Heat, Moisture and Airflow coupled Model for Historical Building

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Abstract. The current building simulation of heat air and moisture (HAM) only regards the indoor air as homogeneous, which cannot accurately predict and evaluate the thermal and humid environment of complex historical buildings. In this study, the heat, moisture, and airflow coupled model (HAM-CFD model) was developed by FORTRAN programming, and then the simulation results of the HAM model and the HAM-CFD model were compared to study the characteristics of indoor environment under the action of airflow. The results show that there is a coupling effect between the indoor airflow and heat and moisture transfer of walls. The HAM-CFD model can reflect the temperature stability of the building center, and has a better correlation with rainfall. The HAM-CFD model can more truly reflect the changes of building temperature and moisture content in complex thermal and humid environment.

1. Introduction
Historical buildings have important cultural value, but various kinds of building diseases often appear in them, which threaten their preservation. Many studies show that the condensation and mold growth of historical buildings are related to the thermal and humidity environment of historic buildings. The climate in some areas is hot, humid, and windy. For historical buildings with the poor air tightness, the outdoor hot and humid air will penetrate into the room, under the action of wind pressure, causing condensation, which often occurs at the corner and the junction of the interior surface [1]. The condensation of the wall will damage the internal structure of building materials [2], and wet building materials may be subject to frost erosion and the migration and crystallization of soluble salts [3]. At the same time, water is also a prerequisite for the survival of organisms [4], and the indoor thermal and humid environment have a great impact on the mold growth of the building. Generally speaking, microorganisms can grow in the temperature range of 0 to 50 °C, but reach the peak at about 25 °C [5]. Li Yonghui et al. [6] found that
mold growth was inhibited in low moisture environment (relative moisture 74%-92%) and extremely high moisture environment (relative moisture over 99.9%), while high moisture environment (relative moisture 94%-99%) was conducive to mold growth. The mold growth in historical buildings will make the wall surface discolor and peel off. Therefore, if the thermal and humid environment of historical buildings can be accurately predicted, it will provide important technical means and support for their protection.

Due to the differences of building technology and material properties, the heat and moisture behavior of historical buildings is more complex than that of new buildings [7]. The surrounding environment and indoor airflow [8] of historical buildings will have a great impact on the heat and moisture transfer of the building. At present, in the HAM simulation of buildings, the coupling effect of airflow and wall heat and moisture transfer is not considered, and the indoor air is only regarded as uniform [9–13]. This assumption cannot truly reflect the complex thermal and humidity environment characteristics in historical buildings. Varas Muriel et al. [14] measured the vertical stratification of a 5-meter-high heated church and found that the air temperature near the ceiling was 4 °C higher than the ground temperature.

In this study, by coupling the HAM model with computational fluid dynamics (CFD) model, a new heat, moisture, and airflow coupled model is established (HAM-CFD model), which realizes the coupling calculation of indoor airflow and heat and moisture transfer of walls, and can more truly reflect the complex thermal and humidity environment of the historical buildings. This study can provide an important technical means for the research of heat and moisture properties of architectural heritage.

2. Mathematical Model

2.1. HAM model [15]

In this research, a HAM model proposed by Japanese scholar Mamoru Mastumoto is used, which is driven by temperature $T$ and water chemical potential $\mu$. This model considers liquid and gaseous phases as water state. The one-dimensional basic equations of the model are as follows. Equation (1) is the heat balance equation and equation (2) is the moisture balance equation.

$$ c\rho \frac{\partial T}{\partial t} = -\frac{\partial q}{\partial x} + r J $$  
(1)

$$ \frac{\partial}{\partial t} \left( \phi_0 \rho_v \right) + \frac{\partial}{\partial x} \left( \rho_v \frac{\partial \Psi}{\partial x} \right) = -\frac{\partial j_w}{\partial x} $$  
(2)

In Equation (1), (2), $c\rho$ is heat capacity of material (J/m$^3$·K), $T$ is absolute temperature (K), $t$ is time (s), $q$ is density of heat flow rate (W/m$^2$), $r$ is latent heat of water phase change (J/kg), $J$ is moisture change caused by phase change (kg/m$^3$·s), $\phi_0$ is material porosity (m$^3$/m$^3$), $\Psi$ is volume moisture content (m$^3$/m$^3$), $\rho_v$ is water vapor density (kg/m$^3$), $\rho_w$ is Liquid water density (kg/m$^3$), $j_w$ is total water flow, including gas phase and liquid phase water (kg/m·s).

