Numerical Simulation of radon migration influenced by heat-moisture coupled transfer in aerated concrete wall under different outdoor temperature and humidity conditions

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Abstract. It is of great significance for indoor radon radiation protection to study the mechanism of radon migration systematically caused by heat-moisture coupled transfer in building walls. The radon migration model of porous building walls under the influence of the heat-moisture coupled model is built. On the base of it, four types of different temperature and humidity conditions, including high temperature and high humidity, high temperature and low humidity, low temperature and high humidity, and low temperature and low humidity, and the real ambient temperature, relative humidity conditions in a southern city of China in July, are set for the numerical simulation. The migration mechanism of the radon through the wall influenced by outdoor temperature and humidity conditions, including its emanation, diffusion and condensation, is studied by numerical simulation, and the main factors leading the results are analyzed, which provides some reference for indoor radon radiation protection.

Keywords: heat-moisture coupled transfer, radon, wall

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1. Introduction

Radon can easily accumulate in indoor environments where most people spend the majority of their time, therefore the harm to human health from the indoor radon cannot be ignored. The indoor radon comes principally from 4 sources: soil, underground water, building materials and outdoor air, while the building walls are one of the major way for radon to the indoor space. Therefore it is of great significance for indoor radon radiation protection to study the mechanism of radon migration in building walls systematically.

Much research has been done on radon exhalation, radon migration and indoor radon concentration distribution. Ref. [1] has carried out a comprehensive investigation and related simulation study on indoor radon in ten cities in China. The main sources of indoor radon, the current indoor radon concentration level in China, and the corresponding control measures have been generally summarized. Ref. [2] measured the radon emission concentration of several common building materials with a radon detector, and calculated the contribution ratio of each building material to indoor radon. Ref. [3] used a radon detector to measure the radon exhalation rate of several building materials, and carried out numerical simulation on the distribution of radon concentration in double-layer porous air emitting medium and indoor. Ref. [4] conducted numerical simulation research on radon migration in adits under different indoor and outdoor pressure differences. Internationally, some scholars have also measured indoor radon concentration in various buildings [5-8].

The coupled heat and humidity transfer is an important research topic in the research field of building walls, and the migration rule of radon in building walls is also closely related to the coupled heat and humidity transfer rule, but this correlation is rarely considered in existing studies [9].

Therefore, this article regards a kind of aerated concrete wall as the research object, four different outdoor climate conditions including low temperature and low humidity, high temperature and low humidity, low temperature and high humidity, high temperature and high humidity, and the real ambient temperature, relative humidity and indoor radon condensation conditions in a southern city of China in July, are set for the numerical simulations of the radon diffusion coefficient, source term and activity concentration distributions in the wall, and the migration mechanism of radon under the influence of heat-moisture coupled model through the wall in different outdoor climate conditions is analyzed.

2. Mathematical Model

2.1 Heat and humidity transfer model

According to the Ref. [10], basing on the Fick's Law, Darcy's Law, Kelvin relation and Fourier's law, the wall heat and moisture transfer model is established:

\[
\frac{\partial T}{\partial t} = \nabla \cdot \left( \lambda \nabla T + h_c \nabla \phi \right) + q + \frac{\partial \varphi}{\partial t}
\]

Eq. (1) is the heat transfer equation, where, \( \rho_m \) refers to the wall material density, kg/m\(^3\), \( c_{pm} \) refers to the constant pressure heat capacity of wall material, m\(^2\)/(s\(^2\)-K), \( \omega \) refers to the volume moisture content of wall material, kg/m\(^3\), described by the isothermal hygroscopic curve function, \( c_{pl} \) refers to the specific heat of liquid water at constant pressure, m\(^2\)/(s\(^2\)-K), \( \lambda \) refers to the effective thermal conductivity of wall material, m\(^2\)/(s\(^-\)-K), \( h_v \) refers to latent heat of vaporization of water, m\(^2\)/(kg·s\(^-\)-K), \( \delta_l \) refers to the water vapor permeability of wall material, s, \( P_e \) refers to the partial pressure of saturated water vapor, Pa. Eq. (2) is the wet transfer equation, where, \( \zeta \) refers to the slope of isothermal hygroscopic equilibrium curve of wall material, namely, partial derivative of isothermal hygroscopic equilibrium curve function with respect to relative humidity, \( D_0 \) refers to the wet diffusivity of wall material, m\(^2\)/s.

