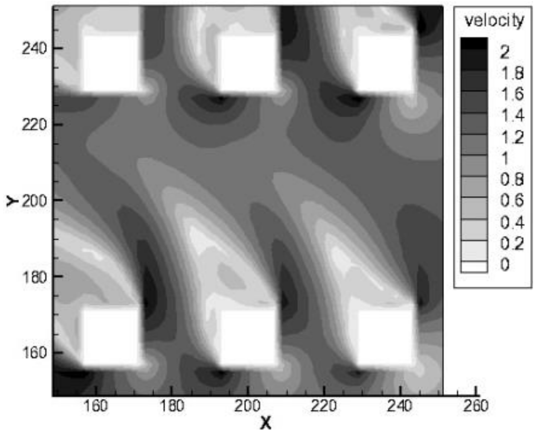
(a) Velocity at 10:00



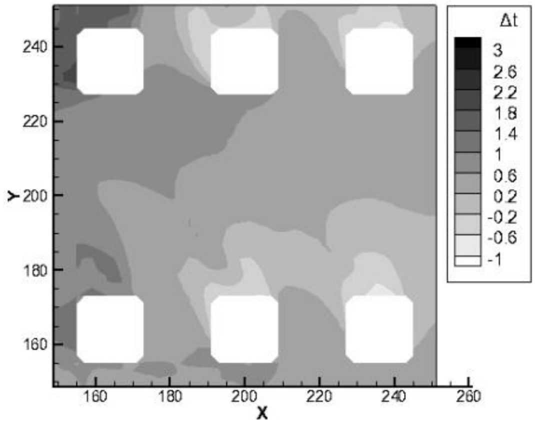
(b) Temperature increase at 10:00



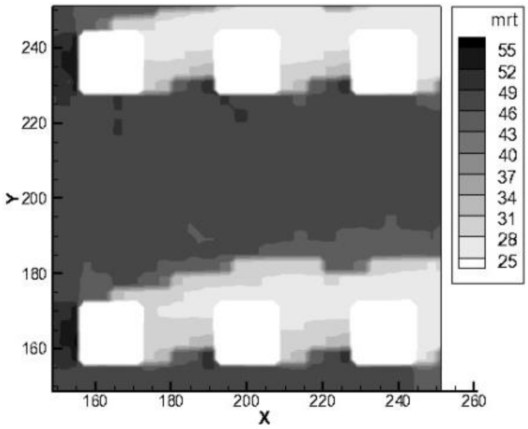
(c) MRT at 10:00



(d) Velocity at 15:00



(e) Temperature increase at 15:00

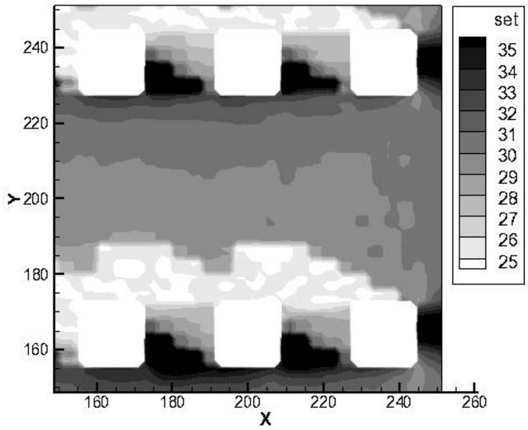


(f) MRT at 15:00

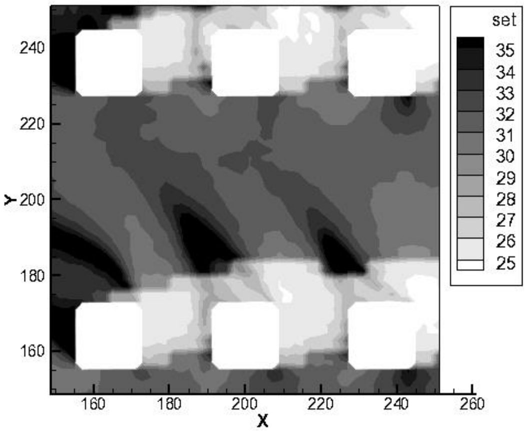
Figure 3 Simulation results at 10:00 (a, b, c) and 15:00 (d, e, f)

Figure 3 and Figure 4 show the simulation results of wind environment, air temperature, MRT and SET at 10:00 and 15:00. The MRT is greatly affected by the direct solar radiation. In shaded areas the average MRT value is near the inflow air temperature, while in areas exposed directly to sun the MRT value is about 50℃ in average. This indicates that the direct solar radiation is absolutely dominant in pedestrian’s radiation heat gain.