2.2. CFD model

In the CFD calculation, the k-ε turbulence model is used to calculate the velocity field, temperature field and humidity field of indoor air. In addition to following the basic rules, such as mass conservation, momentum conservation, energy conservation, the k-ε model also introduces turbulent kinetic energy (k) and turbulence kinetic energy dissipation rate ($\varepsilon$). These two parameters obey the equations (3) and (4).

$$ \frac{\partial}{\partial t}(\rho k) + \text{div}(\rho u k) = \text{div}(\Gamma_k \nabla k) + G - \rho \varepsilon $$  
(3)

$$ \frac{\partial}{\partial t}(\rho \varepsilon) + \text{div}(\rho u \varepsilon) = \text{div}(\Gamma_\varepsilon \nabla \varepsilon) + \frac{\varepsilon}{k} (c_1 G - \rho \varepsilon) $$  
(4)
2.3. Establishment of heat, moisture and airflow coupled model (HAM-CFD model)

HAM model and CFD model are mainly coupled by substituting boundary temperature and humidity data. In the HAM model, indoor air is calculated as a node. The indoor air temperature \( T_{in} \) is determined by the total heat fluxes from all boundary wall temperature nodes, as shown in the equation (5). Similarly, the humidity \( R_{Hin} \) of indoor air can also be obtained according to the humidity conservation equation of HAM model.

\[
T_{in}^{t+dt} = T_{in}^t + \sum h S(T_{w(I,J)} - T_{in}^t) / (c\rho V) \times dt
\]  

Where \( T_{in}^{t+dt} \) is the temperature at this time step (K), \( T_{in}^t \) is the temperature at previous time step (K), \( h \) is convective heat transfer coefficient (W/m\(^2\) K), \( S \) is surface area of wall (m\(^2\)), \( T_{w(I,J)} \) is wall temperature (K), \( c\rho \) is heat capacity of air (J/m\(^3\) K), \( V \) is room volume (m\(^3\)), \( dt \) is time step (s).

In the CFD model, indoor air is no longer regarded as uniform, but divided into several nodes. The indoor air temperature \( T_{in(I,J)} \) and humidity \( R_{Hin(I,J)} \) is defined in a cell (discretized element) and velocity \( U_{(I,J)} \) is defined at the interface of the node. The local convective heat transfer coefficient \( h_{(I,J)} \) at the interior surface is related to the air velocity in the boundary layer, and can be obtained through the functional relationship:

\[
h_{(I,J)} = 0.332Re_{(I,J)}^{\frac{1}{2}}Pr^{\frac{1}{3}} \lambda / x
\]

\[
Re_{(I,J)} = U_{(I,J)} x / \nu
\]

Where \( Pr \) is Prandtl number, \( \lambda \) is thermal conductivity of air (W/(m·K)), \( \nu \) is dynamic viscosity (N·s/m\(^2\)).

Therefore, the air temperature \( T_{in(I,J)} \), humidity \( R_{Hin(I,J)} \) and convective heat transfer coefficient \( h_{(I,J)} \) at the boundary calculated by CFD model can be substituted into the HAM model to obtain the wall temperature \( T_{w(I,J)} \). Figure 1 is the solution flow of boundary substitution.

3. Simulation procedure

In this study, a simple rectangular room was dealt with, as shown in figure 2(a). The material of the building enclosure was brick, and its material parameter setting is shown in Table 1. The grids were evenly distributed along the X direction, including 104 nodes, and were divided into three sections along the Y direction, including 114 nodes. The size of the grid is shown in figure 2(b).

