The effect of rising damp on heat transfer performance and energy consumption of two kinds of Chinese blue-brick masonry walls

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Abstract. Rising damp is common in brick buildings due to groundwater and natural precipitation, which not only causes deterioration of the walls, but also significantly affects the heat transfer coefficient, thermal inertia, and building energy consumption. In order to clarify the effects of rising damp on the heat transfer through traditional Chinese brick solid wall and cavity walls, two types of wall of 1.2 m wide and 3 m high were built in the laboratory. The heat transfer performance under the influence of capillary rising was tested by Simple heating box – heat flow meter method. Based on the data obtained from the experiment, the Energyplus was used to simulate the energy consumption of a Chinese typical residential building influenced by rising damp. The results proposed 3.67 W/m²·K and 3.61 W/m²·K as the recommended heat transfer coefficient for the moisture affected parts in the experimental solid and cavity wall, and the rising capillary water increased the heat transfer coefficients by 74% and 84%, respectively. The heating and cooling load of the solid-wall building under the influence of capillary water increased by 18.5% and 29.6%, respectively, while of cavity-walls building increased by 6.5% and 11.8%.

1. Introduction
Building energy consumption accounts for 40% of global energy consumption, and this proportion is showing an increasing trend [1]. Masonry structures are widely used as building envelopes all over the world. Previous studies have shown that the porosity of bricks and mortars leads to large absorption of capillary water, especially when the wall foundation is exposed to high-humidity soil or runoff water [2–4]. In some church walls with marble veneer, the rising damp can even reach 5–6 meter [5–7]. At the same time, under the influence of moisture, the thermal conductivity will increase for many building materials, such as bricks, adobe, insulation materials, concrete, etc., leading to changes of envelope thermal performance [8–10]. For example, Bednarska et al. have proven that the increase of moisture content will increase the thermal conductivity of clay red brick materials by 125% [11]. The envelope performance directly affects the air-conditioning system load and total energy consumption.

In this research, the different heat transfer performance under dry and wet conditions was experimentally studied both in typical solid and cavity wall. Then, taking a traditional building as an example, we simulated the influence of the rising capillary water on heating and cooling loads.

2. Materials and methods:

2.1. The heat transfer experiment
Using the materials and masonry techniques of traditional Chinese architecture, a real-size cavity wall and a solid masonry wall with a width of 120 cm, a height of 300 cm and a thickness of 24 cm were constructed, which represent the main traditional residential buildings of brick houses in northern and southern China. The construction method is shown in Figure 1. The bottom of the wall is in a metal tank with a depth of 50 cm, which provides the source for capillary water. The material properties of the brick and mortar are shown in Table 1.

Since initially, we used a dynamic environmental chamber to heat the entire wall, the airflow was difficult to control, resulting in a large difference in temperature between the bottom and top of the wall. Therefore, the Simple heating box – heat flow meter method (SHB-HFM method) was used to test the thermal performance of the walls [12].

The layout of the heat transfer experiment devices is shown in Figures 2 and 3, three pairs of heat flow meters were installed on walls at the height of 70 cm (measurement point P1), 110 cm (P2) and 140 cm (P3). The heating box was used to provide the temperature difference. The equipment details are shown in Table 2. The measurement method of the moisture content was declared in our former research [13].

### Table 1. The material properties of brick and mortar. [13]

|                        | Brick | Brick avg. | Mortar | Mortar avg. |
|------------------------|-------|------------|--------|-------------|
| Bulk density, \( \rho \), kg/m³ | 1780-1850 | 1810 | 1580-1620 | 1600 |
| Porosity, \( \varepsilon \), % | 29.3-31.5 | 30.2 | 34.8-35.3 | 35.1 |
| Water absorption coefficient, \( A \), kg/(m²·s⁰.⁵) | 0.204-0.225 | 0.216 | 0.291-0.338 | 0.306 |
| Critical pore size, \( D_c \), nm | 1500-1900 | 1750 | 800-1000 | 920 |
| Sorptivity coefficient, \( S \), cm/h⁰.⁵ | 1.15-1.37 | 1.25 | 2.72-3.15 | 2.97 |
| Capillary saturation, \( w_{cap} \), m³/m³ | 0.227-0.261 | 0.241 | 0.285-0.330 | 0.295 |

