Heat and humidity performance of EPS and Rock wool board external thermal insulation system

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Heat and humidity performance of EPS and Rock wool board external thermal insulation system

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Abstract. A coupled heat and humidity transfer model of external thermal insulation wall is established, and the accuracy of the model is verified by the field test data. Taking Shanghai, a typical hot summer and cold winter area, as an example, this paper simulated and analysed the effects of different climatic conditions (winter and summer) and types of insulation board (rock wool and EPS) on the thermal and humidity properties of concrete-mortar-insulation-mortar external insulation wall. The results show that the temperature variation of the bonding mortar on the inside of the insulation board is much smaller than that on the outside of the insulation board due to the thermal insulation effect; the relative humidity of the bonding mortar layer in the external insulation system of rock wool can reach more than 80% within 7 days in summer, which has a high risk of falling off; and the relative humidity of the coating mortar layer can reach about 73% within 7 days in winter, which is likely to become mildewed; The resistance to moisture migration of rock wool is weaker than that of EPS.

1. Introduction

With the increasing consumption of building energy in China, the improvement of building energy-saving technology has been increasingly valued worldwide. Improving the thermal performance of building envelopes is an effective way to reduce building energy consumption and achieve building energy efficiency. External wall insulation technology has been widely promoted and applied [1]. Due to design and construction reasons, there will be a certain amount of moisture in external insulation system. In the building thermal engineering and energy-saving design, the heat and moisture transfer in the external thermal insulation system is typical coupled heat and humidity transfer [2]. In reality, if designer ignores the control of coupled heat and moisture transfer and moisture content in the external thermal insulation system, the moisture will accumulate. High moisture content will reduce the strength of the bonding parts. System may crack or even fall off, which poses a serious threat to the user's property and life safety. Therefore, studying the coupled heat and moisture transfer process of the external thermal insulation system is of great significance for improving the thermal performance and durability of the building envelopes.

The heat and moisture transfer process inside the building envelopes is very complicated. Usually, establishing mathematical model and numerical simulation analysis by computer are the main means to study the heat and moisture transfer problem of building materials. Many scholars have studied it with the help of mathematical model, and summarized the distribution law of temperature and humidity inside the wall. Tang [3] calculated the temperature and humidity of the internal node of centrifugal glass wool and polyurethane board internal insulation wall system by the analytical method under the steady state condition. They studied the temperature and water vapor pressure distribution curve of internal insulation wall model and analyzed the dew point occurred at the interface between the thermal insulation material and the concrete block. Yu [4] analysed the effects of initial temperature and humidity of the envelope structure and outdoor meteorological conditions on the temperature and humidity distribution and the variation law of internal relative humidity by CHAMPS-BES. Liu [5] developed a coupled heat, air and moisture transfer model on the basis of the Künzel model, choosing the temperature, relative humidity and air pressure as the driving potentials, to predict the temperature and humidity distribution inside the building wall. Guo [6] established a 1-D transient hygrothermal model. The model, based on Liu's, considering the influence of solar radiation, is solved by COMSOL Multiphysics. In addition, Clément established a 2-D transient hygrothermal model and analysed the effect of air permeability on heat and moisture transfer by COMSOL Multiphysics. This way is especially suitable for handling complex geometric models [7] [8].

However, in many cases, numerical analysis methods are difficult to obtain analytical solutions. Some assumptions are needed to simplify the model. It is difficult to ensure the rationality and accuracy of the model with too many assumptions. However, due to limited experimental methods, there are few experimental studies on coupled heat and moisture transfer. Liu [9] established a test bench for coupled heat and moisture transfer of single-layer concrete wall. It was found that moisture transfer rate inside the wall was much lower than that of heat, and the moisture content distribution inside the wall was always high in the middle and low on both sides.

At present, many scholars use numerical simulation method to predict the variation of heat and humidity in the envelope structure, but lack of experimental verification makes the model lacking of convincing. In this paper, the heat and humidity transfer process inside the concrete external insulation wall in the hot summer and cold winter area (Shanghai) is simulated by COMSOL Multiphysics and verified by field experiments. Further simulations show the influence of ambient temperature and relative humidity and the type of insulation materials (EPS, rock wool) on the internal temperature and relative humidity distribution and water storage of the insulation system, which provides a basis for structural design and selection of insulation materials in actual engineering.

