A study on condensation simulation for a building integrated with a capillary ceiling HVAC system

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Abstract

The condensation of capillary ceiling embedded with capillary radiant network (CRN) was simulated. Two types of condensation in capillary ceiling will be produced (i.e. surface and internal condensation of the enclosure). Temperature, humidity distribution and condensation of ceiling in both summer and winter were studied based on principle of coupled heat and moisture transfer. The effect of Expanded Polystyrene (EPS) insulation board thickness has been carefully analyzed. In summer, the thickness of EPS must be greater than 10 mm to avoid wall surface condensation. If the thickness of EPS exceeds 20 mm, the surface relative humidity could be reduced to below 95%. In winter, in order to prevent the ceiling condensation at the internal interface between EPS and concrete, the thickness of EPS should better be less than 20 mm or more than 45 mm. Considering the fact that no condensation occurs within the 30 days in summer and winter, the thickness of the EPS should be greater than 45 mm. The results indicate that even if no condensation occurs on the surface of the capillary ceiling, the risk of internal condensation still exists, especially in winter. Increasing thickness of EPS can reduce the possibility of the radiant ceiling condensation.

Keywords: capillary radiant network; capillary ceiling; internal condensation

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Received 31 August 2018; revised 29 November 2018; editorial decision 6 January 2019; accepted 10 January 2019

1 INTRODUCTION

Currently, energy consumption in buildings mainly consists of domestic hot water, heating, cooling, ventilation, lighting and electrical appliances, over one-third of China’s total energy is used in buildings in which energy consumption for heating and cooling is about 63% of the overall energy consumption of buildings in China [1]. Both energy conservation and indoor thermal comfort are main concerns for architects to select an appropriate HVAC system for their building development [2]. The radiant air-conditioning system (RACS) with CRN as terminal has become prevalent for its energy saving. The CRN composed of micro-plastic tubes (Ø 3.0–6.0 mm) made of polypropylene. RACS is noiseless and use less building space without causing any draughts. It has very short distance (10–30 mm) between each capillary tube. When properly designed, the RACS can also add an aesthetic to buildings as it does not disrupt the designed space and therefore increase the architectural value [3].

The supply water temperature with RACS for heating/cooling are 28–32°C/18–22°C which can meet the demand of indoor thermal comfort. Low-grade energy can be well used, can save 40% energy in the range of 40–70% by using the RACS [4]. Besides the indoor temperature of the RACS radiant heating system is lower, and takes up less space than all-air system.

However, building envelope is made of porous materials in which heat and moisture transfer can exist [5, 6]. Condensation can occur on the surface and inside of the building envelope, where the CRN is installed. When the temperature is lower than the dew point temperature, condensation occurs. The moisture transfer and condensation of the enclosure structure cause many hazards. The thermal conductivity of the insulation material increases due to moisture content which can increase energy consumption of the building [7]. Thermal insulation materials breed lots of fungi due to condensation, and fungi can lead to respiratory symptoms [8, 9].

At present, the research mainly focuses on the surface condensation of radiation, and very few studies on the overall condensation of the wall, especially on the wall embedded with...
CRN. Yin et al. [10] compared three radiant cooling model (pure CRN model, the CRN model with metal covering and the CRN model with gypsum covering) the performance of heat transfer and moisture condensation, found the upper limit of sub-cooling degree by gradually decreasing the chilled water temperature from 17°C until the condensation of moisture occurred. It was concluded that the upper limit of sub-cooling degree for the pure tube, gypsum panel and metal panel were 3.2°C, 6.5°C and 5.4°C, respectively. However, it is inaccurate to determine the upper limit of sub-cooling degree by observing the surface condensation of the model. The internal condensation of the gypsum should be considered.

This paper has mainly studied condensation of the ceiling embedded with CRN, in the hot summer and cold winter areas of China. Temperature, humidity distribution and condensation of ceiling in both summer and winter were studied based on principle of coupled heat and moisture transfer. The influence of the thickness of the insulation board has also been analyzed. This research study has provided a practical way in order to prevent formation of dew in ceiling.

