NUMERICAL ANALYSIS ON HUMIDITY DISTRIBUTION IN A VENTILATED ROOM

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ABSTRACT
We already have had theoretical model to predict temperature and humidity variations in a room. Many works have estimated the accuracy of the numerical model, but they might be influenced by the air movement. Thus, theoretically the temperature and humidity variations should be solved with air movement in a room. In this paper, I calculated the minute temperature and moisture distributions in a room which has the moisture buffering effects by the porous walls. The room space is regarded as rectangular box which has two hole, inlet and outlet for ventilation. A humidifier set on the floor and it starts to add moisture at a point in time. First I calculated the steady air velocity distribution by CFD. I tried two turbulent models, such as standard k-e 2 equations and low-Re model. Then, I calculated the heat and vapor transport process in walls and a space. As results, it was shown that moisture distribution is not negligible. Many works depend on instantaneous diffusion, but this hypothesis should be validated. Also I got the humidity difference which depends on the turbulent model.

KEYWORDS
Moisture, Heat, CFD, Moisture buffering effect, Air movement

INTRODUCTION
Humidity has a lot of effects on room space. Latent heat for cooling energy is very significant in moist climates of temperate regions. It raises overall energy consumption in houses, especially highly insulated and well solar-reflected houses, which have small sensible heat for cooling. Durability of items in a room and the room itself greatly depend on humidity. Excessive moisture causes condensation, which accelerates damage processes. Wood attracts fungi and termites, and metals corrode faster in the presence of liquid water. Some researchers say dry air damages human health, causing sore throats and noses, and skin to dry out. Thus, it is important to predict humidity variation in a room.

According to mass balance, humidity in a room depends on 4 factors: 1) moisture flow through wall surfaces, 2) moisture carried by ventilation, 3) moisture generated in the room, and 4) distribution in the space.

It is known that we can calculate the first flux by applying simultaneous heat and moisture transport processes in a porous medium. The second is simply given by ventilation volume. The third can be solved by research and measurement. This work will be presented in another paper.
If air moves fast, humidity is relatively constant. However, wind velocity in a room is not high, so there is some humidity distribution.

It is also known that air movement in a room can be calculated by CFD simulation, although there are some differences among solutions depending on the type of turbulence models for Reynolds stress and treatment of numerical calculations. A literature survey reveals some reports focusing on humidity distribution in a room space. However, they treat walls as impermeable vapor barriers. Generally, walls are of porous material, even when they are covered with materials such as vinyl wall paper, and they absorb the moisture to some extent.

In this paper, the humidity distribution in a room space inside vapor absorb/desorb walls is calculated by comprehensive models combining H&M transport in walls and CFD simulation. The
subject room is rectangular box-shaped and it has inlet and outlet holes for ventilation. The results are compared with those of simplified models and different CFD turbulence models.

CALCULATION MODELS

1. Governing equations

For porous materials, we use Matsumoto's hygroscopic model1), 2) which is based on simultaneous heat and moisture transport processes. The humidity ratio is used to represent moisture activity.

\[
\left( \rho_e + \kappa \right) \frac{\partial X}{\partial t} + \frac{\partial}{\partial x} \rho_c \frac{\partial X}{\partial x} + \frac{\partial}{\partial y} \rho_c \frac{\partial X}{\partial y} + \frac{\partial}{\partial z} \rho_c \frac{\partial X}{\partial z} = \left( \rho_e + \kappa \right) \frac{\partial \phi}{\partial t} + \frac{\partial}{\partial x} \rho_c \frac{\partial \phi}{\partial x} + \frac{\partial}{\partial y} \rho_c \frac{\partial \phi}{\partial y} + \frac{\partial}{\partial z} \rho_c \frac{\partial \phi}{\partial z} - \frac{\partial}{\partial t} \left( \rho_c + \kappa \right) \frac{\partial T}{\partial t} + \frac{\partial}{\partial x} \rho_c \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} \rho_c \frac{\partial T}{\partial y} + \frac{\partial}{\partial z} \rho_c \frac{\partial T}{\partial z}
\]

