A STUDY ON HUMIDITY DISTRIBUTION IN A ROOM

Atsushi IWAMAE

Department of Architecture, School of Science and Engineering, Kinki University

ABSTRACT

It is well known that humidity influences cooling load, thermal comfort and durability of buildings and various items in them. Many works on prediction of humidity variation in a room have regarded the humidity as unique in a space. However, it does depend on air movement. This paper describes calculations of minute moisture distributions in a room affected by moisture buffering of porous walls. The air velocity distribution is calculated by CFD using two different turbulence models. Then the heat and vapor transient transport in walls and space is calculated. This shows that moisture distribution is not negligible. The difference between the two turbulence models is also determined.

KEYWORDS

Heat and moisture transport, Porous medium, Air movement, Ventilation, CFD, Turbulence model

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

Governing equations

For porous materials, we use Matsumoto's hygroscopic model（Matsumoto 1987, Moisture 1984）, which is based on simultaneous heat and moisture transport processes. The humidity ratio is used to represent moisture activity.

$$(\phi_0\gamma' + \kappa)\frac{\partial X}{\partial t} - \nu\frac{\partial T}{\partial t} = \nabla \bullet J = -\lambda_X'\nabla^2 X \tag{1}$$

$$-r\kappa\frac{\partial X}{\partial t} + (C_\rho + r\nu)\frac{\partial T}{\partial t} = \nabla \bullet q = -\lambda\nabla^2 T \tag{2}$$

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

$$\rho_a\frac{\partial X}{\partial t} = \rho_a\nabla U \cdot X - \lambda_X'\nabla^2 X + j_{add} \tag{3}$$

$$C_\rho\frac{\partial T}{\partial t} = C_\rho\nabla U \cdot T - \lambda\nabla^2 Ta + q_{add} \tag{4}$$

Here, the terms j_{add} and q_{add} are moisture and heat generation rate per unit volume (g/m^{3}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.

In the CFD calculation, constitutive equations for incompressible fluid are as follows:

Mass balance:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0 \qquad (5)$$

Momentum balance: (6), (7), (8)

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=-\frac{1}{\rho_a}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}+\frac{\partial^2 U}{\partial z^2}\right)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-\frac{1}{\rho_a}\frac{\partial P}{\partial y}+\nu\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}\right)$$

$$\frac{\partial W}{\partial t}+U\frac{\partial W}{\partial x}+V\frac{\partial W}{\partial y}+W\frac{\partial W}{\partial z}=-\frac{1}{\rho_a}\frac{\partial P}{\partial z}+\nu\left(\frac{\partial^2 W}{\partial x^2}+\frac{\partial^2 W}{\partial y^2}+\frac{\partial^2 W}{\partial z^2}\right)-g\beta(T-T_0)$$

Energy balance: (9)

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}+W\frac{\partial T}{\partial z}=-\frac{\lambda+\lambda_t}{C_\gamma}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q_S/C_\gamma$$

Moisture mass balance: (10)

$$\frac{\partial X}{\partial t}+U\frac{\partial X}{\partial x}+V\frac{\partial X}{\partial y}+W\frac{\partial X}{\partial z}=-(D_m+D_{mt})\left(\frac{\partial^2 X}{\partial x^2}+\frac{\partial^2 X}{\partial y^2}+\frac{\partial^2 X}{\partial z^2}\right)+J_S$$

$$\nu=\mu/\rho_a \qquad (11)$$

Here,

- ν : kinetic viscosity coefficient (kg/ms)
- μ : viscosity coefficient $\quad \mu=\mu_s+\mu_t$
- μ_s : molecular viscosity (kg/ms)
- μ_t : eddy viscosity $\quad \mu_t=0.09\,\rho_a k^2/\varepsilon \quad$ (kg/ms)
- λ : thermal conductivity (J/msK)
- λ_t : eddy thermal conductivity $\quad \lambda_t=1.1\,C_\gamma\mu_t$ (J/msK)
- D_m : diffusivity coefficient (m^2/s)
- D_{mt} : eddy diffusivity coefficient $\quad D_{mt}=1.1\,\mu_t/\rho_a$ (m^2/s)
- k : turbulence kinetic energy $\quad k=\frac{1}{2}\left(\overline{u'u'}+\overline{v'v'}+\overline{w'w'}\right)$
- ε : turbulence dissipation rate $\quad \varepsilon=\frac{k^{\frac{3}{2}}}{l}=\nu\overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}}$
- l : turbulence scale

Table-1 shows the name of the calculation model and its component, as used in this paper.