At 10:00, the incoming wind direction and temperature is E and 28.6℃. The surrounding walls and the ground are heated by the sun, especially the east and south walls and the non-shaded ground areas. The higher temperature appears at locations where lack ventilation and are exposed to the sun. At 15:00, the incoming wind direction changes to SE and the air temperature rises to 32.4℃. The air temperature of the non-shaded area is also higher than that in shade. Highest temperature regions are to the northwest of the two building in the left where are in the leeward areas and exposed to the sun.



(a) SET distribution at 10:00



(b) SET distribution at 15:00

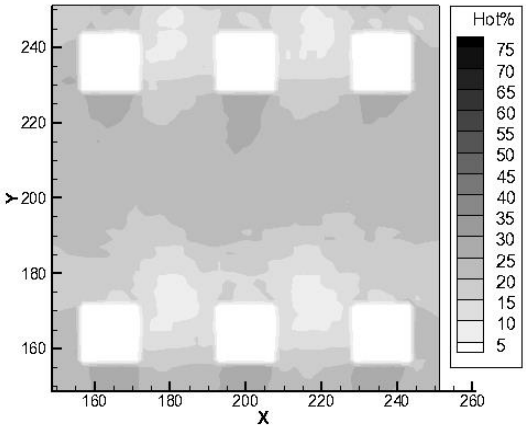
Figure 4 Thermal comfort evaluation comparison

At both hours, the SET distribution is similar to that of MRT indicating that shading is the first priority in summer. However, although solar radiation plays a most important role in pedestrian's thermal comfort, it is not adequate to predict the comfort level with just one parameter. As Figure 3 and Figure 4 show that in low velocity regions the value of SET is higher than other regions, which means that convection between human and environment is also important.

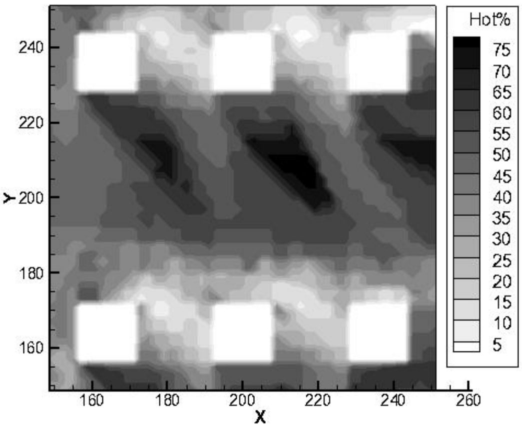
The simulation results of the two hours show that outdoor thermal comfort condition is greatly affected by the weather which changes every hour, meaning that every one specific hour is unique. We can conclude that the simulation within one specific hour cannot be an overall evaluation of one lasting period.

Results of a typical day: the "typical hottest day"

In air conditioning design and cooling load estimation, there is one kind of definition called "outdoor design dry-bulb temperature for summer air conditioning" (National standard of the people's republic of China, GBJ19-87) which represent the typical hottest day of the summer. In this paper we made up one "typical hottest day" by comparing the outdoor temperature.



(a) Percentage of hot hours of the entire summer



(b) Percentage of hot hours of the "typical hottest day"

Figure 5 Percentage of hot hours (a) the entire summer (b) the "typical hottest day"

Figure 5 shows the percentage of hot hours each for the entire summer and the "typical hottest day". The highest percentage of the "typical hottest day" reaches about 75% and it is apparently located in the leeward area of the buildings. However, the highest percentage of hot hours is only about 30% in the plane and the hottest areas are all located to the south of the buildings where are always directly exposed to sun. Besides, the reflection from both the south walls and the ground also deteriorates the thermal condition in these regions. Furthermore, these regions are close to the buildings where are frequently blocked by the buildings and poorly ventilated.