2 PHYSICAL MODEL

A radiant air conditioning room with ceiling is used as physical model whereas an adjacent room without air conditioning is present above that ceiling. The two-dimensional model was built of ceiling, as shown in Figure 1, this ceiling consists of 20 mm cement mortar + EPS + 100 mm reinforced concrete + 20 mm cement mortar, and capillary network of PVC material is laid in the cement mortar of the radiation air conditioning room side. The thickness of the EPS is d mm. The section is at the middle of two micro tubes.

3 MATHEMATICAL MODEL

3.1 Dynamic modeling of heat and moisture transport

Two-dimensional governing equations with coupled temperature and moisture for a multi-layer porous wall are considered with the effect of the absorption or desorption heat has been added. A local thermodynamic equilibrium between the fluid and the porous matrix is assumed as shown in given equations [11]:

Equation 1: Moisture transfer governing equation.

\[
\xi \frac{\partial \varphi}{\partial t} = \nabla \left( \left( \delta_w + D_w \xi \right) \nabla \varphi + \xi \frac{\partial P_s}{\partial T} \right)
\]

Equation 2: Heat transfer governing equation.

\[
\left( \rho_m \xi + wc_p \right) \frac{\partial T}{\partial t} = \nabla \left( \left( \lambda \nabla T \right) + h_v \left[ \varphi \frac{\partial P_s}{\partial T} \nabla T + P_s \nabla \varphi \right] \right)
\]

where:

- \( \delta_w \) = the permeability coefficient of water vapor in porous materials (s),
- \( P_s \) = the saturated water vapor pressure (Pa),
- \( \varphi \) = relative humidity (%),
- \( \xi \) = the slope of sorption moisture retention curve, (kg/m³),
- \( D_w \) = the moisture diffusion coefficient with the moisture content as the gradient (m²/s),
- \( \rho_m \) = dry material density (kg/m³),
- \( c_{p,m} \) = specific heat of dry materials (J/(kg K)),
- \( c_{p,l} \) = the specific heat of liquid water (J/(kg K)),
- \( \lambda \) = thermal conductivity coefficient (W/(m K)),
- \( h_v \) = latent heat of evaporation (2500 kJ/kg),
- \( T \) = object temperature (K),
- \( w \) = moisture content (kg/m³),
- \( t \) = time (s),
- \( H \) = specific enthalpy of material (J/kg),
- \( h_v \) = specific enthalpy of water vapor (J/kg),
- \( h_l \) = specific enthalpy of liquid water (J/kg),
- \( q_c \) = heat flux density (W/m²).

\( P_{sat} \) is the single value function of temperature, \( T \) [12].

Equation 3: The saturated water vapor pressure.

\[
P_{sat} = 611 \cdot \exp \left( \frac{a \cdot T}{T_0 + T} \right)
\]

where:

\[
T_0 = 273.15 \text{K}, a = 3795.8 \text{K}
\]
Table 1. Both side boundary conditions of ceiling in summer.

| Position                                         | $h\ (W/(m^2 \cdot K))$ | $\beta \times 10^8\ (s/m)$ | $T_{air}\ \ (^{\circ}C)$ | $\phi_{air}$ |
|--------------------------------------------------|-------------------------|-----------------------------|--------------------------|--------------|
| Floor surface of adjacent room (Non radiant air conditioning) | 5.3                     | 3.7                         | 32                       | 85%          |
| Ceiling surface of room (Radiant air conditioning)  | 11                      | 8.4                         | 26                       | 60%          |

Table 2. Both side boundary conditions of ceiling in winter.