2. Numerical Simulation

2.1. Control equations

The equation for the heat and moisture transfer model in COMSOL is based on the heat and humidity transfer calculation model proposed by Künzel in 1997. Künzel [10] believes that the diffusion of vapor in building materials is mainly transmitted in large pores, while the liquid water transfer mainly occurs in the pore surface, cracks and small pores. The two flow directions are opposite. Among them, the driving potential of vapor diffusion is partial pressure of water vapor, while the driving potential of liquid water transfer is capillary pressure, ignoring the interaction between the two flows and treating them as two independent processes.

In the model of this paper, both the transport of liquid moisture by capillary pressure and the transport of vapor by diffusion are computed, and the latent heat effect due to vapor diffusion is modeled. In addition, heat and moisture storage is considered, and moisture dependent thermal properties are used. The corresponding equations, defined in the BS EN 15026, are solved by default by the Moisture Transport in Building Materials and Heat Transfer in Building Materials interfaces. In order to simplify the calculation process, we don't consider the effect of air permeability and solar radiation on water transfer inside the wall. The coupled heat and moisture transfer process of the external thermal insulation wall is regarded as a one-dimensional transfer process along its thickness direction. To ensure the continuity of the moisture storage performance (hygroscopicity and dehumidification) at the interface of the material, we established the coupled equation of heat source and water vapor source by using continuous variable temperature and relative humidity as driving potentials:

$$Q=(\rho C_p)_{eff}\partial T/\partial t-\nabla\cdot[k_{eff}\nabla T+L_v\delta_p\nabla(\Phi p_{sat})] \qquad (1)$$

$$G=\xi\partial\Phi/\partial t-\nabla\cdot[\xi D_W\nabla\Phi+\delta_p\nabla(\Phi p_{sat})] \qquad (2)$$

Among them, $(\rho C_p)_{eff}=\rho_s C_{p,s}+wC_{p,w}$ is the effective volumetric heat capacity at constant pressure, $J/(m^3\cdot K)$; ρ_s is dry density, kg/m^3; $C_{p,s}$ is the specific heat capacity of dry material, J/(kg·K); $C_{p,w}$ is the specific heat capacity of liquid water, J/(kg·K); w is moisture content, kg/m^3; k_{eff} is the effective thermal conductivity, W/(m·K); L_V is the latent heat of evaporation, J/kg; δ_p is the vapor permeability, s; p_{sat} is the vapor saturation pressure, Pa; ξ is the moisture storage capacity, $\xi=dw/d\Phi$, kg/m^3; D_w is the moisture diffusivity, m^2/s, using to represent liquid water flux.

2.2. Boundary conditions

The heat flux $q_{0,i}$ passing through the inner surface of the wall includes convective heat transfer and latent heat of water vapor between the inner surface of the wall and the indoor air:

$$q_{0,i}=h_i(T_i-T_{surf,i})+L_V\beta_i(P_i-P_{surf,i}) \qquad (3)$$

Since the influence of solar radiation is not considered, the heat flux $q_{0,e}$ through the outer surface of the wall is similar to that of the inner:

$$q_{0,e}=h_e(T_e-T_{surf,e})+L_V\beta_e(P_e-P_{surf,e}) \qquad (4)$$

Moisture flow through the inner surface of the wall $g_{0,i}$:

$$g_{0,i}=\beta_i(P_i-P_{surf,i}) \qquad (5)$$

Moisture flow through the outer surface of the wall $g_{0,e}$:

$$g_{0,e}=\beta_e(P_e-P_{surf,e}) \qquad (6)$$

Among them, h_i, h_e are the convective heat transfer coefficients of inner and outer surface of the wall, respectively, $W/(m^2\cdot K)$; T_i, T_e are temperatures of indoor and outdoor, respectively, K; $T_{surf,I}$, $T_{surf,e}$ are the indoor and outdoor wall surface temperatures, respectively, K; β_i, β_e are the moisture transfer coefficients of inner and outer surface of the wall, respectively, $kg/(Pa\cdot m^2\cdot s)$; P_i, P_e are the partial water vapor pressures of indoor and outdoor, respectively, Pa; $P_{surf,I}$, $P_{surf,e}$ are the partial water vapor pressures of inner and outer surface of the wall, respectively, Pa.

