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Numerical Analysis of Heat and Moisture Transfer in Underground Air-conditioning Systems

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Abstract: In view of the influence of humidity of room air on room heat load, indoor environment and building energy consumption in underground intermittent air-conditioning systems, numerical simulation was used to dynamically analyze the coupling condition of room air temperature and relative humidity. Based on an experimental simplified model that considers dynamical moisture transfer on the soil wall, an energy equation with variable of enthalpy is solved, with the addition of solving the transport equation of water vapor percent in moist air. Results are presented in terms of temperature, humidity and heat flux at the interface between room air and the floor, showing the importance of the approach presented and the model robustness for long-term simulations with a high time step. Finally, the results are compared with those of simulation without consideration of humidity. The results show that room air temperature with moisture transfer is 0.6～1.5 less, and the average conjugate heat flux on soil wall is 20% higher than that without humidity.

Key words: Intermittent air-conditioning；Coupling heat and moisture transfer；Relative humidity

NOMENCLATURE

h *Specific enthalpy*
d *Moisture contain*
T *Temperature*
C *Concentration*
G *Supply Air volume*
W *Moisture transfer volume on wall*
$\vec{U}$ *Indoor air velocity vector*
Γ *Equivalent thermal diffusivity*
S *Equivalent heat source*

SUBSCRIPT

ϕ u,v,w,T
h_2o *Water-vapor*
J *1,2,3*

1 INTRODUCTION

Since the 1970s, several codes have been developed to evaluate the building air-conditioning system energy consumption under various conditions. However, most of them do not take into account the coupling heat and moisture presence within building envelopes. To most underground buildings, the heat and moisture transfer in porous soil has much influence to room thermal environment and energy consumption. There is an additional mechanism of transport absorbing or releasing latent heat of vaporization that will affect the hygrothermal building performance or cause mold and mildew on interior surfaces, rotting or corrosion of wall materials.

The energy impact associated with moisture accumulating within the building envelope is enormous. It is reported that interior wall material can absorb one third of indoor moisture [1]. And in intermittent air-conditioning system, it is even needed to take 1～2 hrs for removing the absorbed moisture on walls during the night time ventilation and leakage of outdoor air [2]. Total economic impact is anticipated to be much greater since the impact of moisture on the soil walls is not included in this estimate. The impact associated with just low-slope roofs and residential walls is approximately $200 million per year at an assumed oil price of $20 per barrel [3].

Actually, some studies have been carried out to model the moisture transport mechanisms and their effects on heat transport through walls of buildings [4] [5] [6]. Some simplified models can be also found in the literature such as the model utilized by the MOHID program. This code using the Richards's equation, is utilized for simulating quality processes in reservoirs and water flow in unsaturated media. The computer modeling of MOIST program also is made generally available considering one-dimension heat and moisture transfer. Subsequent research extended MOIST to deal with transient interior temperatures and humidity, and to provide a user-friendlier program for designers, builders and investigators of moisture problems.

However, all of these works present so much more simplifications on their calculations. In order to precisely predict ground heat transfer, room air temperature and humidity, a combined model has been developed and conceived to calculate both the coupled heat and moisture transfer in soil and room air.

2 PHYSICAL PROBLEM AND MATH-MATICAL MODEL

Combined heat and moisture transfer in indoor air and soils is to solve numerical simulation. General mathematical models of this include N-S equations and continuum, energy equations, also with mass fraction equation of water vapour in moist air. However, the energy equation considering moist air must be numerically solved with the specific enthalpy of controlling volume, not with the temperature. Because the assumption of enthalpy and temperature will be ineffective to moist air which including water-vapour, energy equilibrium can but expressed with the original physical variable-specific enthalpy. In order to solve the temperature of moist air, that is,

$$h = 1.01T + d(2500 + 1.84T) \quad (1)$$

And the additional mass fraction controlling equation of water-vapour which is like other controlling equations is:

$$\frac{\partial(\rho C_{h_2o})}{\partial t} + \frac{\partial(\rho u_j C_{h_2o})}{\partial x_j} = \frac{\partial}{\partial x_j}(\Gamma_c \frac{\partial C_{h_2o}}{x_j}) + S_c \quad (2)$$

As we all know, there is always lack well theory formulation to solve the complex coupling heat and moisture transfer problem of space air and envelopes. Many heat and moisture transfer in soils is based on the theory of Philip and De Vries [7], which is one of the most disseminated and accepted mathematical formulation for studying heat and moisture transfer through porous soils, considering both vapor diffusion and capillary migration.