| Position                                         | $h\ (W/(m^2 \cdot K))$ | $\beta \times 10^8\ (s/m)$ | $T_{air}\ \ (^{\circ}C)$ | $\phi_{air}$ |
|--------------------------------------------------|-------------------------|-----------------------------|--------------------------|--------------|
| Floor surface of adjacent room (Non radiant air conditioning) | 9                       | 7.2                         | −2                       | 80%          |
| Ceiling surface of room (Radiant air conditioning)  | 6                       | 4.8                         | 18                       | 60%          |

Table 3. Properties of the material.

| Properties                                      | Equations                                                                 |
|-------------------------------------------------|---------------------------------------------------------------------------|
| Moisture content (kg/m³)                         | $w = \frac{146}{(1 + (-8 \times 10^{-8} \times R_{wv} \ln(\varphi))^{0.575})}$ |
| Moisture diffusivity (m²/s)                     | $D_w = -K_w \frac{\partial}{\partial w}$                                |
| Suction stress (Pa)                              | $P_c = 0.125 \times 10^2 \left( \frac{146}{w} \right)^{0.625}$           |
| Liquid Water Permeability (s)                    | $K_l = \exp(-39.2619 + 0.0704 \times (w - 73) - 1.742 \times 10^{-6} \times (w - 73)^2 - 2.7953 \times 10^{-6} \times (w - 73)^3 - 1.1566 \times 10^{-7} \times (w - 73)^4 + 2.5969 \times 10^{-10} \times (w - 73)^5)$ |
| Vapor Permeability (s)                          | $\delta_p = \frac{M_{wv}}{R_{wv} \ln w} \times \frac{26.1 \times 10^{-6}}{200} \times \frac{1 - \frac{w}{146}}{0.503 \left(1 - \frac{w}{146}\right)^2 + 0.497}$ |
| Thermal Conductivity (W/(m K))                  | $\lambda = 1.5 + 0.0158w$                                               |
| Density of Dry Material (kg/m³)                  | $\rho_w = 2145.88$                                                      |
| Specific Heat of Dry Material (J/(kg K))         | $C_{pm} = 850$                                                          |

Figure 2. Comparison between the numerical simulation of CHM and the analytical solution of EN15026 in moisture content distribution after 7 days, 30 days and 365 days.
- $a$ = the constant,
- $T_o$ = Reference temperature (K),

When $T < 0$, $a = 22.44$, $T_o = 272.44$ K; $T \geq 0$, $a = 17.08$, $T_o = 234.18$ K.

Equation 4: Moisture storage capacity.

$$\frac{\partial w}{\partial \varphi} = \xi$$

Water vapor pressure $P_v$ can be expressed as follows:

Equation 5: Water vapor pressure.

$$P_v = \varphi P_{sat}$$


BOUNDARY CONDITIONS

The heat flux on the building elements surface can be calculated as:

Equation 6: The heat changes at the ceiling surface.

\[ q = h(T_{\text{air}} - T_{\text{surf}}) + h_{\text{v,g}} \]

where:

- \( q \) = heat flux density (W/m\(^2\)),
- \( h \) = total heat transfer coefficient (W/(m\(^2\) k)),
- \( T_{\text{air}} \) = temperature of the ambient air (K),
- \( T_{\text{surf}} \) = temperature of the building elements surface (K).

The moisture flux through the building surfaces can be calculated as follows:

Equation 7: Moisture transfer governing equation.

\[ \beta \phi_{\text{air}} = g(\phi_{\text{air}} P_{\text{sat,air}} - \phi_{\text{surf}} P_{\text{sat,surf}}) \]

where:

- \( g \) = water vapor diffusion flux density (kg/(m\(^2\) s)),
- \( \beta \) = water vapor transfer coefficient (kg/(m\(^2\) s Pa)),
- \( \phi_{\text{air}} \) = relative humidity of air (%),
- \( \phi_{\text{surf}} \) = relative humidity on the surface of the ceiling (%),
- \( P_{\text{sat,air}} \) = saturated pressure of water vapor in the ambient air (Pa),
- \( P_{\text{sat,surf}} \) = saturated pressure of water vapor of the ceiling surface (Pa).