In the air space, humidity and temperature are given by balance equations as:

\[
\rho_e \frac{\partial X}{\partial t} = \rho_e \frac{\partial U}{\partial t} - \rho_c \frac{\partial X}{\partial x} + \rho_{add}\]

\[
C_p \frac{\partial T}{\partial t} = C_p \frac{\partial U}{\partial t} - \rho_c \frac{\partial T}{\partial x} + q_{add}\]

Here, terms of \( q_{add} \) and \( q_{add} \) are moisture and heat generation rate per unit volume (g/m³ s) by something in a room such as a humidifier. Velocities on 3 rectangular axes are given by CFD steady state calculation, as given below.

The humidity variation which is based on the assumption of instantaneous diffusion without the porous wall's moisture sorption/desorption is given by sum of flow rate carried by ventilation and humidity source added by humidifier.

\[
\frac{1}{\rho_c} \frac{\partial X}{\partial t} = \left( 1 - \exp(-C_f t) \right)
\]

Here, \( C_f \) is the ventilation ratio, given by \( V_c / V_r \). In this paper this is called "Theoretical solution".

In the CFD calculation, constitution equations for incompressible fluid are as follows, mass balance:

\[
\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0
\]

Momentum balance:

\[
\frac{\partial U}{\partial x} + \frac{\partial W}{\partial y} + \frac{\partial V}{\partial z} + \rho_c \frac{\partial \rho_e}{\partial t} = -\frac{1}{\rho_c} \frac{\partial}{\partial x} \left( \rho_e \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho_e \frac{\partial U}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho_e \frac{\partial U}{\partial z} \right) + g \beta \left( T - T_a \right)
\]

Energy balance:

\[
\frac{\partial T}{\partial x} + \frac{\partial W}{\partial y} + \frac{\partial V}{\partial z} + \rho_c \frac{\partial \rho_e}{\partial t} = -\frac{\lambda + \kappa}{\rho_c C_p} \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} \left( \rho_c \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho_c \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial x} \left( \rho_c \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho_c \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho_c \frac{\partial T}{\partial z} \right) + q_{add}
\]

Moisture mass balance:

\[
\frac{\partial X}{\partial x} + \frac{\partial W}{\partial y} + \frac{\partial V}{\partial z} + \rho_c \frac{\partial \rho_e}{\partial t} = -\left( D_e + D_p \right) \frac{\partial X}{\partial x} + \frac{\partial}{\partial y} \left( \rho_c \frac{\partial X}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho_c \frac{\partial X}{\partial z} \right) + q_{add}
\]
Here,

\( \nu \): kinetic viscosity coefficient \( \nu = \mu / \rho_a \) (kg/ms)

\( \mu \): viscosity coefficient \( \mu = \mu_s + \mu_t \)

\( \mu_s \): molecular viscosity (kg/ms) \( \mu = \mu_s + \mu_t \)

\( \mu_t \): eddy viscosity \( \mu_t = 0.09 \rho_a k \) (kg/ms)

\( \lambda \): thermal conductivity (J/msK)

\( \lambda_t \): eddy thermal conductivity \( \lambda_t = 1.1 C_p \mu_t \) (J/msK)

\( D_m \): diffusivity coefficient (m²/s)

\( D_{en} \): eddy diffusivity coefficient \( D_{en} = 1.1 \mu_t / \rho_a \) (m²/s)

\( k \): turbulence kinetic energy

\( \varepsilon \): turbulence dissipation rate

\( \lambda \): turbulence scale

Table-1 shows the calculation model and its components which are used in this paper. Simplified model is based on the assumption of no distribution in the space. Thus, it is the solution of Eq. (3).