To quantitatively analyze the influence of airflow on indoor thermal and humidity environment, the difference of calculation results between the HAM model and HAM-CFD model under the same operation conditions was compared. In this study, Fortran language was used to program HAM and CFD simulation, instead of other software. In the HAM model, the ventilation rate of the room was set to 3 ACH, while in
the HAM-CFD model, a uniform inlet wind speed was input. 3 ACH in the HAM model corresponds to the inlet wind speed 0.1m/s in the HAM-CFD model. The outdoor meteorological data of Nanjing, including outdoor air temperature, relative humidity, solar radiation, and rainfall were referenced. Both models were simulated with a cycle of one year.

Table 1. Physical parameters of brick.

| Physical parameters                          | Value                                                                 |
|---------------------------------------------|----------------------------------------------------------------------|
| Thermal conductivity in dry state $\lambda_0$ | $\lambda_0=0.3$ [W/(m·K)]                                           |
| Thermal conductivity in wet state $\lambda_b$ | $\lambda_b=\lambda_0+1.617\varphi$ [W/(m·K)]                       |
| Equilibrium moisture content $\varphi$       | $\varphi = \begin{cases} 0.0018\lg(-\mu)^3 + 0.0276\lg(-\mu)^2 + 0.216 \quad (-1 < \mu < -5) \\ 0.0051 \quad (-5 \leq \mu < -1) \\ 2.81\lg(-\mu)-6.7634 \quad (\mu < -6.35) \end{cases}$ [m$^2$/m$^3$] |
| Volume specific heat capacity $c_b$          | $c_b=1825320+c_{\text{water}}\varphi$ [J/K]                         |

Figure 2. Simulated model(a) and meshing(b).

4. Result and Discussion

4.1. The influence of indoor airflow on the calculation results

Through the HAM-CFD model, the airflow distribution can be obtained. The air velocity at 10 am on 1 August is shown in figure 3. It shows that the wind speed was large at the inlet and outlet, and the maximum was 0.1 m/s. In the three corners of the room, there were velocity stagnation zones.

Figure 3. Indoor air velocity distribution. (a) velocity vector; (b) Horizontal velocity distribution.

Figure 4 and figure 5 compare the calculated results of temperature and relative humidity between the
HAM model and the HAM-CFD model at 10 am on 1 August. It indicates the temperature and humidity distribution of HAM model was uniform. However, in the HAM-CFD model, due to the existence of airflow, the indoor air temperature and relative humidity were stratified. It is worth noting that the stagnant zones had low temperature and high relative humidity, which might lead to condensation in the room corner and easy to breed mold.

Therefore, in the HAM-CFD model, the temperatures and relative humidity of different positions in the room are different. Because the indoor air will exchange moisture and heat with the interior wall, the uneven airflow will affect the heat and moisture transfer of the building walls.

**Figure 4.** Temperature distribution at 10 am on 1 August. (a)HAM model; (b)HAM-CFD model.

**Figure 5.** Relative humidity distribution at 10 a.m. on 1 August. (a)HAM model; (b)HAM-CFD model.

4.2. Temperature and moisture content distribution of interior wall surfaces

Under the disturbance of indoor airflow, the temperature and moisture content of the wall will fluctuate correspondingly. The fluctuation in winter was more obvious.