3. Model verification

The control equations of the model in this paper include the heat transfer equation and the moisture transfer equation, which are solved by the partial differential equations in the form of coefficients in COMSOL software. Since the coupled heat and moisture transfer model of external thermal insulation wall simplifies and abstracts the actual physical process and ignores some realistic factors, it is necessary to verify the accuracy of this simplified model. In this paper, the accuracy of the model is verified by comparing the simulation results with the field test results.

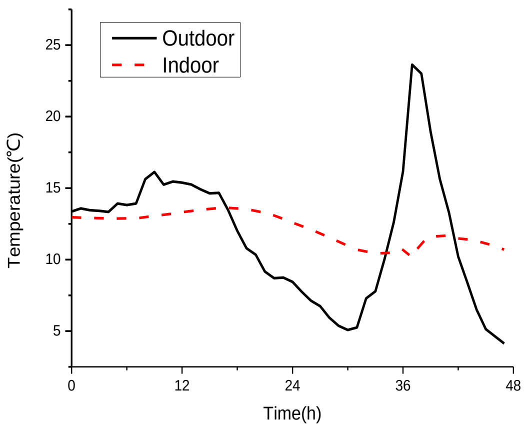
The test wall is an EPS external thermal insulation wall, which is cement concrete wall (240mm), bonding mortar (7mm), EPS insulation board (50mm) and coating mortar (3mm) from inside to outside. Temperature sensors and humidity sensors are embedded on the inner surface of the concrete, bonding mortar layer, insulation board and the outer surface of coating mortar to record the temperature and relative humidity. The test wall and sensors are shown in Figure 1.

Figure 1. Test wall and sensors.

The indoor and outdoor environmental conditions are input into the model as boundary conditions. The variation of temperature and humidity of the bonding mortar layer with time is simulated. Then the result is compared with the temperature and humidity data recorded by the bonding mortar layer sensors to analyse the accuracy of the model. In order to eliminate the influence of initial conditions on the prediction results of the model, we assume the initial temperature and relative humidity of all layers of materials in the wall to be the same. Initial values are determined by the test values of the bonding mortar layer before the beginning of the calculation time. Since the thermal and humidity parameters of the wall materials have not been systematically measured at present, the parameters used in this paper (some of the parameters are shown in Table 1) are taken from British standard EN 15026 and relevant literature [11]. The convective heat transfer coefficient and moisture transfer coefficient of the inner and outer surfaces of the wall are taken from BS EN 15026. The simulation time is 2 days and time step is 1 hour. The temperature and relative humidity data of indoor and outdoor are shown in Figure 2 and Figure 3.

Table 1. Part of thermal and humidity parameters of each layer.

Parameters	Concrete	Mortar	EPS
Dry density (kg/m^3)	2280	230	30
Heat capacity (J/(kg·K))	800	920	1200
Thermal conductivity (W/(m·K))	1.5+0.0158w	0.6+0.0024w	0.0364-0.003798exp (-0.1251w)



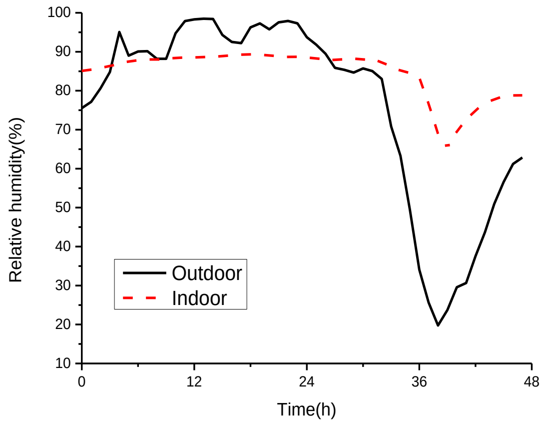


Figure 2. Temperature of indoor and outdoor. Figure 3. Relative humidity of indoor and outdoor.