Water vapor transfer coefficient \( \beta \) can be carried out by the Lewis criterion correlation formula reflecting the relationship between the thermal boundary layer and the concentration boundary layer [13].

Equation 8: Lewis’s principle of analogy.
\[ \beta = \left( \frac{h}{461.4 \times c_{p,a} \times \rho_a \times T} \right) \]

where:
- \( c_{p,a} \), \( \rho_a \) = air specific heat capacity, density, (J/(kg K)), (kg/m³). Detailed boundary conditions are presented in Tables 1 and 2.

### Table 4. Properties of the ceiling components [16].

| Component               | Cement mortar | Reinforced concrete | EPS   |
|-------------------------|---------------|---------------------|-------|
| \( \rho \) (kg/m³)      | 1800          | 2500                | 30    |
| \( c_p \) (J/(kg K))    | 840           | 940                 |       |
| \( \omega \) (kg/m³)    | \(-0.022\omega^2 + 0.025\omega + 0.0001\) | \(0.018\omega^2 - 0.027\omega + 0.020\) | \(-0.5277\omega^2 + 0.9647\omega + 0.07086\) |
| \( \delta_s \) (10⁻¹²s) | 16.67         | 6.76                | 11.00 |
| \( \lambda \) (W/(m K)) | \(0.854 + 4.5 \times 10^{-5}w\) | \(2.7 + 0.0032 \times 10^{-3}w\) | \(0.0331 + 1.23 \times 10^{-5}w\) |
| \( D_w \) (m²/s)        | \(1.4 \times 10^{-12} \text{exp}(0.027w)\) | \(1.8 \times 10^{-11} \text{exp}(0.0582w)\) | N/A   |

### Figure 7. Temperature and humidity distribution with 0 mm EPS (a) temperature distribution at the 30th day, (b) relative humidity distribution at the 30th day, (c) relative humidity distribution at the section, (d) saturated and partial water vapor pressure distribution at the section.

5 **MODEL VALIDATION**

The presented coupled transient heat and moisture transfer model (CHM) is validated by comparing with the two benchmark test of (1) EN15026 [14] and (2) HAMSTAD project [15], which were initiated in order to develop a platform for assessment in computational modeling of heat, moisture and air transport mechanism in building physics.
5.1 Comparison with the benchmark test of EN 15026
In this physical model, geometry is comprised of a single segment for the building component. Its size has been taken as large enough to represent it as a semi-infinite region for the simulation time-scale. A relative humidity of 50% and a temperature of 20°C are set as initial conditions while on the left boundary, the relative humidity is set as 95% with temperature of 30°C. The time-dependent study is run over one year, with a control of the temperature and relative humidity distributions at 7, 30 and 365 days. The material properties are given in Table 3.

The simulation results produced by CHM model has been illustrated in Figures 2 and 3 which has shown an agreement with benchmark physical model of EN15026.

5.2 Comparison with the HAMSTAD Benchmark Case #5
In HAMSTAD benchmark Case #5, a wall with insulation applied at the internal side of the construction has been applied. The challenges in this model are related to highly nonlinear material properties and discontinuities at interfaces between materials. It consists of brick having width of 365 mm towards outside, 15 mm mortar and 40 mm of insulation material. The boundary conditions are constant and the results are adopted from the last time step, i.e. 60 days. In this case, results are relative humidity and the moisture content of the last time step at 60 days, as shown in Figures 4 and 5. Properties of the material are given in literature [15].

Figure 5 shows the model credibility which demonstrates an agreement with the results of numerical simulation. The

Figure 8. Temperature and humidity distribution with 10 mm EPS (a) temperature distribution at the 1st day, (b) relative humidity distribution at the 30th day, (c) relative humidity distribution at the section, (d) saturated and partial water vapor pressure distribution at the section.
distribution curve of moisture content has shown discontinuity due to the fact that each material has its own sorption isotherms curve. In different materials, the relative humidity is same and the moisture content may be different. Figure 6 shows the sorption isotherms curve of the inside insulation and mortar, it can explain why there is a discontinuity in moisture content at the interface between inside insulation and mortar, the relative humidity has shown continuity in Figure 4 which is about 94% at the interface. The moisture content of inside insulation and mortar are 38 kg/m³, 68 kg/m³ respectively.