### Table 2. Result of the heat transfer experiment.

| Object                | Brand | Model | Unit | Precision | Resolution |
|-----------------------|-------|-------|------|-----------|------------|
| Air Temperature       | T&D   | RTR-53A | ºC     | ±0.3ºC    | 0.1ºC      |
| Air Relative Humidity | T&D   | RTR-53A | % RH  | ±5%       | 0.1%       |
| Moisture Content      | TESTO | Testo616 | % wt  | ±2%       | 0.1%       |
| Surface Temperature   | Captec | HS-30 | ºC   | ±0.3ºC    | 0.1ºC      |
| Heat Flow Meter       | Captec | HS-30 | W/m² | ±3%        | 2.5μV/(W/m²) |

**Figure 1.** Masonry methods and detail size of two walls
(left: solid wall, right: cavity wall).
The heat transfer resistance $R_{\text{wall}}$ of each measurement position can be obtained by equations (1), and the total heat transfer coefficient $U_{\text{total}}$ include surface resistance of heat transfer can be obtained by equations (2). The effective thermal conductivity of the wall is calculated by equation (3).

\[
R_{\text{wall}} = \frac{T_{\text{in}} - T_{\text{out}}}{q_{\text{avg}}} \quad (1)
\]

\[
U_{\text{total}} = \frac{1}{R_{\text{in}} + R_{\text{wall}} + R_{\text{out}}} \quad (2)
\]

\[
\lambda_{\text{eff}} = \frac{d}{R_{\text{wall}}} \quad (3)
\]

Where, $q_{\text{avg}}$ is the average value of $q_{\text{in}}$ and $q_{\text{out}}$, in here, $q_{\text{in}}$ and $q_{\text{out}}$ are the sensible surface heat flux density of the inner and outer sides, respectively [W/m$^2$], $q_{\text{avg}}$ of was taken as the equivalent heat flow in order to decrease the error caused by heat transfer loss [14]; $T_{\text{in}}$ and $T_{\text{out}}$ were the surface temperature of the inner and outer sides of the test points, [°C]; $R_{\text{in}}$ and $R_{\text{out}}$ are surface resistance of heat convection, [m$^2$·K/W], which are 0.11 m$^2$·K/W and 0.04 m$^2$·K/W; $\lambda_{\text{eff}}$ is the effective thermal conductivity of the wall, [W/m·K], and $d$ is the thickness of the wall, [m].

In order to compare the impact of the high-humidity on the heat transfer, this experiment first tested the heat transfer performance in the dry state when the measured moisture content of the two walls was around 0.5%. The test was conducted for 7 days, and the average value of the stable data in last 48 hours were used for the calculation. Then, the water height level in tanks was kept at 40cm, and the capillary rose freely. After the water rising experiment, the capillary water reached at around 1.8 m height, which exceeds the upper part of the heating box. Then, the heat transfer performance in the wet state was tested for 4 days to avoid the over-dried situation in two walls, and the average data of the last 24 hours were used to evaluate the thermal performance of the walls.

2.2. The heating/cooling load simulation

Based on the heat transfer data obtained from the heat transfer experiment, this section used EnergyPlus simulation, taking the Zhu’s ancient house built one hundred years ago as a case building, to analyse the impact of capillary water on its cooling and heating load and annual energy consumption. The case model is shown in Figure 4. Through one-year on-site monitoring, it was found that the wetting front in the wall located around height of 1.2 meter for a long time, and the water content of the capillary water is about 8%-14%. Then, the wall in the model was divided into two parts. The dark grey part at the bottom represented the capillary water affected area, and the light grey part at the upper part represented the dry area.

In the Energyplus simulation, the thermal conductivity of the two kinds of walls were set according to the results of the thermal experiment, the thermal conductivity of the middle point was selected to evaluate the thermal performance of the walls. Because, in central part of the heating box, the heat transfer is more close to the one-dimension heat transfer[12]. The weather data of Nanjing city is
supposed as the environment conditions, the ideal air conditioner will turn on heating when the temperature was lower than 18°C, and will turn on cooling when the temperature was higher than 26°C. The air-conditioning system works all day at weekends and only works from 6 pm to 8 am on weekdays.

Figure 4. Building thermal model of Zhu’s ancient house

3. Result

3.1. The results of heat transfer experiment

The heat transfer experiment data of test points P1, P2 and P3 at different stages on the solid wall and the cavity wall is shown in Table 3.

