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Numerical analysis on the thermal environment of an old city district during urban renewal

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ABSTRACT

Urban renewal has become a key issue all through China's Transitional Period. The social, economic, political factors, and their correlations have been seriously considered. However, the effects of outdoor pedestrian thermal comfort and fluid ventilation effects as well as the residence living conditions in old city districts under urban reconstruction should, to some extent, be paid closer attention to. As an example, take an old city district in Wuhan where a comprehensive mathematical model describing the fluid flow and heat transfer characteristics has been presented. Considering the influences of ambient crosswind, solar radiation, and natural convection and radiation heat transfer, numerical analysis based on the original layout has been executed. By analyzing the temperature and velocity distributions of the old city district, a new planned layout has been presented in this research. By comparison, some basic rules have been advanced to achieve favorable thermal comfort and flow ventilation effects.

1. Introduction

Urban renewal has been one of the key issues throughout the transitional period of large and medium-sized cities in China or even all over the world in recent decades, and it has also become a very important research area in the field of urban and rural planning [1–3]. Recent research publications on urban renewal mainly focus on the issues of social, economic, and political policies and criteria as well as the process and effect of urban reconstructions [4–6].

However, the local outdoor microclimate and the thermal comfort of human beings have also aroused wide attention, with the former being mainly connected to the urban planning and the latter being considered in indoor environments. During the urban renewal process with old, disorderly buildings especially in hot-summer and cold-winter areas, we should keep an eye on the issues of local outdoor microclimates and the thermal comfort of human beings in outdoor environments.

The research on human thermal comfort has never been neglected. Mishra and Ramgopal [7] presented an exhaustive overview on human thermal comfort mainly for an indoor environment carried out in the past few decades. Chen et al. [8] presented a mathematical model coupled with thermal conduction, convection, and radiation to analyze the outdoor thermal environment of apartment blocks in Shenzhen, China, by numerical simulation. Then, they presented measurement results of the actual situation of the outdoor thermal environment in summer in an apartment block in Shenzhen City. Later, the authors examined the effect of schemes to improve the outdoor thermal environment in this apartment block, such as changing building shapes, planting arrangements, and so on.

Mirzaei and Haghighat [9] proposed a systematic approach to quantify the level of environmental condition inside a street canyon which is also capable of evaluating the possible advantages of passive and active mitigation strategies using a "frequency of occurrence" concept. They also developed a computational fluid dynamic model to investigate the impact of contributing parameters on the pollution exposure. Ng et al. [10] presented an experiment and analysis on the cooling effect of urban greening in a high-density, high building-height-to-street-width (H/W) ratio city such as Hong Kong. The research results indicated that planting trees or even grass is beneficial to improve the human thermal comfort. Gulyás et al. [11] examined the outdoor thermal comfort conditions through two field-surveys in Szeged, a South-Hungarian city. Through the application of the thermal index PET, the authors gave special emphasis on the human-biometeorological assessment of

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Nomenclature

c_p	specific heat at constant pressure (J/(kg K))
g	acceleration of gravity (m/s^2)
G	solar radiation intensity (W/m^2)
Gr	Grashof number (dimensionless)
G_k	turbulence kinetic energy generation due to the mean velocity gradients (J)
G_b	turbulence kinetic energy generation due to turbulence (J)
h	specific enthalpy (J/kg)
H	height (m)
i	angle (rad)
I	radiation heat flux (W/m^2)
k	turbulent kinetic energy (J)
L	optical depth (m)
p	pressure (Pa)
Re	Reynolds number (dimensionless)
T	temperature (K)
u	velocity (m/s)
v	velocity in y-direction (m/s)
w	velocity in z-direction (m/s)
x, y, z	Cartesian space coordinates
α	angle (rad)
β	volume coefficient of expansion (1/K); tilt angle (rad)
ν	kinematic viscosity (m^2/s)
λ	thermal conductivity (W/(m K)
ε	turbulent kinetic energy dissipation rate (J)
ω	humidity ratio (kg/kg)
μ	dynamic viscosity(kg/(m s)
ς	relative humidity (–)
γ	surface reflectance (–)
ρ	density (kg/m^3)
τ	shear stress caused by viscosity (N/m^2)
κ	karman constant

Subscripts

a	air
e	environment
t	turbulent
s	the state of saturated water vapor in air; surface of the ground
v	water vapor
i,j	any direction of x, y and z.

the microclimate of complex urban environments and then carried out an analysis using the RayMan model. The results showed that differences in the PET index among these places can be as high as 15–20 °C due to the different irradiation.