The inner boundary conditions are described by Eq. (3) and (4):

\[
g_{ss} = h_v (T_i - T_s) + h_c g_{si} \quad (3)
\]

\[
g_{es} = h_m (P_{sl} \varphi_i - P_{el} \varphi_2) \quad (4)
\]

Eq. (3) is the heat exchange equation between the wall inner surface and the indoor environment, where, \( q_{e,c} \) refers to heat flow, kg/s\(^3\), \( h_i \) refers to the internal heat
transfer coefficient, kg/(s³·K), $T_i$ refers to the indoor temperature, $T_{in}$ refers to the inner surface temperature of the wall. Eq. (4) is the moisture exchange equation between the inner surface of the wall and the indoor environment, where, $g_{n,i}$ refers to moisture flow, kg/(m²·s), $h_{m,i}$ refers to internal moisture transfer coefficient, s /m, $P_{n,i}$ refers to the saturated vapor pressure of indoor water vapor, $\varphi_i$ refers to indoor relative humidity, $P_{s,i}$ refers to the saturated vapor pressure of the inner surface of the wall, $\varphi_{n,i}$ refers to the relative humidity of the inner surface of the wall.

The outer boundary conditions are described by Eq. (5) and (6):

$$q_{n,e} = h_i(T_r - T_{r,e}) + h_m g_{n,e} + a I$$

(5)

$$g_{n,e} = h_m (P_s \varphi_r - P_{s,e} \varphi_{r,e})$$

(6)

Eq. (5) is the heat exchange equation of wall surface and outdoor environment, where, $q_{n,e}$ refers to heat flow, kg/s², $h_m$ refers to external heat transfer coefficient, kg/(s·K), $T_r$ refers to the outdoor temperature, $T_{r,e}$ refers to the outer surface temperature of the wall, $a I$ refers to the product of solar radiation absorption rate and solar radiation intensity on the outer surface of the wall, kg/s². Eq. (6) refers to the moisture exchange equation of the outer surface of the wall and the outdoor environment. $g_{n,e}$ refers to moisture flow, kg/(m²·s), $h_m$ refers to the external moisture transfer coefficient, s/m, $P_{s,e}$ refers to outdoor vapor saturation vapor pressure, $\varphi_{r,e}$ refers to outdoor relative humidity, $P_{s,e}$ refers to the saturated vapor pressure of the outer surface of the wall, $\varphi_{r,e}$ refers to the relative humidity of the outer surface of the wall.

2.2 Radon migration model

According to Ref. [11], radon migration in uniform porous media is described by Eq. (7):

$$\frac{\partial C}{\partial t} + \nabla \cdot (CU) + \lambda C = \nabla \cdot (D_{n,e} \nabla C) + \alpha$$

(7)

In the Eq. (7), $C$ refers to the activity concentration of radon (hereinafter referred to as radon concentration), Bq/m³, $U$ refers to convective velocity, m/s, $\lambda$ refers to the decay coefficient of radon, whose value is approximately $2.1\times10^{-6}$s⁻¹. $D_{n,e}$ refers to the diffusion coefficient of radon, m²/s, $\alpha$ is the radon source term, Bq/(m³·s). Ref. [11] describes the relationship between radon diffusion coefficient $D_{n,e}$ and temperature field and humidity field in porous media, as shown in Eq. (8):

$$D_{n,e} = D_o \alpha^{4.68 \cdot e^{-6.9 \cdot 10^6}} \left(\frac{T}{273}\right)^{0.75}$$

(8)

In the Eq. (8), $D_o$ refers to the diffusion coefficient of radon in the air, and its value is approximately $1.05\times10^{-5}$m²/s. $e$ refers to the porosity of wall material, $S_e$ refers to water saturation. It can be seen that radon diffusion coefficient is positively correlated with temperature and negatively correlated with water saturation.