Table 3. Result of the heat transfer experiment.

| Item          | Unit | Solid Wall | Cavity Wall |
|---------------|------|------------|-------------|
|               |      | P1         | P2          | P3          | P1         | P2          | P3          |
| Water content | wt%  | 0.50%      | 0.50%       | 0.50%       | 0.50%      | 0.50%       | 0.50%       |
| T_in          | °C   | 24.730     | 25.552      | 25.285      | 25.147     | 24.665      | 23.663      |
| T_out         | °C   | 13.678     | 14.703      | 13.732      | 11.898     | 12.905      | 12.266      |
| q_avg         | W/m² | 36.632     | 32.208      | 25.203      | 43.769     | 36.741      | 33.856      |
| R_wall        | m²·K/W | 0.302     | 0.337       | 0.458       | 0.303      | 0.320       | 0.337       |
| λ_eff         | W/m·K | 0.795     | 0.713       | 0.524       | 0.793      | 0.750       | 0.713       |
| U_total       | W/m²·K | 2.214   | 2.054       | 1.644       | 2.209      | 2.127       | 2.055       |
| Average U_total | W/m²·K | 1.970 | 2.130       |             |            |             |             |

In dry condition, the effective thermal conductivity, $\lambda_{\text{eff}}$, is 0.524-0.795 W/m·K, which is close to values in other research [15–17]. The average $U_{\text{total}}$ obtained from dry state is 1.970 W/m²·K for solid wall and 2.130 W/m²·K for cavity wall, respectively. The effective thermal conductivity, $\lambda_{\text{eff}}$, obtained from wet state is 1.146-2.720 W/m·K, and the average $U_{\text{total}}$ for solid wall and cavity wall is 3.671 W/m²·K and 3.611 W/m²·K, respectively. The $U_{\text{total}}$ of the two walls in the wet state are much larger than that in the dry state, and The $U_{\text{total}}$ of the two walls shows more significant difference in the dry state than that in the wet state.
3.2. The results of heating/cooling load simulation

Figures 5 and 6 show the monthly simulated load in solid and cavity wall building. In simulation Group dry, the thermal conductivity of the solid wall and cavity wall was set as 0.713 W/m·K and 0.750 W/m·K. In Group wet, the thermal conductivity of the 1.2-m wet area was set as 1.848 W/m·K and 2.280 W/m·K in two typical walls, respectively. In general, the lower temperature in winter and the higher temperature in summer, the larger heating or cooling load of the air conditioning system. It is also clear from the graph that the higher the monthly heating or cooling load, the greater the difference between the values for Group dry and Group wet.

![Figure 5. Monthly air conditioning load of the solid wall building.](image)

![Figure 6. Monthly air conditioning load of the cavity wall building.](image)

Figure 7 shows a simulation of the heating and cooling loads considering only the heat transfer from the building envelope and the ground. Rising capillary water has a large impact on both heating and cooling loads. In solid masonry walls the heating load increased by 18.5%, the cooling load by 29.6% and the total by 20.2% under the influence of capillary water. In the cavity wall, the heating load increases by 6.5%, the cooling load by 11.8% and the total by 7.3%. It should be noted that the cooling and heating loads in the result come from the heat transfer through the walls, roof and floor, and the simulation do not include the sensible and latent heat loads from air convection, appliances, people etc.

![Figure 7. Annual heating and cooling load of the solid-wall and cavity-wall buildings.](image)

![Figure 8. Design heating and cooling load of the solid-wall and cavity-wall buildings.](image)

Another parameter to be considered is the peak load, which represents the amount of energy that the air conditioning system needs to provide in the most extreme case. As shown in Figure 8, the cooling demand of the building is significantly lower than the heating demand. The results obtained for Group wet more accurately simulate the maximum hourly average load throughout the year than models that do not take into account the effect of capillary water. The design heating power rises by 23.6% to 7773
W and the cooling power rises by 6.8% to 4447 W for solid masonry walls, and by 8.5% to 6902 W and 3.3% to 4316 W for cavity walls.