Recently, the issues of thermal comfort in offices, occupant response, and human health have aroused more and more attention, including experiments [12–14], CFD simulation [15–20], and assessments in various climates [21,22]. Specifically, the influence of early color degradation of asphalt pavements on the thermal behavior [23], the implementations of various renewable energy technologies to reduce harmful greenhouse gas emissions [24], and the influence of pervious pavement types on storm-water storage under specific conditions [25] have been thoroughly analyzed and very interesting findings have been presented. However, a more extensive model considering solar radiation, shading effect of buildings, ambient crosswind velocity, air humidity, and buoyancy due to air density difference under the gravity field, has not been found yet. In this work, the authors intend to present a detailed mathematical model and a numerical method to analyze pedestrian thermal comfort, and the air ventilation effects to avoid residents from being exposed to air pollution in the old city district. The effects of all the parameters mentioned above have been taken into consideration. The methodology and analytical results are expected to be beneficial to urban renewal.

2. Model description

2.1. Geometric model

Wuhan, the capital of Hubei Province with a population over 10 million, lying in the center of China, is composed of three parts: Wuchang, Hankou, and Hanyang, which is divided by the Yangzi River and Hanjiang River which finally merges into the Yangzi River. The old city district occupies about 30% of the Hankou and Hanyang where the buildings are very old, dilapidated sitting side by side with very narrow in-between distances even as low as 2 m. Some of the buildings in this main urban area are over 100 years old, which puts great pressure on urban renewal. As a result, the living conditions, thermal comfort of property, and air ventilation conditions are all abominable, and they significantly influence the health and life of the residents and pedestrians. Thereby, it becomes urgent to consider the urban renewal strategy in regards to China's large cities such as Wuhan. It is vital to improve the inhabitants' living quality.

As shown in Fig. 1, the concerned old city district in this paper lies on the west side of the Yangzi River, which has been unchanged for about 100 years since the Qing Dynasty. This old city district was selected to be analyzed for the influences of solar radiation and air ventilation on the pedestrian thermal comfort in the outdoor environment, as shown in the lower right corner of Fig. 1. This area lies in Dazhimen district whose geographical location is in the east of Jinghan Avenue, the west of Zhongshan Road and Youyi Street, the South of Dazhi Road, and the North of Yiyuan Road. The buildings in this area, shown in Fig. 2, are very dense with very narrow streets, wriggling in different directions. Sometimes, the street tunnels are blocked by some buildings which cause non-circulated airflow. The basic dimensions of the original layout to be considered in this paper are shown in Fig. 3(a). By comparison, a new planned layout at the same position has also been presented in Fig. 3(b).

2.2. Mathematical model

The fluid flow and heat transfer characteristics within the old city district are quite complex. The fluid flow, if the ambient crosswind velocity (ACV) is 0, is considered to be purely natural convection induced by solar radiation which heats the ground surface and building walls and then results in the increase of air temperature. Rayleigh number is used to measure the intensity of buoyancy-induced flow. However, the ACV plays a significant role in our investigation as the buildings are all exposed to the ambience, which causes the system to be a combination of natural and forced convection. The combined natural and forced convection of the area with ACV is different from the flow characteristics (assisting flow, opposing flow, and transverse flow) as defined by Bergman et al. [26]. The natural flow should be vertically upward due to the effect of horizontal ground surface having high temperature; however, the ACV flowing horizontally enhances this heat transfer effect, which puts the ground surface at a lower temperature level. The flow regimes can also be classified according to the ratio of Gr and Re^2 shown as:

$$\frac{\mathrm{Gr}}{\mathrm{Re}^2} = \frac{\left(g\beta\Delta TL^3/\nu^2\right)}{\left(U_e L/\nu\right)^2} = \frac{g\beta\Delta TL}{U_e^2} \qquad (1)$$