As shown in Figure 4 and Figure 5, the simulation results of temperature and relative humidity at the bonding mortar are compared with the test results. Figure 4 compares the tested and simulated values of the temperature at the interface between bonding mortar and EPS insulation board. The simulation results and the test results show similar trends. The maximum deviation of the model prediction is 0.8°C, and the average deviation is 0.34°C. The results of numerical simulation may have some deviations, which are within acceptable range. The cause of the errors may be the deviation of the accuracy of numerical simulation. Figure 5 compares the test and simulated values of the relative humidity at the interface between bonding mortar and EPS insulation board. Since the humidity sensor is highly sensitive and easily damaged, it is greatly affected by the surrounding environmental conditions, so the test values of the relative humidity show a state of continuous fluctuation. The trend of the simulation results is similar to that of test values. The maximum deviation between them is 1.97%, and the average deviation is 1.43%. The main reason for the errors may be that there are some differences between the real thermal and moisture parameters of materials and that of the literature, and the individual differences cannot be excluded.

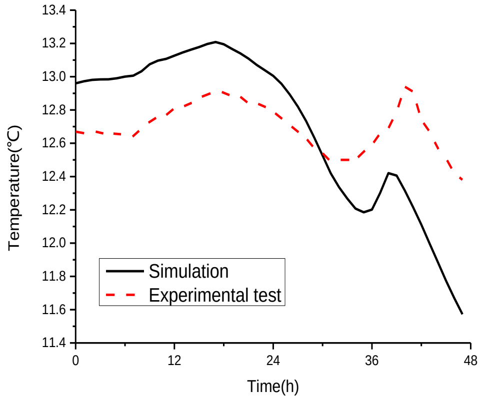


Figure 4. Temperature between bonding mortar and EPS insulation board.

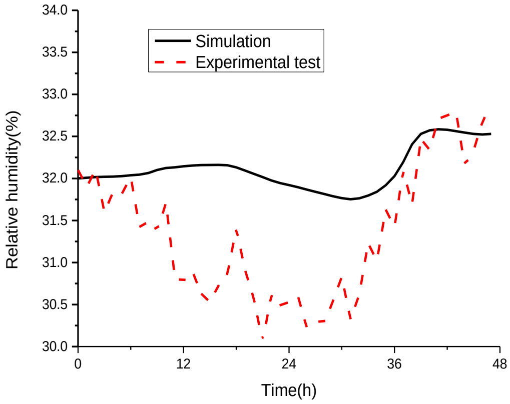


Figure 5. Relative humidity between bonding mortar and EPS insulation board.

In summary, based on the heat and moisture transfer model in COMSOL, the experimental values of thermal and moisture parameters of materials can be input, which can accurately predict the temperature and humidity changes and distribution inside the external thermal insulation wall. This method has been verified by the field tests and has certain guiding significance.

4. Simulation results

This paper takes Shanghai as an example to analyse the distribution of temperature and humidity and the change of water storage in the external thermal insulation system. The wall structure is the same as the test wall structure in Figure 1. The physical parameters of concrete layer and mortar layer are the same as those of Table 1. The parameters of insulation layer materials are taken from literature. Some parameters are shown in Table 2. The indoor temperature and relative humidity are taken as 20°C and 60%. The initial temperature and humidity of the wall is the same as the indoor temperature and humidity. The outdoor temperature and relative humidity are taken from the meteorological data of the coldest month (January) and the hottest month (July) in the Shanghai Hongqiao area meteorological database, as shown in Figure 6 and Figure 7. The heat transfer coefficients of the inner and outer surfaces of the wall are 8 W/(m^2·K) and 25 W/(m^2·K), respectively. The moisture transfer coefficients of the inner and outer surfaces of the wall are 5.8823×10^{-8} s/m and 1.8382×10^{-7} s/m, respectively. The total simulation time is 7 days and the time step is 1 hour. Considering that the initial value of outdoor temperature and humidity is quite different from that of the wall and indoor, in order to ensure the consistency of data and the authenticity of simulation, we discarded the sudden change of the temperature and humidity of each layer of material within one hour after the start of the simulation.

Table 2. Some parameters of insulation layer materials.