The method in this paper is set out from the experimental data in existence. Through some typical experiments, it analyzes a few main factors which affect the moisture transfer on wall and gets the tested fitting formulation with pressure difference of water-vapour, indoor air temperature and relative humidity, indoor air velocity and time of being used. Water-vapour pressure difference between in indoor moist air and soil wall is the main power to drive the transfer of infiltrated water in soil when it arrives on the wall. It is shown in tested analysis that, the higher is indoor air temperature or air velocity, the more is wall moisture transfer. And with the increase of relative humidity in space air, or with the longer using time, the wall moisture transfer is few [8]. According to the following experimental data of wall moisture transfer of underground buildings (Tab.1), the multi-dimension nonlinear regression tool of Matlab is applied to fit these data and get a formula that can be expressed as:

$$W = \frac{0.0175d - 0.2845G + 7.5982}{7.5443 - 8.1097 \cdot t} \quad (3)$$

Tab 1 Experimental data of affecting factors to wall moisture transfer in underground buildings

Supply air volume G (m^3/h)	Indoor air temperature t (℃)	Indoor air relative humidity ϕ (%)	Moisture transfer on wall W ($g/m^2 \cdot h$)
49.5	19.6	71	1.18
66.5	19.6	71	1.72
79	19.6	71	2.89
81.5	19.6	71	2.1
91.5	19.6	70	1.45
114	19.6	70	2.04
128	19.6	70	2.08
136	18.9	74	3.46
147	18.8	74.5	3.15
150	18.6	76	3.2
150	19.4	70	2.38
165	18.9	74	3.54

This formula can be loaded with user defined function in Fluent 6.1, and also used as boundary condition which is to be added to every time step of numerical calculation. Thus the frame map of compute program to solve indoor air temperature and relative humidity is shown in Fig.1:

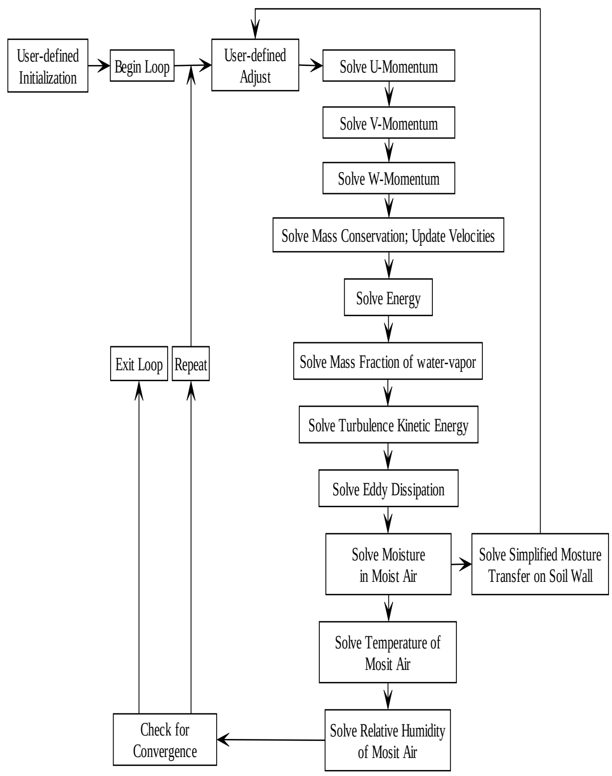

Fig.1 Frame map of compute program

For the simulation part, some an underground tested room in Nanjing with length of 9m, width of 6m, height of 3m (See in Fig.1). Here the plane symmetric case is modeled and coupling characteristics of heat convection in room air and heat conduction in ambient soil is analyzed. Thermal properties of soil, which is assumed homogeneous, keep constant shown in Tab.2. Inner intermittent heat source is taken 30w/m^3 to be as heat loss of room personnel and equipments. And the inner intermittent moisture source is 2.04e-03g/m^3.s. The working time of intermittent air-conditioning system and inner heat source are same with 8:00~18:00 in one period (24 hours).