6 PARAMETERS OF THE CEILING

The selection of performance parameters of the ceiling are as shown in Table 4.

7 NUMERICAL SOLUTION

The capillary tubes wall temperature is assumed as mean value of water supply and return temperature. In summer, the water supply/return temperatures are 20/22°C. In winter, water supply/return temperatures are 30/32°C. The multi physical field coupling simulation software COMSOL Multiphysics is used to solve the coupled heat and moisture transfer model of the enclosure structure. COMSOL Multiphysics uses the finite element method to discretize the model automatically and solve the discrete algebraic equations with the numerical solver. The model temperature, relative humidity initial value is set to be the same as radiation air conditioning room.

8 RESULTS AND DISCUSSIONS

8.1 Effect of EPS thickness on condensation in summer

The temperature and moisture content distribution calculated by the model presented in this paper. Figures 7 and 8 show the relative humidity and water vapor pressure distribution at the section when 0 mm and 10 mm EPS were laid in summer, respectively. Since moisture transfer is very slow, the temperature and humidity distribution on Day 1, Day 7 and Day 30 were studied. Figure 4 shows the relationship between the ceiling surface relative humidity on the adjacent room side and EPS thickness.

In summer, from Figure 7(a, b), the ceiling surface temperatures on radiant air-conditioning room side and the adjacent room side are 21.05°C, 24.88°C, respectively, and the relative humidity of ceiling surface on the adjacent room side reaches maximum, the numerical solution of relative humidity is greater than 1, indicating that surface condensation occurs. Figure 7(c) shows the relative humidity distribution at the 1st, 7th and 30th day. The ceiling’s moisture transfer inertia is very strong, and it is not stable after 30 days, especially at the position of 50–70 mm. it can be found from Figure 7(d), $P_{w,v}$ and $P_{sat,wv}$ represent the partial water vapor pressure and the saturated water vapor pressure, respectively, when EPS is not laid, $P_{sat,wv}$ is less than the $P_{w,v}$ which results in condensation. The saturated vapor pressure is a single value function of temperature. Since the heat transfer inertia is very small, the ceiling temperature quickly becomes stable, and the temperature changes very little between the 1st, 7th and 30th days, so the saturated vapor pressure lines almost coincide like the temperature lines. Since moisture content distribution changes over time slowly and the rate of heat transfer through the ceiling is faster than moisture transfer, the temperature distribution varies little with time.

Figure 8 shows the temperature and moisture content distribution of the ceiling when 10 mm EPS was laid. Figure 8(a, b) show that the ceiling surface temperature at the adjacent room side rise to 29°C, meanwhile, the relative humidity is down to 100%. Figure 8(c, d) shows the relative humidity from the interface between EPS and reinforced concrete to the adjacent room side is reduced, $P_{sat,wv}$ is equal to the corresponding $P_{w,v}$. This means that EPS can be used to prevent condensation of the ceiling on the adjacent room side in summer.

To prevent the ceiling surface condensation within 30 days on the adjacent room side, the thickness of EPS has been changed. It can be concluded from Figure 9 that as the thickness of the insulation board increases, the surface relative humidity gradually decreases. When the thickness of EPS is 10 mm, the numerical value of the relative humidity drops to 100%, indicating that 10 mm is the minimum thickness to prevent surface condensation within 30 days, to reduce the risk of condensation, the relative humidity should be reduced to 95%, at which time the thickness of EPS is 20 mm.