Materials	Density (kg/m^3)	Heat capacity (J/(kg·K))	Vapor permeability (kg/m·s·Pa)	Moisture diffusivity (m^2/s)	Thermal conductivity (W/(m·K))
EPS	30	1200	4.4×10^{-12}	4×10^{-6}	0.0342+3.61×10^{-4}T
Rock wool	152	604	6.7×10^{-11}	0	0.0362+4.09×10^{-4}T

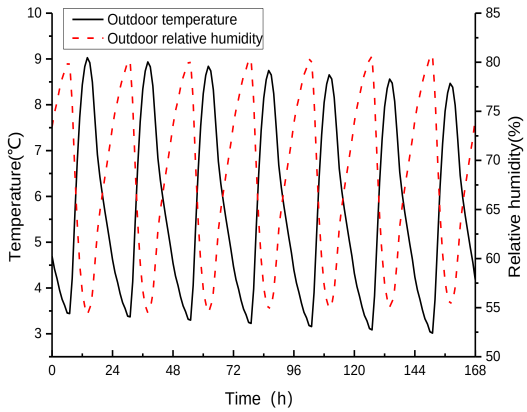


Figure 6. Temperature and Relative humidity in Hongqiao, Shanghai, January 1st-7th.

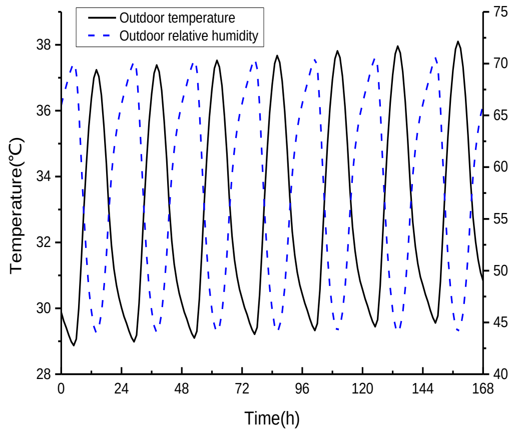


Figure 7. Temperature and Relative humidity in Hongqiao, Shanghai, July 1st-7th.

Figure 8 and Figure 9 show variation of temperature and relative humidity with time in different positions of EPS external insulation system from January 1st to 7th, respectively. As can be seen from Figure 8, the temperature of the EPS external insulation system decreased overall in January. By comparing the temperature changes at different locations, it is found that the temperature inside the insulation board is higher than that outside the insulation board, and the change range is significantly smaller than that outside the insulation board, because the insulation materials have lower thermal conductivity and higher thermal resistance than concrete and mortar. It can be seen from Figure 9 that with the increase of time, the relative humidity of the interior of the concrete is basically maintained at the initial value of 60%, and the relative humidity of the interface between the EPS thermal insulation board and the coating mortar fluctuates obviously, reaching a maximum of about 74%. Because the coating mortar is in contact with the external environment, and the migration of water vapor is faster due to the higher external humidity; but the relative humidity near the central position of concrete has little change because of the close accumulation of mortar blocks and aggregates and the lack of connected pores for water vapor migration. The relative humidity of bonding mortar gradually decreases within 7 days, which indicates that EPS external thermal insulation system has no risk of moisture falling off under this environment conditions.

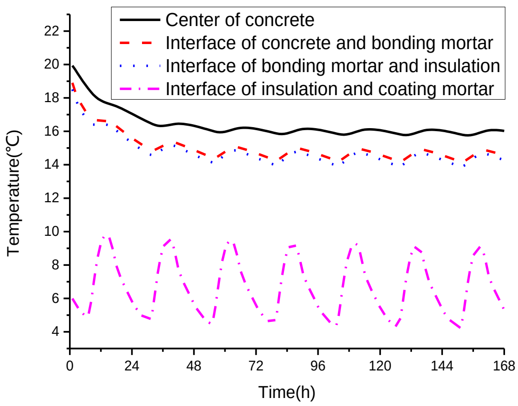


Figure 8. Temperature changes of EPS external insulation system from January 1st to 7th.

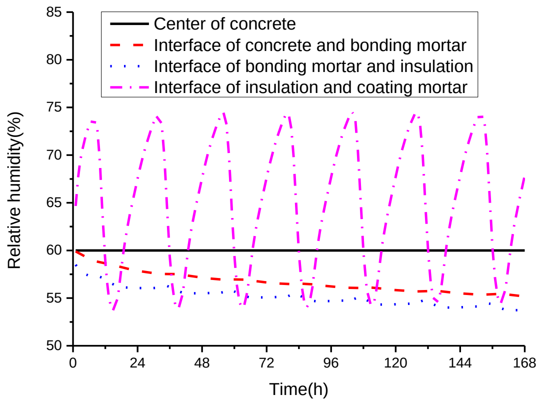


Figure 9. Relative humidity changes of EPS external insulation system from January 1st to 7th.