The temperature of the interior wall surfaces at 10 a.m. on January 1 is shown in Figure 6(a). In the HAM model, the temperature distribution of the four walls was relatively uniform, and the temperatures of the four interior walls ranged from 4°C to 10°C. Among them, the temperatures in the south wall were the highest, the temperatures in the north wall were the lowest. For the HAM-CFD model at the same time, the simulation results show greater temperature fluctuation, and the temperature distribution of the four interior walls ranged from 4°C to 11°C. Among them, the surface temperatures of the roof were relatively uniform, about 6°C. The surface temperatures of the floor fluctuated greatly, and the maximum temperature difference between the HAM model was 3°C. Moreover, the temperature distribution of the north wall and
the south wall was more significantly affected by airflow. The moisture content of the interior wall surfaces at 10 a.m. on January 1 is shown in Figure 6(b). The results of the two models show that the moisture contents of the four interior walls were different, the south wall and the north wall were the driest, while the roof had the highest moisture content due to rainfall and other factors. Among them, the simulation results of the north wall and the south wall of the two models were consistent, with the moisture contents of the north wall were about 0.002 m$^3$/m$^3$ and the moisture contents of the south wall were about 0.001 m$^3$/m$^3$. On the floor and roof, due to the influence of airflow, the moisture content distribution in the HAM-CFD model fluctuated, and the moisture contents of the floor ranged from 0.004 m$^3$/m$^3$ to 0.022 m$^3$/m$^3$, and that of the roof ranged from 0.08 m$^3$/m$^3$ to 0.09 m$^3$/m$^3$. However, in the HAM model, the moisture contents of the floor and the roof were evenly distributed, and the moisture contents of the floor were about 0.01 m$^3$/m$^3$, and that of the roof were about 0.08 m$^3$/m$^3$.

4.3. Annual distribution of temperature and moisture content at feature points

According to Section 4.2, the floor and roof were greatly affected by airflow. In this section, three points at the roof and floor surfaces are selected as feature points, as shown in Figure 7. The annual changes of temperature and moisture content of these three feature points were analyzed, as shown in Figure 8. As the moisture content is related to outdoor rainfall, rainfall (grey curve) is added as a reference in Figure 8(d), (e), (f).

It can be seen from Figure 8(a), (b), (c) that the temperatures of the roof were greatly affected by the outdoor environment, while floor were more stable. Figure 8(a), (b) shows that the annual temperature changes of the two models at point B were similar, but there was a gap between the results of the HAM model and the HAM-CFD model at point A. The temperature variations of point A in the HAM model were between 1 °C and 30 °C, and that in the HAM-CFD model were between -0.5 °C and 27 °C. Therefore,
the HAM-CFD model can better reflect the temperature stability of the center position.

It can be seen from Figure 8(d), (e), (f) that the annual moisture content variations of points A and B on the floor were relatively stable, while the moisture content variations of point C on the roof were greatly affected by outdoor rainfall. Figure 8(f) shows that the HAM model fluctuated with rainfall only in January-March and April-May, while the HAM-CFD model showed fluctuation with rainfall in January-September. Therefore, the results of the HAM-CFD model have a better correlation with rainfall, and can more truly predict the change of moisture content in the natural environment.

![Figure 8](image_url)

Figure 8. Annual variation of temperature and moisture content at wall feature points. (a) Point A temperature variations; (b) Point B temperature variations; (c) Point C temperature variations; (d) Point A moisture content variations; (e) Point B moisture content variations; (f) Point C moisture content variations.
To sum up, there is a coupling effect between the indoor airflow and the heat and moisture transfer of the wall, resulting in the fluctuations of the wall surface temperature and moisture content. If the indoor air is regarded as uniform, the temperature and moisture content distribution curves are flat, which cannot predict the heat and moisture characteristics of different wall positions in detail. According to the annual temperature and moisture content variations of wall feature points, HAM-CFD model can more accurately predict the thermal and humidity change process of building indoor environment.

5. Conclusion

In this study, the HAM model and the HAM-CFD model were used to simulate a simple building, and the difference of calculation results between the two models was compared. The results show that under the disturbance of indoor airflow, the temperature and humidity distribution of indoor air was uneven, which further affected the heat and moisture transfer of the wall. The HAM-CFD model simulation results can more truly reflect the variation of building temperature and moisture content in a complex thermal and humid environment, especially, it can better reflect the temperature stability of the center position, and has a better correlation with rainfall that can more truly predict the change of moisture content in the natural environment. The HAM-CFD model can provide a technical mean for the study of preventive protection of historical buildings.

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