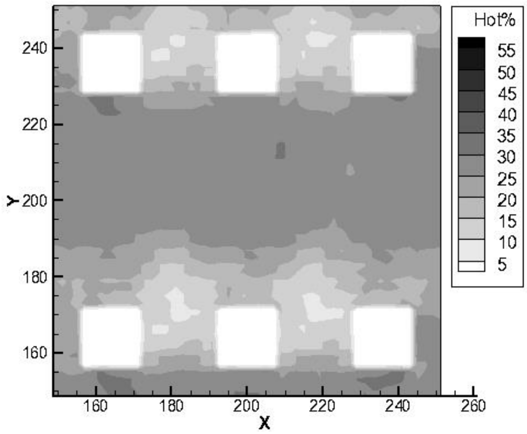
The simulation result of the chosen "typical hottest day" is not corresponding with that of the entire summer, either in magnitude or in distribution. The main reason is that the "typical hottest day" substantially represents only the hottest conditions while the cool or mild conditions also occur in the lasting summer days.

Results of a typical day: the "monthly average day"

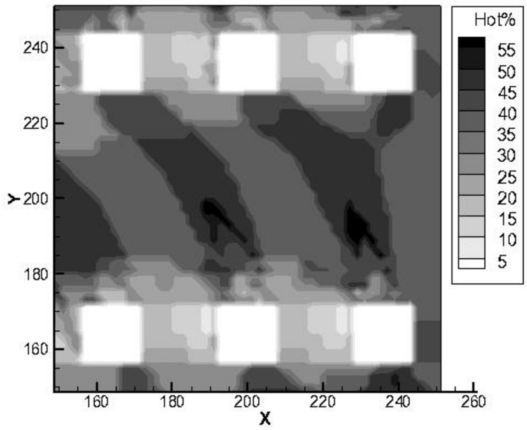
In meteorological sense, the monthly average temperature is always used as an index to demonstrate the average outdoor thermal condition of the month, and it is also one possible option to define the monthly average thermal comfort condition.

In Beijing, the monthly average temperature of July is 26.5℃ and the average highest/lowest temperature is 30.7℃/22.7℃. July 10th which is closest to the monthly average temperature is chosen as the representative day on which the average temperature is 26.6 ℃ and the highest/lowest temperature is 31.0℃/22.8℃.

However, as Figure 6 shows that although the temperature of the day is similar to the average level of the month, the percentage of hot hours is significantly higher than that of the month. Moreover, the simulation result of July 10th is apparently affected by the dominant wind direction (SSE) of the day that regions in the leeward areas are much hotter due of the lower wind velocity.



(a) Percentage of hot hours of the entire July



(b) Percentage of hot hours of July 10th

Figure 6 Percentage of hot hours (a) the entire July (b) July 10th

The comparison indicates that the monthly average temperature is not an effective criterion to define a typical day in sense of thermal comfort. Although the chosen day is representative in air temperature, the solar radiation and the wind environment is unique and so is the thermal comfort condition.

CONCLUSION

In this paper, a simulation system that can predict the outdoor thermal environment and thermal comfort in annual time scale is developed, which can take consideration of the influence of time dependent variables and give more detailed simulation results in time scale.

The concept of „best clothes insulation' is proposed to evaluate the outdoor thermal comfort. A comfortable outdoor environment is defined as an environment in which pedestrians can reach comfortable state by adjusting the clothes insulation in a reasonable region.The best clothes insulation is defined as that can make people feel most comfortable in the specific environment. Based on this definition, some annual thermal comfort indices are proposed.

To evaluate the annual outdoor thermal comfort, several typical cases of typical hours or typical days are studied the comparison shows that the results of annual prediction are more helpful for improving the design plan.

From the results of annual simulation, it can be concluded that the outdoor thermal environment is greatly affected by the weather which changes every hour, so that the simulation within one specific hour cannot be an overall evaluation of one lasting period.

By comparing with the results of annual simulation, it can be concluded that the two typical days studied here are not representative for a lasting period neither. One principal reason is that the simulation result of one lasting period contains much more information, while in one day all these possibilities can never be fully accomplished. Therefore these "typical" days can hardly represent the whole season/month, and the annual simulation is necessary.

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