Table-1: Models and equations

In walls	In Air	(turbulent model)
H&M process (1)	Humidity and temperature (2)	Standard k-e model
	Velocity and turbulent diffusivities (5)~(8)	ANK low-Re model

2.2 Calculated room space

H. Yoshino et al.(2006)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 transfered 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.

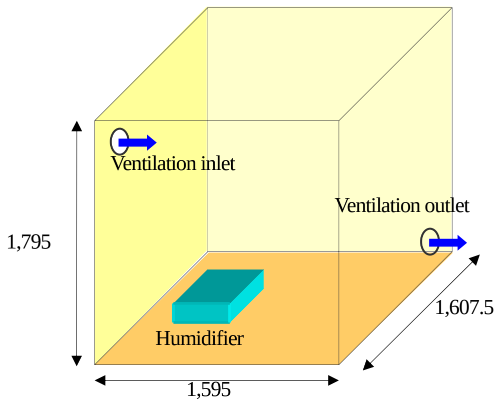


Figure-1: Schematic view of calculated space

Table-2 shows the hygrothermal properties of gypsum board. In the calculation, a 100mm thickness of polystyrene is regarded as creating an adiabatic wall(Kunmara)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.

Table-2: Hygrothermal properties of Gypsum board

Thickness [m]	Density [kg/m^3]	Porosity [m^3/m^3]	Cp [J/kgK]
0.0125	850	0.65	850
λ_{dry} [W/mK]	μ_{dry} [-]	W_{80} [kg/m^3]	W_f [kg/m^3]
0.2	8.3	6.3	400

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_{80} and W_f).

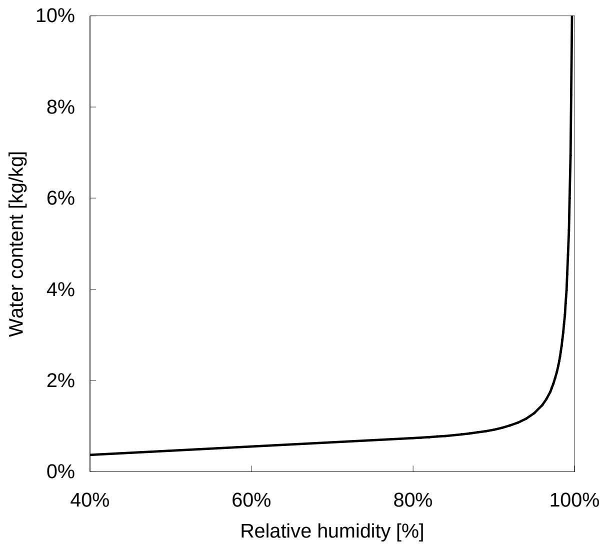


Figure-2: Equilibrium water content related to relative humidity of Gypsum board used in this paper

The curve is numerically fitted by two equations as follows.