Figure 10 and Figure 11 show variation of temperature and relative humidity with time in different positions of rock wool external insulation system from January 1st to 7th, respectively. From the comparison of Figure 8 and Figure 10, it can be seen that the temperature variations of the two insulation systems are approximately the same. This is because the thermal conductivity of EPS and rock wool are both linear functions of temperature. The moisture absorption capacity and capillary water absorption capacity of the two materials are weak, so the influence of water on the thermal conductivity can be neglected. It can be found from Figure 11 that the relative humidity at the interface of the coating mortar and the rock wool board fluctuates and rises with the increase of time, reaching a maximum of 73%, with a higher risk of mildew.

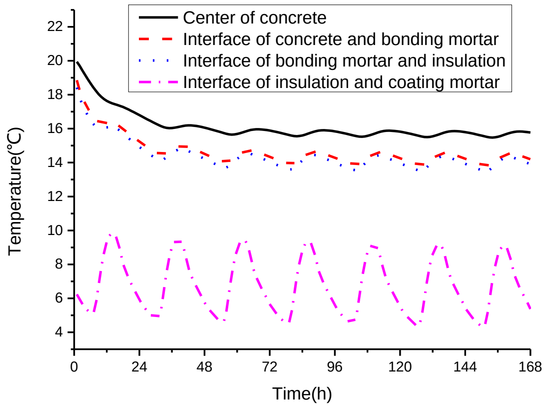


Figure 10. Temperature changes of rock wool external insulation system from January 1st to 7th.

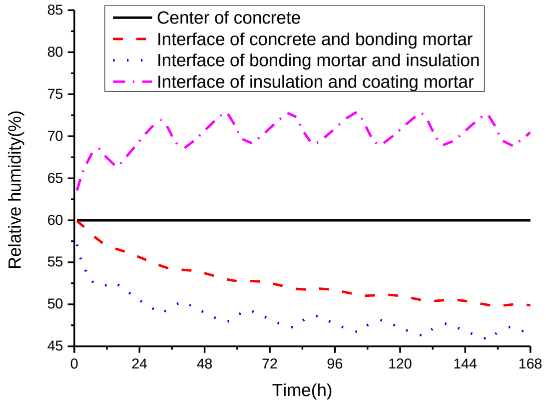


Figure 11. Relative humidity changes of rock wool external insulation system from January 1st to 7th.

Figure 12 and Figure 13 show variation of temperature and relative humidity with time in different positions of rock wool external insulation system from July 1st to 7th, respectively. Comparing Figure 10 and Figure 12, it can be seen that the temperature of the rock wool system in summer is higher than that in winter, and the temperature difference between inside and outside of the board is 5-10℃. From Figure 13, it can be seen that the relative humidity of bonding mortar of rock wool system increases in summer. After 7 days, the relative humidity at the interface of bonding mortar and rock wool board reaches 80%, which has a higher risk of moisture falling off. Comparing Figure 11 and Figure 13, it shows that the relative humidity of mortar inside and outside of rock wool board varies quite opposite in different seasons. Therefore, the influence of outdoor conditions must be taken into considered when discussing the mildew and falling off of external insulation system.

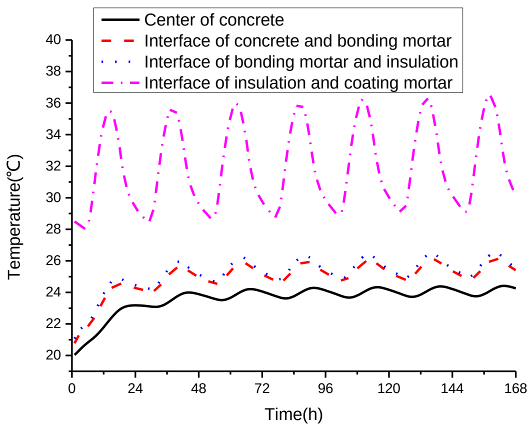


Figure 12. Temperature changes of rock wool external insulation system from July 1st to 7th.