The radon source term is described by Formula (9):

$$\alpha = 2.562\times10^7 \rho \uk e$$

(9)

In the Eq. (9), $\rho$ refers to the density of radon emitting gas medium, kg/m³, $U$ refers to the uranium grade, $\uk$ refers to the uranium-radium equilibrium coefficient, $E$ refers to the emission coefficient of radon emission media. Ref. [12] describes the relationship between the emission coefficient of water-bearing radon gas media and water saturation, as shown in Eq. (10):

$$E = E_0 \left(1 + 1.85 \left(1 - e^{-1.885\cdot w}\right)\right)$$

(10)

Where, $E_0$ refers to the radon emission coefficient of radon emission media in a completely dry state. From the concept of water saturation, $S_e$ can be described as:

$$S_e = \frac{V_w}{V_e}$$

(11)

Where $V_w$ refers to the volume of water in porous media, m³, $V_e$ refers to the volume of pores in porous media, m³. According to the relationship between mass, density and volume, as well as the relationship between porosity and volume, Eq. (11) can be transformed into Eq. (12):

$$S_e = \frac{m_w}{\varepsilon V_m \rho_w}$$

(12)

Where, $m_w$ refers to the mass of water in porous media, m³, $V_m$ refers to the volume of porous media, m³, $\rho_w$ refers to the density of water, and its value is 1000kg/m³. According to the relationship between material volume moisture content and volume, Eq. (12) can be transformed into Eq. (13):
\[ S_e = \frac{\omega}{1000 \varepsilon} \]  

Assuming that the ambient radon concentration in contact with the wall surface is \( C_0 \), and the porosity of the wall material is \( \varepsilon \), the radon concentration at the wall surface \( C_0 \) can be described by Formula (14):

\[ C_0 = \varepsilon C_{air} \]  

By solving the coupled heat and humidity transfer model, the temperature field and relative humidity field inside the building wall can be obtained. Volumetric moisture content \( \omega \) is a function of relative humidity \( \varphi \), by substituting the value of relative humidity field into Eq. (13), water saturation field can be obtained. Finally, by substituting the values of temperature field and water saturation field into Eq. (7), Eq. (8), Eq. (9), Eq. (10), the radon migration model of porous media wall under the influence of heat-moisture coupling can be obtained.

3 Numerical simulation

3.1 Heat and moisture parameters and boundary conditions

Aerated concrete wall parameters in Ref. [12] are used for numerical simulation of radon migration under the influence of heat-moisture coupling, as shown in Table 1:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity ( \lambda ) (m(^2)/(s(^3)·K))</td>
<td>0.177+0.00098 ( \omega )</td>
</tr>
<tr>
<td>Constant pressure heat capacity ( c_{pm} ) (m(^2)/(s(^3)·K))</td>
<td>950</td>
</tr>
<tr>
<td>Density ( \rho ) (kg/m(^3))</td>
<td>615</td>
</tr>
<tr>
<td>Water vapor permeability coefficient ( \delta ) (s)</td>
<td>3.47 × 10(^{-11})</td>
</tr>
<tr>
<td>Isothermal moisture absorption equilibrium curve ( \omega_0 ) (kg/m(^3))</td>
<td>( \omega = \varphi/(A\varphi^3+B\varphi+C) )</td>
</tr>
<tr>
<td>Moisture diffusion coefficient ( D_m ) (m(^2)/s)</td>
<td>( D_m = d \cdot \exp(e \cdot \omega) )</td>
</tr>
</tbody>
</table>