$Rh < 0.8$: $WC = 0.009265\,Rh$

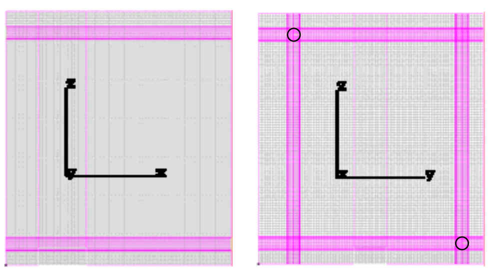
$Rh \geq 0.8$: $WC = -0.00037/(Rh - 1.0008) + 0.005551$

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

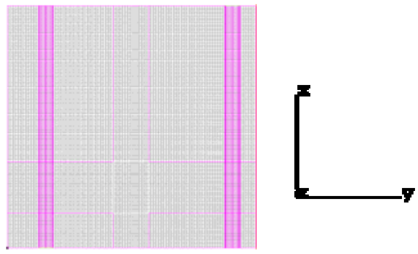
Table-3: Properties of dry air

Density [kg/m^3]	Molecular viscosity [kg/ms]	Cp [J/kgK]	Thermal conductivity [W/mK]	Volume expansion rate [1/K]
1.206	1.83e-5	1007	2.56e-2	3.495e-2

Figure-3 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.



X-Z section *Y-Z section*



X-Y Plane

Figure-3: Grid for CFD simulation

3. Calculation Results

3.1 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 (4.6m^3/h / $0.05^2\pi$). 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.

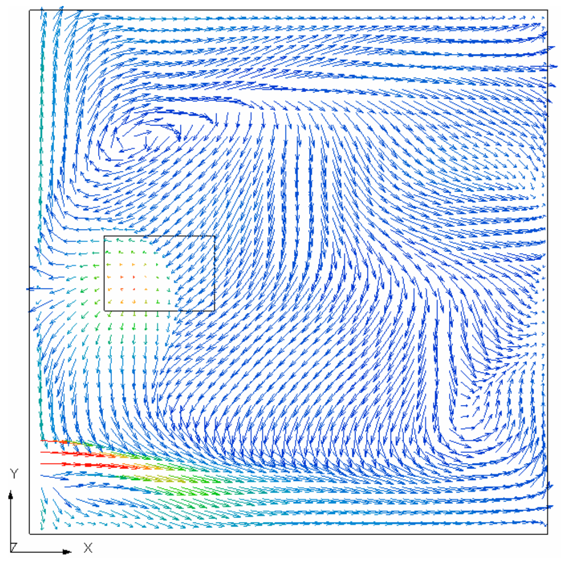
Figures-4 - 7 show the results for each model. Figures-4 and 5 show the distributions of air velocity and temperature in the X-Y horizontal plane at the inlet hole center height, which is 1,645 mm above the floor surface.

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.

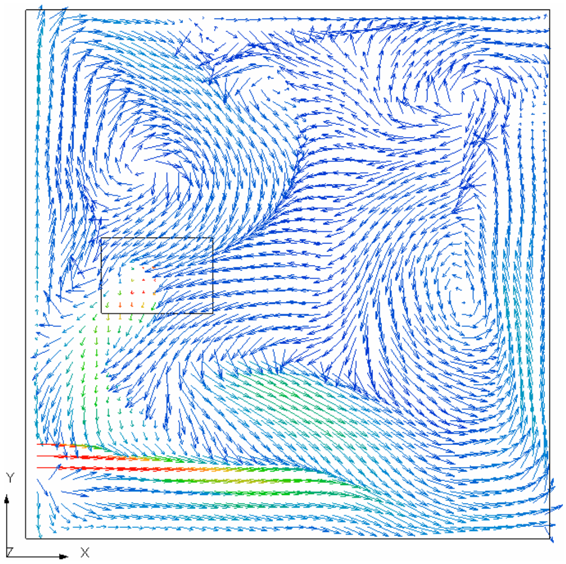
Moisture diffusion process

Figure-8 shows the calculated variation of humidity ratio at some points in the space, depicted in Figure-11. All the wall surfaces are impermeable to vapor.