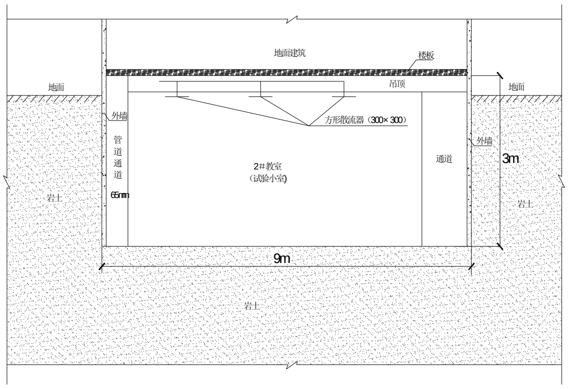

Fig.2 Geometric model of simulated shallow-buried intermittent engineering

Tab. 2 Thermal property of underground soil

Mat-erial	Thermo-physical properties			
	ρ (kg/m^3)	c_p (J/kg.)	λ (W/m.)	a (m^2/h)
Soil	2400	921.1	2.04	0.0033

Because in coupling heat transfer problem both wall temperature and heat flux of interface are parts of calculation outcomes, but not known conditions. Thus the paper will discuss complicated intermittent air-conditioning real-time heat/cool and moisture loads in shallow-buried underground buildings with view to the intermittent variation of indoor air situation and strong thermal storage of underground soil. The governing equation of heat transfer and flow in united calculation regions of solid and fluid is,

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho\bar{U}\phi) = div(\Gamma_\phi grad\phi) + S_\phi \tag{4}$$

This equation can not only solve heat transfer and flow in fluid region, but also be described to solve heat conduction in solid. After setting dynamical viscosity of solid to be infinite, that is $\mu_s \to +\infty$, the velocity in whole solid would be "0" if velocity on the outer boundary of region is assumed to be zero. Thus continuum, momentum and turbulent model equations become unnecessary to be solved, and energy equation is transformed to heat conduction equation (Eq.(5)) automatically:

$$\frac{\partial(\rho T)}{\partial t} = div(\frac{\lambda}{c_p} gradT) + S_T \tag{5}$$

Along the bounding surface which is beyond the thermal influenced range of indoor air, the soil temperature is assumed to be undisturbed and is simply considered to be a linear function of depth according to the given local outdoor weather data in area of Nanjing.

3 NUMERICAL SOLUTION METHODS

Usually numerically whole-field solution method is applied to solve this three dimension unsteady conjugate heat transfer problem of convection and thermal conduction. However Sub-area solution is not used due to repeated iteration between different solid and fluid regions. This paper discussed some important processing measures during numerically solving three dimension unsteady conjugate heat transfer with the whole-field solution. For example, it applied false density method, used harmonic average value to compute interfacial equivalent diffusivity, improved PISO algorithm in collocated grid system [9] and so on. Finally a numerical simulation example was done to show correctness and validity of before-mentioned measures. And the results showed that with the method of this paper, energy saving and green buildings are convenient to be reached. The paper applied improved PISO algorithm, which is originated from SIMPLE algorithm, to solve the coupling relationship of pressure and velocity with the use of collocated grids. This improved algorithm applies one step of hidden scheme to predict and two steps of obvious scheme to revise. So this algorithm is more valid to accelerate iterative convergence of unsteady conjugate heat transfer problem, especially those with large time step.

In simulation, some parameters such as the boundary conditions, initial conditions, calculation time period (including warm-up), time step and grid refinement have to be carefully chosen and combined in order to reach accuracy without using excessive computational processing. And all of the governing equations of this three-dimensional model for describing the physical phenomena of heat and mass transfer in unsaturated moist porous soils and indoor air are discretized and linearized using the finite-volume method. Tri-Diagonal Matrix Algorithm is applied to solve and ensure the numerically stability.