In the table, \( A = -0.1196 \), \( B = 0.1226 \), \( C = 0.0011 \), \( d \) is 9.2 × 10\(^{-11}\), \( e \) is 0.0215. The porosity of the wall material is 0.7, the heat transfer coefficient and mass transfer coefficient of the inner and outer surfaces are set according to Ref. [13]. The heat transfer coefficient of the inner surface is 8.72 kg/(s\(^3\)·K), and the mass transfer coefficient is 18.5 × 10\(^{-9}\) s/m. The heat transfer coefficient of the outer surface is 23.26 kg/(s\(^3\)·K), and the mass transfer coefficient is 1.4 × 10\(^{-7}\) s/m. The uranium grade \( U \) is set as 7 × 10\(^{-5}\). The uranium-radium equilibrium coefficient \( K_p \) is set as 1, The radon emission coefficient of radon emission media in a completely dry state \( E_0 \) is set as 30%. The wall thickness is set as 200mm.

Indoor temperature \( T_i \) is 298.15K, relative humidity \( \varphi_i \) is 0.5. Four kinds of outdoor climates are set as outdoor temperature and relative humidity conditions: Low temperature and low humidity climate, \( T_e \) is 278.15 K, \( \varphi_e \) is 0.2, High temperature and low humidity climate, \( T_e \) is 308.15 K, \( \varphi_e \) is 0.2, Low temperature and high humidity climate, \( T_e \) is 278.15 K, \( \varphi_e \) is 0.8, High temperature and high humidity climate, \( T_e \) is 308.15 K, \( \varphi_e \) is 0.2.

In order to simplify calculation and facilitate analysis, heat, moisture and radon transfer are assumed to be one-dimensional transfer along the wall thickness, only the type of air flow caused by temperature difference in the wall is considered. Air density is 352.716/T kg/m\(^3\), and gravity acceleration \( g \) is 9.8067 m/s\(^2\). Condensation, icing and solar radiation are ignored in the cases. The physical model used for simulation is illustrated in Fig. 1.

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The boundary conditions for radon transfer of the numerical simulations are shown in Table 2.

<table>
<thead>
<tr>
<th>Boundaries</th>
<th>Boundary conditions</th>
</tr>
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</table>

Table 2 Boundary conditions for radon transfer
3.2 Simulation results and analysis

In the first case, the numerical simulation results of heat-moisture-radon transfer of wall in four climates are shown in Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9, which correspond to temperature distribution, water saturation distribution, source term of radon, radon diffusion coefficient distribution and radon concentration distribution of the four outdoor temperature and humidity conditions respectively.

- **Left boundary**
  \[
  \frac{\partial C_{Ra}}{\partial x} \bigg|_{x=0} = 0
  \]

- **Right boundary**
  \[
  \frac{\partial C_{Ra}}{\partial x} \bigg|_{x=0.2} = 0
  \]

- **Upper boundary**
  \[
  - \frac{\partial C_{Ra}}{\partial y} \bigg|_{y=0.6} + u C_{Ra} = 0
  \]

- **Lower boundary**
  \[
  - \frac{\partial C_{Ra}}{\partial y} \bigg|_{y=0} + u C_{Ra} = 0
  \]
The overall level and variation trend of radon source term and water saturation of the four climates are similar, which means that the distribution of water saturation can reflect the distribution of radon source in wall well.

The distribution of radon diffusion coefficient on the wall is shown in Fig. 5. From the perspective overall level, the value of the high temperature and low humidity climate is always highest, because it has always the highest temperature and the lowest water saturation. The value of low temperature and high humidity climate is always the lowest. From around 75mm to 200mm away to the outer surface, since it has always the lowest temperature and the highest water saturation, From 0mm to 75mm to the outer surface, it has low water saturation, but its temperature is much lower than that of the high temperature and high humidity condition. At this period, temperature plays a leading role in radon diffusion coefficient, resulting in the low diffusion coefficient. In most areas of the wall, i.e. 0mm to 120mm from the outer surface, the distribution of radon diffusion coefficient in low temperature and low humidity climate is higher than that in high humidity climate. It can be seen that humidity has a more significant effect on radon diffusion coefficient than temperature.