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

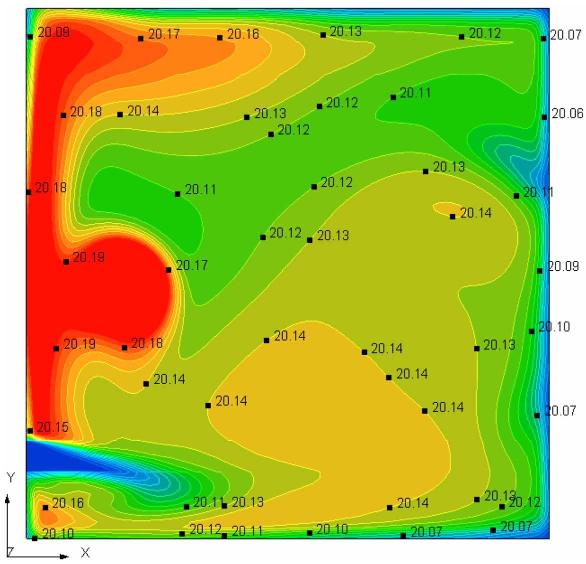


(*a*) *Standard k-e model*

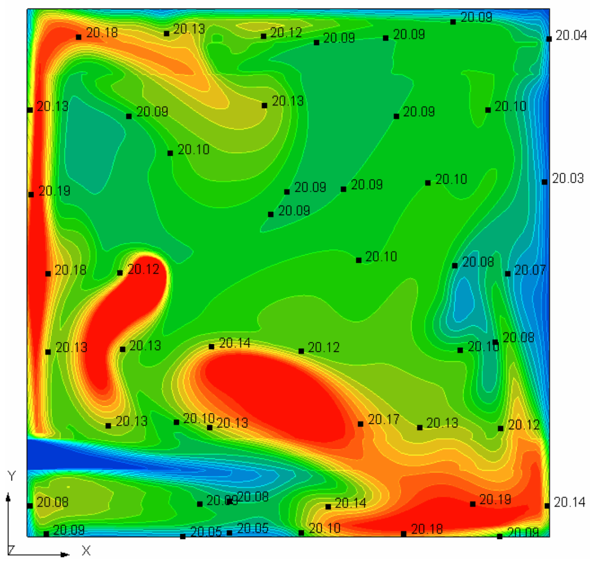


(*b*) *Low-Re AKN model*

Figure-4: Air velocity in X-Y plane at inlet hole center height

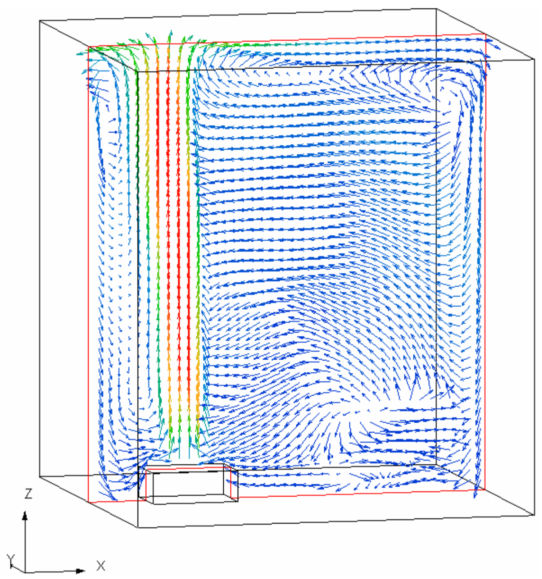


(*a*) *Standard k-e model*

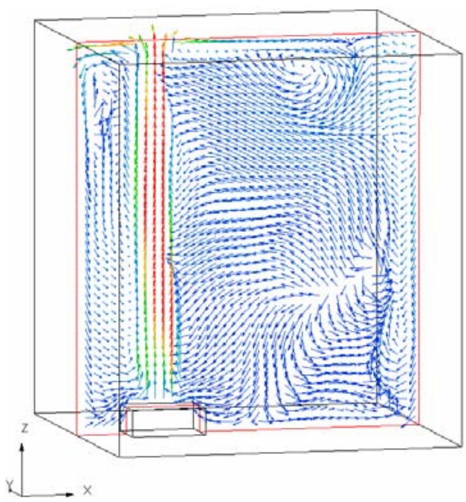


(*b*) *Low-Re AKN model*

Figure-5: Temperature in X-Y plane at inlet hole center height

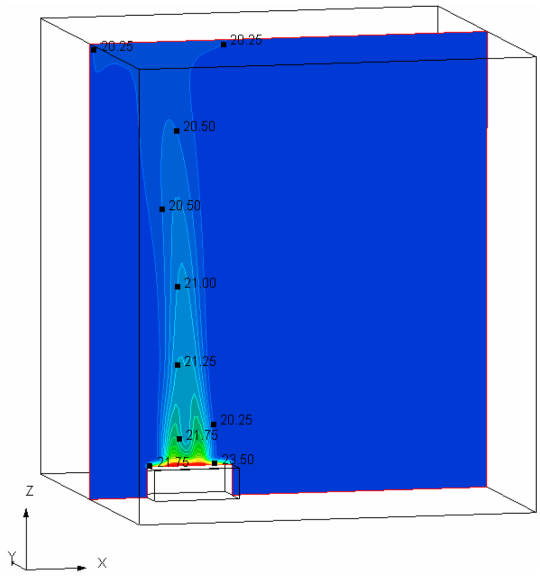


(*a*) *Standard k-e model*

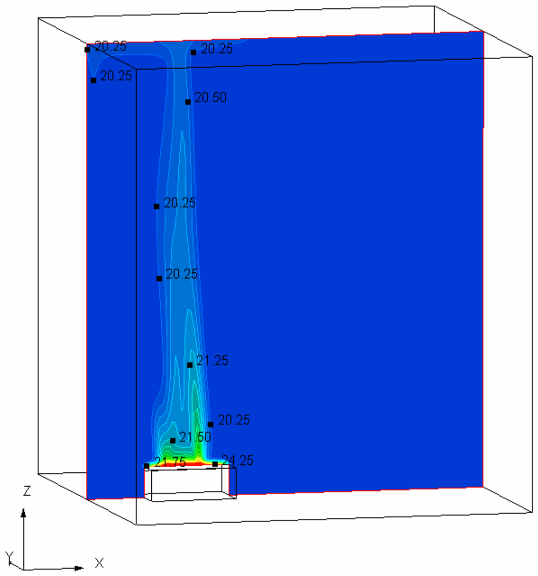


(*b*) *Low-Re AKN model*

