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Bioclimatic design of historic villages in central-western regions of China

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ABSTRACT

Historic settlements adapting to local climate and geographical environment contain rich and precious scientific design concepts which should be investigated extensively. The paper is the further study on the sustainable design and planning experiences of Chinese historic settlements. In our previous works, we simulated the wind environment of the Shang-gan-tang village in the central-western region of China which is characterized with hot-humid climate and examined the relationship between settlement selection and layout and the wind environment of the village. In this study, the thermal environment of the village was simulated and the traditional bioclimatic design concepts and techniques were investigated in order to explore a more comprehensive guide for creating sustainable modern human settlement adapting the changing climate.

1. Introduction

1.1. Historic settlements in central-western regions of China

China is a large country with complex and diverse climate. According to "Thermal Design Code for Civil Building (GB 50176-93)", China is divided into five climate subareas: severe cold, cold, temperate, hot summer and cold winter, hot summer and warm winter [1].

The similarities between "hot summer and cold winter" subarea and "hot summer and warm winter" subarea are high air temperature, high humidity, large precipitation, small daytime temperature differences, with very little wind. All these are typical characteristics of the hot-humid climate. So these two subareas are collectively called "Hot-humid area". Buildings in this climate area must meet insulation, ventilation and shading requirements in summer. The central-western regions of China, e.g. Hunan province, Sichuan province, etc., belong to this climate area.

While the difference between the two climate subareas is that buildings in "hot summer and cold winter" subarea should also meet heat preservation requirements.

It has been widely accepted in the academia that historic settlements in hot-humid regions, e.g. the central-western regions of China, followed a series of bioclimatic design strategies for very hot and humid summers [2]. With Chinese unprecedented rapid development and urbanization, our planners and architects are facing a big challenge. That is how to design and plan our cities sustainably with less energy consumption. Compared with modern people creating a livable environment with mechanical means, the traditional bioclimatic design of these historic settlements are more adaptable to the changes of natural environment under conditions involving low energy consumption and environmental protection [3]. Thus, they are worth exploring and studying extensively.

Therefore, the purpose of this study is to use CFD (Computational Fluid Dynamics) techniques to simulate the microclimate of the historic settlements in hot-humid regions, and then explore their bioclimatic design strategies.

1.2. Application of CFD in the built environment

Since Thom, a British Scholar, created CFD, it has become progressively a discipline studied and understood by numerous scholars, scientists and engineers. In some developed countries such as UK, USA and Japan, the research on CFD has reached practical stage [4–6]. For example, before planning a residential district, they analyze the urban air quality and the heat and moisture state of the residential district to find scientific and accurate design parameters for urban planning or residential district planning. This enables to improve the thermal environment around the building clusters and prevent gaseous harmful substance from congesting around the clusters, reducing the energy consumption required by the mechanical ventilation and electric power air conditioning as far as possible.

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Nomenclature

u, υ, w	x, y, z velocity component
k	turbulence kinetic energy
ε	turbulence energy dissipation rate
ν_t	turbulent viscosity
$\sigma_1, \sigma_2, \sigma_\mu$	constants in the standard k–ε model
U_h	mean wind velocity at the gradient height
H_m	altitude of the local meteorological station
d_m	boundary layer thickness at the local meteorological station
α_m	surface roughness of the ground at the meteorological station
I	turbulence intensity
u_*	friction velocity
x, y, z	Cartesian co-ordinates
ν_{eff}	turbulent effective viscosity
$\Gamma_{k.\text{eff}}$	effective diffusion coefficient for turb. kinetic energy
$\Gamma_{\varepsilon.\text{eff}}$	effective diffusion coefficient for turb. energy dissipation rate
$\sigma_k, \sigma_\varepsilon, \sigma_T, C_\mu$	constants in the standard k–ε model
U_m	mean wind velocity at 10 m agl of the local meteorological station
h	the altitude of the target area
d	boundary layer thickness in the target area
α	surface roughness of the ground
κ	von Kámán constant

In this study, we used this method to simulate the three-dimensional thermal environment of a Chinese village which is much more complex than the two-dimensional wind environment we simulated in the previous works [3,7]. It is a challenge for us because the physical model and especially the boundary conditions are much more complicated.

2. Case study: the simulation of thermal environment of Shang-gan-tang historic village

2.1. Physical model and problem statements

Shang-gan-tang village is a typical historic village in Hunan province and situated based on the ideal Feng-shui model, as most of the villages did at the time. The village has thousands years of history and well-preserved buildings, most which were built in the Ming and Qing dynasty.