<table>
<thead>
<tr>
<th>Table-1: Models in this paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>In walls</td>
</tr>
<tr>
<td>Theoretical model</td>
</tr>
<tr>
<td>Simplified model</td>
</tr>
<tr>
<td>Comprehensive model</td>
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</tbody>
</table>

2. Calculated room space

H. Yoshino et al. measured the time variation of humidity distribution in about a 2m cubic box. All the calculations in this paper correspond to the measurements of Yoshino. Figure-1 shows a schematic view of the calculated space. Ventilation was created by a sucking fan set at the outlet hole and its rate is identified by measurement of wind velocity at the outlet hole. The measured rate was 0.8 – 1.0 times per hour. In the CFD simulation, it is set to 1.0 times/h.

Yoshino et al. measured humidity and temperature variation in the box for a number of cases. They covered some of the gypsum walls with vinyl sheet to suppress gypsum’s Moisture Buffering Effects. This paper shows calculations for two cases: with no vinyl-covered walls, and with 5 vinyl-covered walls.

In Yoshino’s measurement, the humidifier comprised a plastic tray with an electric heater filled with water. In this paper, the tray is omitted and the humidifier is regarded as merely hot water, or more precisely, the surface of the hot water. Moisture vaporizes from the top and heat is transferred by convection. The other surfaces are adiabatic and impermeable. In the CFD simulations, temperature at the water surface is regarded as constant at 29 degrees Celsius. In addition, the wall surface temperature in the CFD simulation is constant at 20 degrees Celsius, as for the inlet air for ventilation.

Table-2 shows the hygrothermal properties of gypsum board. In the calculation, a 100mm thickness of polystyrene is regarded as creating an adiabatic wall. Thus, we calculate humidity and temperature variations only for the gypsum board. Behind it, on the surface of aluminum sheet, the heat flux and moisture flux are equal to zero.

To calculate the moisture variation in gypsum board, we need the moisture capacity, which is the RH differential of equilibrium water content. Figure-2 shows the relation between RH and water content based on the two points in Table-2 (\( W_{w0} \) and \( W_t \)). The curve is numerically fitted by two equations as follows.

\[ Rh < 0.8 \quad WC = 0.009265 \times Rh \]
\[
Rh \geq 0.8 \quad WC = -0.00037/(Rh - 1.0008) + 0.005551
\]

Table 3 shows the properties of dry air in the CFD calculation.

Table-2: Hygrothermal properties of Gypsum board

<table>
<thead>
<tr>
<th>Thickness [m]</th>
<th>Density [kg/m³]</th>
<th>Porosity [m³/m³]</th>
<th>Cp [J/kgK]</th>
<th>λ dry [W/mK]</th>
<th>µ dry [-]</th>
<th>W80 [kg/m³]</th>
<th>Wf [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0125</td>
<td>850</td>
<td>0.65</td>
<td>850</td>
<td>0.2</td>
<td>8.3</td>
<td>6.3</td>
<td>400</td>
</tr>
</tbody>
</table>

Table-3: Properties of dry air

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.206</td>
<td>1.83e-5</td>
<td>1007</td>
<td>2.56e-2</td>
<td>3.455e-2</td>
</tr>
</tbody>
</table>

Figure-2 shows the calculation grid used for the CFD simulation. The space is divided into 1,728,000 cells (120 x 120 x 120 for each axis). Each cell comprises about a 15mm cube. The grid defining the inlet and outlet holes for ventilation are divided more minutely, as shown in the figure.

CALCULATION RESULTS
1. Air movement and Temperature distribution at steady state
   The velocity in the space is a maximum at the inlet hole and its value is about 0.16 m/s, since air of 1.0 times/h ventilation rate flows through a 0.1m-diameter hole (4.6m³/h / 0.05²π). Generally, it is
thought that the turbulence effect is not large, especially near the wall surface. Thus, the low-Re model is better than the standard k-e model to be applied to this problem.

Figures 3, 4 show the calculation results of the distributions of air velocity and temperature in the X-Y horizontal plane at the inlet hole center height, which is 1,645 mm above the floor surface.