Figure-6: Air velocity in X-Z center section



(*a*) *Standard k-e model*



(*b*) *Low-Re AKN model*

Figure-7: Temperature in X-Z center section

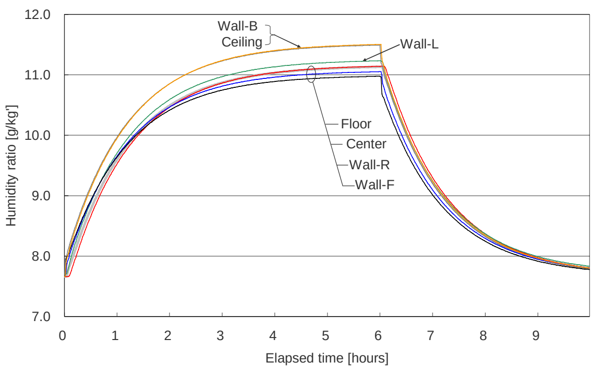


Figure-8: Calculation result of humidity ratio

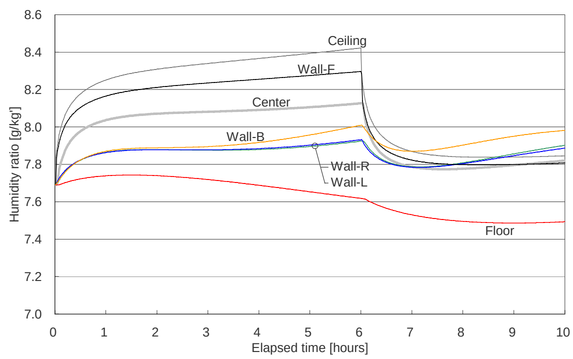


Figure-9: Calculation result of humidity ratio in the space whose walls are gypsum board

Figure-10 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-11 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-12 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 13 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.