4 EXPERIMENT

For the experimental part, the tested room was chosen as 2# classroom in Fig.2. All the testing points were set hygrothermal sensors include the two kinds of interior and exterior points: the interior points were near the inlet, on the center line of the room or on soil wall and floor; the exterior were set outdoor (see in Fig.3). Some of testing points on soil wall and floor were put with self- recording heat flux sensors also which can self-record and save every 10s or other user defined time steps. All of the temperature points applied Pt100 resistance sensor which can gather the temperature signal and transmit it through ADAM-4015 and sent to upper computer with communication term of RS-485 to attain real-time data. The on-site photo is shown in Fig.4.

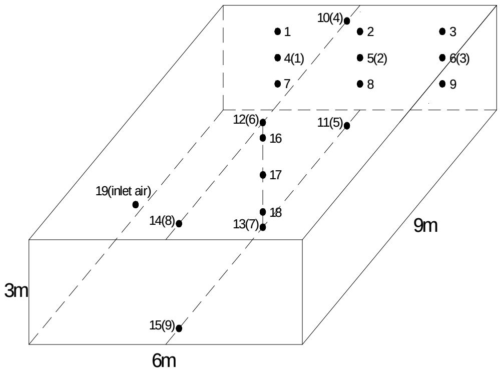

Fig. 3 Sketch map of testing points to measure temperature and heat flux

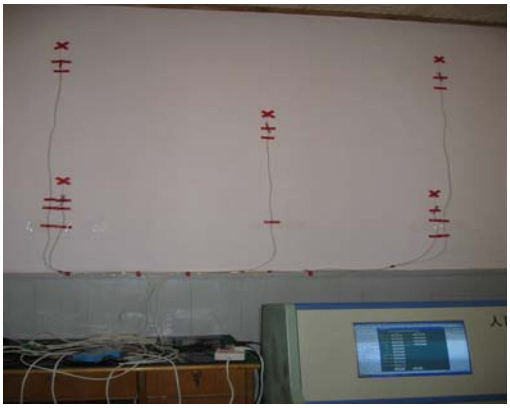

Fig. 4 Testing points on soil wall in an example underground engineering

5 RESULTS AND DISCUSSION

It is shown in Fig.5 that transient variation of room air humidity in two working days with moisture transfer. The dynamical variation of indoor air relative humidity can be used to improve the dehumidification of air-conditioning system and analyze the dewing situation on wall in underground buildings.

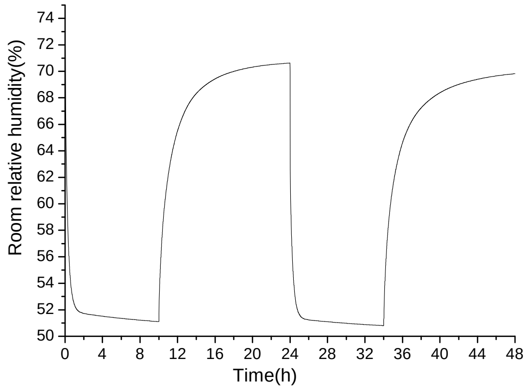

Fig. 5 Transient variation of room air humidity in two working days with moisture transfer

In addition, it is shown in Fig.6 that indoor air temperature decreases 0.6～1.5℃ if considering the latent heat load which dues to water-vapor. This is because that the conjugate heat flux on wall with moisture transfer will increase especially in the working stage of air-conditioning system. At this stage the difference of maximum heat flux on wall will reach at 2 w/m^2 (see in Fig.7). The enhanced surface heat flux on wall will result in the increase of air-conditioning load including apparent heat load and latent heat load also.