![Figure 9. Relationship between the ceiling surface relative humidity on the adjacent room side and EPS thickness in summer.](https://academic.oup.com/ijlct/article-abstract/14/2/256/5307065)
8.2 Effect of EPS thickness on condensation in winter

In winter, Figures 10 and 11 show the temperature and humidity distribution of the whole ceiling, the relative humidity and water vapor pressure distribution at the section when 0 mm and 32 mm EPS were laid, respectively. From Figure 10 (a–c), the ceiling surface temperature on air-conditioning room side and adjacent room side are 29.09°C, 19.37°C, respectively. Due to the initial relative humidity of the model was set to 60% and the moisture transfer is very slowly, the relative humidity inside the ceiling gradually decreases after 30 days. The relative humidity of the ceiling surface on the adjacent room side and the radiation air conditioning room side were 0.2 and 0.3, respectively. By simulating the heat and humidity distribution of the ceiling after 1, 7 and 30 days, it is found from Figure 10(d), when EPS is not laid, the vapor pressure of radiant air-conditioning rooms is higher than that of adjacent rooms, and water vapor permeates from the radiant air-conditioning room to adjacent room. The saturated water vapor pressure is greater than the water vapor pressure, no condensation occurs.

In winter, the ceiling is in a high temperature state without EPS laid because CRN heats the whole ceiling, the ceiling is not easy to condense. However, Figure 11 shows that, when the EPS is laid, the heat insulation and moisture resistance of insulating board cause high humidity area between EPS and concrete which has the highest relative humidity in the whole ceiling. When the thickness of EPS is 32 mm, the relative humidity reaches the maximum, up to 99%, and water vapor permeates from the radiant air-conditioning room to adjacent room. The saturated water vapor pressure is greater than the water vapor pressure, no condensation occurs.

Figure 12 shows that as the thickness of EPS increases, the relative humidity at the interface increases first and then decreases on the 30th day. When the thickness of EPS is increased to 32 mm, the relative humidity reached the maximum, up to 99%,
and the relative humidity is more than 95%, when the thickness of EPS is between 20 mm and 45 mm. In order to prevent the ceiling condensation at the interface between EPS and concrete in winter, the thickness of EPS should be less than 20 mm or more than 45 mm.

9 CONCLUSIONS

In this study, condensation of a building integrated with capillary radiant ceiling in cooling and heating seasons based on theory of coupled heat and moisture transfer has been investigated. A physical model of transient heat and moisture transfer was solved by using COMSOL Multiphysics and validated by comparing with the benchmark test of EN15026 and HAMSTAD project. It was found that results of numerical simulation agreed well with those benchmarks which testify the credibility of physical model developed.

The temperature and humidity distribution of capillary radiant ceiling were simulated without using EPS. Meanwhile, condensation appeared on the floor of adjacent room which is adjacent to air-conditioned room during summer whereas it did not appear in winter season. Moreover, the effect of EPS thickness on the ceiling condensation has also been investigated which showed that only a suitable thickness of EPS can prevent surface and internal condensation. In winter, with using EPS between 20 mm and 45 mm laid on the ceiling which showed that it is more prone to condensation at the interface between EPS and reinforced concrete, i.e. relative humidity showed a significant range (more than 95%) at the interface. Similarly, refer to Figure 10(c), without using EPS, relative humidity is gradually decreased with respect to initial value of 60% as

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Figure 11. Temperature and humidity distribution with 32 mm EPS thickness (a) temperature distribution at the 1st day, (b) relative humidity distribution at the 30th day, (c) relative humidity curve of the section, (d) saturated and partial water vapor pressure curve of the section.
number of days has been increased which shows that condensation will not occur at its interface. In summer, relative humidity on the floor of adjacent room is suddenly decreased with increasing thickness of EPS. Moreover, when thickness of EPS is kept more than 20 mm then surface condensation can be prevented.

Finally, it has been concluded that the thickness of EPS should be kept greater than 45 mm in order to prevent condensation both in summer and winter. This study has provided a substantial guidance for preventing condensation in the enclosure of capillary radiant ceiling in summer and winter seasons.

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