The concentration distribution of radon on the wall of the four different outdoor temperature and humidity conditions is shown in Figure 6, Figure 7, Figure 8 and Figure 9. From the perspective of the overall level, the concentration distributions of the 4 Figures ranks from high to low as follow: low temperature and high humidity, high temperature and high humidity, low temperature and low humidity, and high temperature and low humidity, which is mainly determined by the distributions of radon sources as shown in Figure 4. It can be seen that when the outdoor humidity is high, the radon concentration in the wall is always at a high level, which has slight relation with the temperature. When the outdoor humidity is low, the radon concentration is low in high outdoor temperature condition, while the radon concentration is high in low outdoor temperature condition.

In the second case, the climatic conditions of a southern city in China in July are used as the outdoor temperature and relative humidity boundary condition, the data is from the ASHRA (American Society of...
Heating, Refrigerating and Air-Conditioning Engineers).

The numerical simulation results are shown in Fig. 10, Fig. 11, Fig. 12, Fig. 13, Fig. 14 and Fig. 15.

Fig. 10 Distributions of temperature $T$(K) in wall (In July)

Fig. 11 Distributions of relative humidity in wall (In July)

Fig. 12 Distributions of water saturation $S_e$ in wall (In July)

Fig. 13 Distributions of radon source $\alpha$ (Bq/(m$^3$·s)) in wall (In July)

Fig. 14 Distributions of radon diffusion coefficient $D_{Rn}$(m$^2$/s) in wall (In July)

Fig. 15 Distributions of Radon concentration $C_{Rn}$(Bq/m$^3$) in wall (In July)

The transient distribution of temperature and relative humidity from the outer surface to the inner surface in wall is shown in Fig. 10 and Fig. 11. As the city is located in southern China in summer, the outdoor temperature and relative humidity are always at a high level.

The water saturation of the wall material depends largely on its hygroscopic capacity. The isothermal hygroscopic curve $\omega$ in Table 1 shows that the hygroscopic capacity of the material is weak, therefore, the water saturation in wall is always at a low level (less than 10%) as shown in Fig. 12.

According to Eq.(9) and Eq.(10), radon source is positively correlated with water saturation, therefore Fig. 12 and 13 are similar. The outdoor relative humidity is high at night and low in the daytime, and the radon source in the wall is also higher at night than in the daytime. Indoor relative humidity is always lower than outdoor relative humidity, so the radon source of wall gradually decreases from outdoor side to indoor side.

The water saturation distribution in wall shown in Fig. 12 and the radon diffusion coefficient distribution in wall shown in Fig. 14 were compared, showing a significant negative correlation. Where water saturation is high, the radon diffusion coefficient is low. It can be seen that water saturation of
materials plays a crucial role in radon diffusion coefficient.

The radon concentration distribution of radon is shown in Figure 15. Wall is a continuous source of radon, so the radon concentration in wall keeps rising. When it reaches nearly 360h, radon concentration tends to be stable, and its value is about 33Bq/m³.

4 Conclusion

Combined with the wall heat and humidity coupled transfer model and radon transfer model, the following four different outdoor climate conditions, including low temperature and low humidity, high temperature and low humidity, low temperature and high humidity, high temperature and high humidity, and the real ambient temperature, relative humidity and indoor radon condensation conditions in a southern city of China in July are set, on this basis, the numerical simulation of radon migration in one kind of aerated concrete wall is conducted. The main conclusions are as follows:

1. The main factor affecting the migration of radon on the wall is the transfer of water, which can effectively inhibit the diffusion of radon; Heat transfer promotes radon diffusion to a certain extent. Temperature plays a leading role in radon diffusion under similar humidity.

2. For the wall containing radon emanation media, the radon concentration in the wall mainly depends on the radon source term, which is positively correlated with the relative humidity in the wall and the hygroscopic capacity of the wall material. Under different outdoor temperature and humidity conditions, the general distribution of radon concentration in the wall from high to low is: low temperature and high humidity, high temperature and high humidity, low temperature and low humidity, high temperature and low humidity.

Reference

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