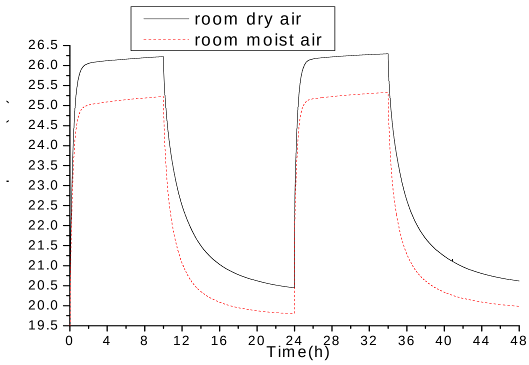

Fig. 6 Comparison of transient indoor air temperature variation with moisture transfer

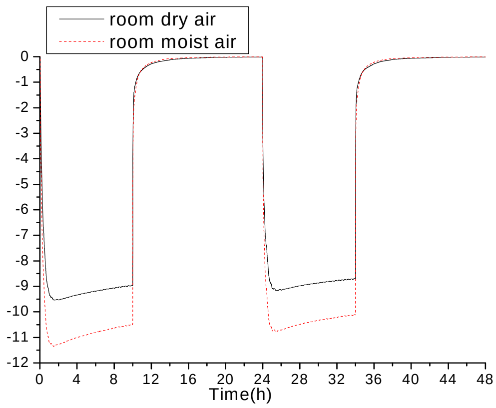

Fig. 7 Comparison of total transient surface heat flux variation of soil walls with moisture transfer

Error analyses, which aim at the indoor air hygrothermal performance and the conjugate surface heat, flux on soil wall (see in Fig.8) show that the mean relative error of simulation is 15%. There are some main causes:

Variation of water or moisture containing fraction in ambient soil has effect to the thermal parameters of soil;

The simplified model of moisture transfer on soil wall has some error in comparison with the fact;

The initialization of soil temperature has influence on the indoor air temperature and humidity simulation with the original temperature in typical area.

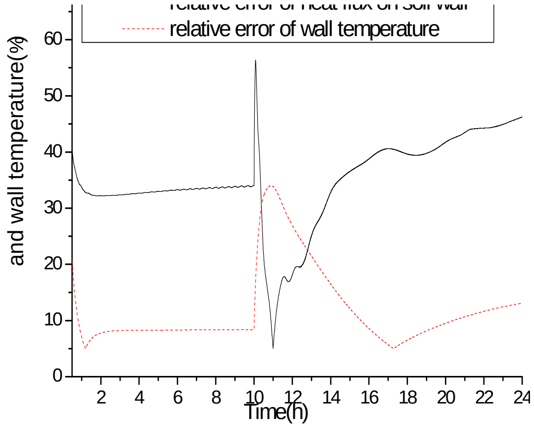

Fig. 8 Relative error analysis of heat flux on soil wall and wall temperature

6 CONCLUSION AND IMPLICATIONS

Models like the one presented here will help to improve energy simulations because latent heat loads and their temporal pattern can be calculated more accurately.

At first, three dimension unsteady conjugate heat transfer problem can be numerically solved with the whole-field solution which used harmonic mean value to set interfacial equivalent thermal diffusivity, and employed the improved PISO algorithm in collocated grid system. With the outcomes of simulation it afforded sufficient real-time data, which covered two coupling regions of indoor air and ambient soil. It analyzed influence of intermittent air-conditioning system to resumption of soil temperature with certain on/off controlling strategy, with comparison to simulation of continuous air-conditioning system. This will show some contribution to save energy consumption of underground building and better indoor thermal environment due to different on/off control strategies, also to improve heat transfer performance of soil to make sustainable utilization.

Concerning the moisture effects on indoor air analysis, it is showed a significant difference of 15% in terms of wall temperature and surface conjugate heat flux. Therefore, higher energy consumption could be expected when an air conditioning system is used due to the augmentation of building latent loads. And a building with a greater area of contact with the ground or in underground zones where the solar radiation effect is not predominant, the moisture flux through the floor could contribute more effectively for the room air energy balance.

We also noticed the importance of a pre-simulation period of several years for the correct estimation of temperature and moisture content profiles. And the water contain of ambient soil in fact would be analyzed more and deeply. Thus the simplified model can be modified by the further research also.

In conclusion, some recommendations are addressed for further work:

(i) Analysis of the conjugate heat and mass transfer coefficient ;

(ii) Modification of empirical correlations for coupling heat and moisture transfer through the envelopes ;

(iii) Consideration of surface dewing on soil wall in underground situation.

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