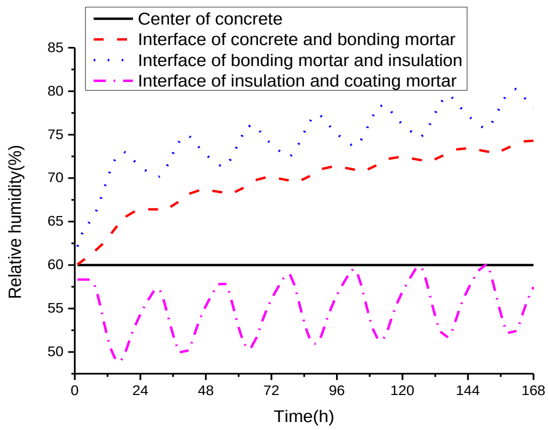


Figure 13. Relative humidity changes of rock wool external insulation system from July 1st to 7th.

Figure 14 compares the internal water storage distribution of the EPS on January 7th, the rock wool on January 7th and the rock wool on July 7th of the external thermal insulation system. It is worth mentioning that the internal water storage of the wall is related to the initial value of each layer of material. This paper only discusses the change of the water storage under the initial values set above. As can be seen from the figure, with the increase of indoor distance, the water storage of the rock wool system in July reached the highest of the three, which was 161.61 kg/m^3. In the interior of the thermal insulation board, the rock wool system showed a completely opposite trend in January and July. From outdoor to indoor, the water storage in January decreased slightly, and gradually increased in July. It is speculated that the rock wool is a kind of fiber material, and there are many open holes and connecting holes in the interior. Therefore, water is basically accumulated in the bonding mortar layer through migration, which makes the water storage at the interface of bonding mortar layer and rock wool insulation board relatively high; while in July, because of the high ambient temperature and the large moisture content of outdoor air, the speed of water vapor migration is fast. So the internal moisture of the rock wool will accumulate near the bonding mortar. In addition, although EPS has a certain liquid water migration ability, its internal pores are mostly closed pores, more than 90% of the closed void rate, which will hinder the migration process of external moisture to the inside. The internal water storage is nearly 0.

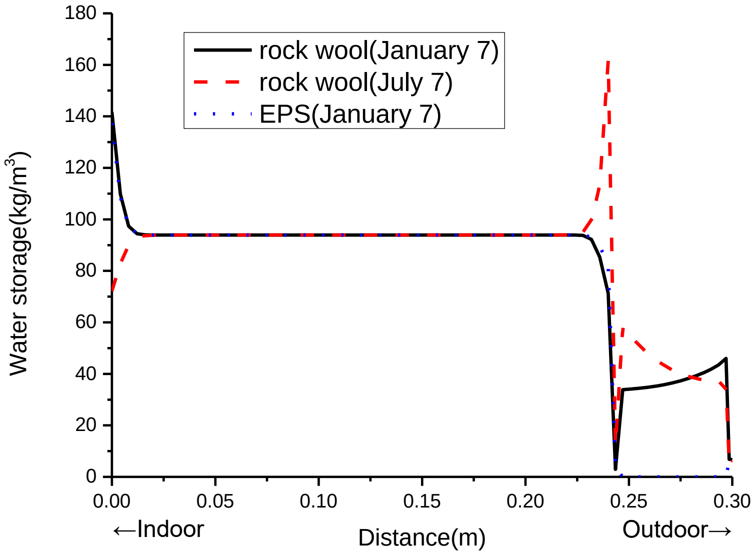


Figure 14. Water storage distribution of external thermal insulation system.

5. Conclusion

In this paper, the accuracy of the COMSOL coupled heat and humidity transfer model is verified by the field test data. Using Shanghai area as an example, this paper compared and analysed the thermal and moisture performance of EPS and rock wool thermal insulation systems under different climatic conditions. The results show that:

1) The model of EPS and rock wool thermal insulation systems established by COMSOL in this paper is verified to be feasible by field tests.

2) With changes in environmental conditions, the temperature variation of the bonding mortar on the inside of the thermal insulation board is much smaller than that of the coating mortar on the outside of thermal insulation board.

3) The change of internal relative humidity of rock wool external insulation system shows opposite trend in winter and summer, in which the relative humidity of bonding mortar layer can reach more than 80% within 7 days in summer, which has a high risk of falling off; the relative humidity of coating mortar layer can reach about 73% within 7 days in winter, which is likely to become mildewed.

4) Resistance to moisture migration of rock wool is weaker than that of EPS. Under the conditions of high temperature and humidity in July, the water storage capacity of bonding mortar can reach 161.61 kg/m^3 for 7 days.

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