The direction of the whole village is due west, surrounded by hills: Ang Hill (north), Ping-feng Hill (east) and Jiang-jun Hill (south). The altitudes of these hills are from 300 m to328 m. In the front of the village, there is the Xie-mu River. The village and all these natural elements create a typical Feng Shui landscape (see Fig. 1). However, the direction of the village is not due south, which was considered as the best direction of the dwellings according to Feng Shui theory.

The village, lying at latitude 25°09′–25°09′19″ N and longitude 110°10′38–111°11′6′ E, is a Humid Subtropical region with four distinctive seasons, characterized by long, very hot, humid summers and short, cool, cloudy and dry winters. The average annual temperature is 18.4 °C. The average temperature in winter is 7.6 °C and 28.5 °C in summer. The annual relative humidity is 79%. It receives an average annual rainfall of 1586.7 mm. The annual sunshine duration is 1453.6 h. The prevailing wind in winter has a northerly direction and southerly in summer. The annual mean wind speed is 2.3 m/s [8].

The detailed architectural description of the village is provided in Tang et al., 2012 [3]. The master plan of it is shown in Fig. 2.

A 3-dimensional physical model, 650 m long, 850 m wide and 90 m high, was created by AUTOCAD based on the actual terrain. Due to the very large area of the village and the surrounding terrain, as well as the limited computer capacity, the model of the surrounding terrain was simplified properly (see Fig. 3).

The computing domain size is 1500 m long, 1200 m wide and 270 m high in the longitudinal (y), lateral (x), vertical (z) directions, respectively. The length of the inlet and outflow are both three times the height of the physical model.

FLUENT software was used in this study. The 3306223 computational grids were generated using a commercial package, GAMBIT.

Furthermore, due to the very big scale of the target area, the fairly high building density, and the limited computer capacity, it is hard to simulate the thermal environment of the whole village directly, and the whole village domain was simplified and set as a fluid-saturated Darcy-Brinkman porous model in order to use relatively large size grids, thereby reduce the number of the grids. The fluid porosity is 0.54, i.e. the building density.

2.2. Mathematical model

We used the same model (the standard k–ε model) in this study as in our previous works [3,7]. But the solved equations are different because we here simulated the three dimensional thermal environment of the village instead of its two dimensional wind environment in our previous works.

The pressure–velocity coupling SIMPLE arithmetic is adopted to solve the equations. Discretization scheme of Momentum, Turb. Kinetic Energy and Turb. Dissipation Rate is Second Order Upwind.

The solved equations can be written as follows:

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial \upsilon}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

Momentum equation

$$\frac{\partial}{\partial x}\left(uu - \nu_{\text{eff}}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(u\upsilon - \nu_{\text{eff}}\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(uw - \nu_{\text{eff}}\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\nu_{\text{eff}}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{\text{eff}}\frac{\partial \upsilon}{\partial x}\right) + \frac{\partial}{\partial z}\left(\nu_{\text{eff}}\frac{\partial w}{\partial x}\right) \tag{2}$$

$$\frac{\partial}{\partial x}\left(\upsilon u - \nu_{\text{eff}}\frac{\partial \upsilon}{\partial x}\right) + \frac{\partial}{\partial y}\left(\upsilon\upsilon - \nu_{\text{eff}}\frac{\partial \upsilon}{\partial y}\right) + \frac{\partial}{\partial z}\left(\upsilon w - \nu_{\text{eff}}\frac{\partial \upsilon}{\partial z}\right) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(\nu_{\text{eff}}\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial y}\left(\nu_{\text{eff}}\frac{\partial \upsilon}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_{\text{eff}}\frac{\partial w}{\partial y}\right) \tag{3}$$

$$\frac{\partial}{\partial x}\left(wu - \nu_{\text{eff}}\frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(w\upsilon - \nu_{\text{eff}}\frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(ww - \nu_{\text{eff}}\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left(\nu_{\text{eff}}\frac{\partial u}{\partial z}\right) + \frac{\partial}{\partial y}\left(\nu_{\text{eff}}\frac{\partial \upsilon}{\partial z}\right) + \frac{\partial}{\partial z}\left(\nu_{\text{eff}}\frac{\partial w}{\partial z}\right) \tag{4}$$

where ν_{eff} was calculated from

$$\nu_{\text{eff}} = \frac{1}{R_e} + \nu_t \tag{5}$$