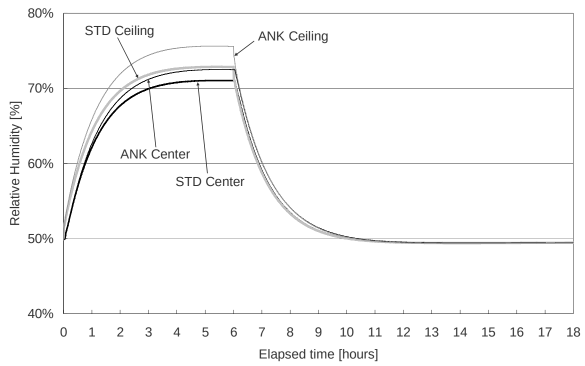


Figure-10: Difference between turbulence models

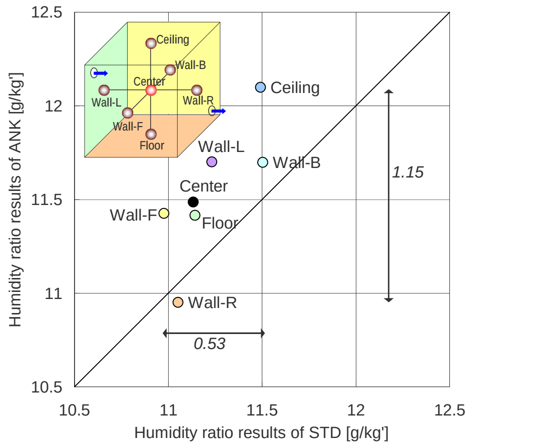


Figure-11: Comparison between two turbulecet model results

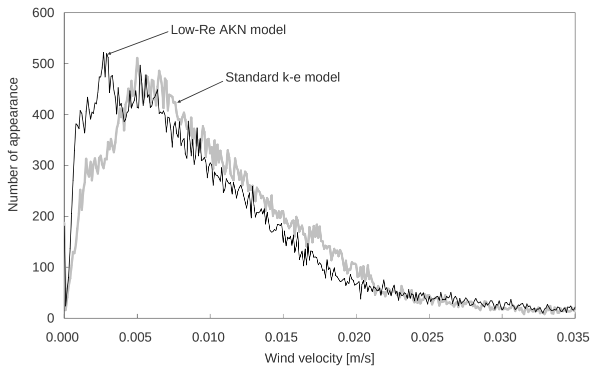


Figure-12: Appearance frequency of scalar of velocity

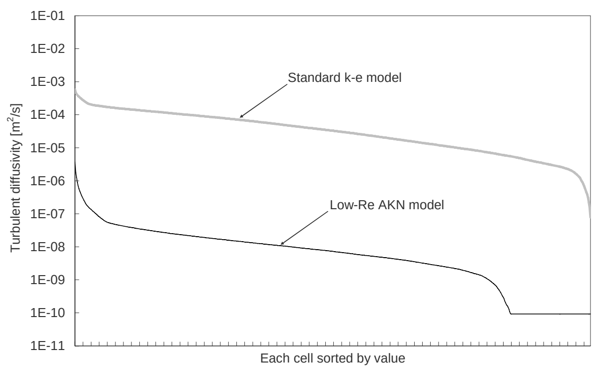


Figure-13: Turbulence diffusivity (sorted by value)

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.

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.

Mamoru Matsumoto, Simultaneous heat and moisture transfer in porous wall and analysis of internal condensation, Energy Conservation in Heating, Cooling and Ventilating Building, Hemisphere, 1978, pp.45 – 58

M. Matsumoto, Moisture, Physics of Environment, Architectural Science series, Vol.10, Shokokusya, 1984, (in Japanese)

4) 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