The Low-Re model result is complex compared with the simplicity of the standard k-e model result. This follows the basic theory. In the low-air-velocity region, turbulence effect is small and the difference of velocity becomes relatively large. When eddy is small, the turbulent thermal transfer is also small. Thus, temperature difference is also relatively large.

2. Moisture diffusion process

Figure 5 shows the calculated variation of humidity ratio at some points in the space, depicted in the schematic figure. All the wall surfaces are impermeable to vapor. The theoretical solution and simplified solution are also showed.

The simplified solution perfectly corresponds with theoretical solution. It is shown that there are some differences among the humidity ratios at these points. Until now, the humidity ratio has been regarded as unique in the space since the vapor diffusion speed is very fast. However, if there is an air flow, even though most spaces experience it, the vapor moves with the bulk air flow creating some distribution in the space.

This figure also shows that the average of the distribution is roughly equal to the theoretical solution.

Figure 6 shows the results for a space enclosed by gypsum board. Gypsum board absorbs the vapor. The difference between the humidity ratios is greater than the former. Humidity absorption by the
walls causes bigger differences between the humidity ratios in the space.

Figure-5: Calculation result of humidity ratio

Figure-6: Calculation result of humidity ratio in the space whose walls are gypsum board

Figure-7 shows the two results of different turbulent models. One is the standard k-e 2 equation model and the other is the Low-Re k-e model. As shown in the flow pattern, Low-Re model has a big distribution of air velocity in the space. In this figure, it makes greater difference of humidity ratio.

Figure-11 shows the comparison with two results. It clearly shows 2 issues as follows,

1) The Low-Re model has wider distribution of humidity ratio in the space than the standard k-e model.

2) At most points, Humidity ration calculated with the Low-Re model is bigger than with the standard model.

Figure-7 shows the results of the two different turbulent models: the standard k-e 2 equation model and the Low-Re k-e model. As shown by the flow pattern, the Low-Re model has a big distribution of air velocity in the space. The figure shows greater differences among humidity ratios.

Figure-8 compares the two results. It clearly shows 2 issues:
1) The Low-Re model shows a wider distribution of humidity ratios in the space than the standard k-e model.

2) At most points, the humidity ratio calculated from the Low-Re model is bigger than that from the standard model.
Figure 7: Difference with turbulent model

Figure 8: Comparison with the two turbulent model results

Figure 9 shows the appearance frequency of scalar air velocity at each calculated point in the space. At a glance, it can be seen that the Low-Re model’s velocity is smaller than the standard k-e model’s velocity. In the high-velocity range, however, the frequency of Low-Re is greater. The bigger the velocity distribution, the bigger distribution of the humidity ratio in a space.

Figure 10 shows the turbulence diffusivity at each calculated point, sorted by value. It is clear that the standard k-e model has much bigger turbulence diffusion, which creates a smaller distribution of humidity ratio in the space.
CONCLUSIONS
It has been considered that humidity ratio in a space has no distribution since it diffuses so fast. In this study, however, air velocity caused by ventilation creates some distribution. Comparison of turbulence models has shown that the standard k-e model has a small distribution since it has smaller air velocity and bigger turbulent diffusivity.

It is also shown that vapor-absorbing walls creates a wider distribution of humidity ratio. In another words, the locations of walls should considered when estimating the moisture buffering effects of building materials.

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REFERENCES
Hiroshi Yoshino, Teruaki Mitamura and Ken-ichi Hasegawa: ANNEX41 Subtask 1 Common Exercise 2 “Small chamber test (THU test room) in the climate chamber”, IEA ANNEX41 meeting report, 2006
M. Kumar KUMARAN, IEA ANNEX24 Heat, Air and Moisture Transfer Through New and Retrofitted Insulated Envelope Parts (Hamtie) Final Report Volume 3 TASK 3: MATERIAL PROPERTIES