4. Discussion

4.1. Effect of different masonry types on heat transfer in the dry state

The heat transfer experiments in the dry state compared the effect of different masonry methods on the heat transfer performance of the walls. The thermal resistance data in Table 3 shows that the average thermal resistance at three points is 0.366 m²K/W of solid masonry walls and 0.320 m²K/W of cavity walls, the value of the solid wall is 14.4% higher than cavity walls. The heat transfer coefficient is 1.970 W/ m²K in solid walls and 2.130 W/ m²K in cavity walls, the $U_{total}$ of the cavity wall is 8.1% higher than solid wall. This means that in winter, even in dry conditions, the cavity wall will be less insulating than the solid wall.

As a rule, the thermal conductivity of air is very small, if the cavity in the middle was considered as an air insulation layer, the cavity wall should have a higher thermal resistance and a lower heat transfer coefficient. The reason for the lower thermal resistance of the cavity wall in the experiments is that, in the experimental setup, the heating box heats the middle part of the wall and the air in the cavity is heated up. Then, a part of the heat is transferred to the upper part of the cavity and convects with the inner surface of the wall. This phenomenon is evidenced by the fact that the temperature at the high point of P3 is lower than that of P1 in the hot box of the cavity wall, while the temperature at the high point of P3 is higher than that of P1 on the outside of the chamber. Also, on the heating side, the heat flow into the walls all decreases as the height of the point increases, which is related to the heating mechanism of the heating box, where the temperature probe of the heating box is located at point P2, but the hot air outlet is located in the lower part, near point P1, and the return air outlet is located in the upper part near point P3. In the hot box, the air in the lower part is hotter and therefore also counter-generates a more intense heat exchange with the walls.

4.2. Effect of rising capillary water on heat transfer of the wall

Table 3 also reflects the change in heat transfer performance of the wall under the influence of capillary water. Compared to the dry state, the water content of the lower, middle and upper points of the solid wall increased to 15%, 15% and 13%, respectively, and the thermal resistance decreased by 70.9%, 61.4% and 65.5%, respectively, with an average decrease of 65.6%. The water content of the lower, middle and upper points of the cavity wall was 15%, 14% and 9%, respectively, and the thermal resistance decreased by 69.6%, 67.2% and 38%, respectively, with an average decrease of 57.5%. Taking into account the heat exchange resistance of the internal and external surfaces of the wall, the average heat transfer coefficient of the three points of the solid wall in the experiment was 3.671 W/ m²K, increased by 86.3% compared to the dry condition; the average heat transfer coefficient of the three points of the cavity wall was 3.611 W/ m²K, increased by 69.5% compared to the dry condition.

It can be seen that the moisture content has a great influence on the thermal resistance of the wall, and the higher the moisture content, the greater influence on the thermal resistance. In general, there are significant differences in the heat transfer coefficients of different parts of the wall affected by the rise of capillary water. Therefore, in the case of high moisture in the wall base, if only a single heat transfer coefficient is used in the calculation of the heat and moisture coupling in the wall, this will result in large deviations, which in turn will affect the accuracy of the building energy evaluation. It is therefore recommended to divide the wall into wet and dry zones according to the stable height of the capillary water line. Different heat transfer coefficients should be used to improve the reliability of the final results. In addition, in the energy simulation part, the value of the middle point (P2) was selected to reflect the thermal performance of the wall, at where the heat transfer is closer to one-dimension transfer.

4.3. Effect of capillary water rise on heating and cooling loads
Historic dwellings similar to the Zhu’s old house are widely distributed in China and are mostly without additional insulation measures. Energy simulation results that do not take into account the effects of moisture at the bottom are subject to large errors and can have a significant impact on the assessment of energy efficiency retrofits in shallow groundwater areas and traditional dwellings affected by the rainy season. This study proposes an innovative method for simulating wall partitioning to address the phenomenon of rising capillary water, and combines the recommended values of heat transfer coefficients for damp and dry conditions derived from large scale brick wall heat transfer experiments with simulations of real buildings. The simulation results obtained with this method are closer to the real situation and are more conducive to the accurate positioning of energy-efficient retrofitting of traditional residential buildings.

The results of the simulations are only based on a purely heat transfer perspective. The differences in heating/cooling loads of traditional Chinese residential buildings in the dry and wet states are compared. The research further clarified the differences in cooling and heating loads due to the differences in thermal conductivity of the damp areas, and provided a basis for the application of several recommended equivalent thermal conductivity for walls proposed in this study.

The heating/cooling and total loads of the building in both the solid wall and the cavity wall, taking into account the influence of capillary water, are higher than the loads of the building in the dry condition. In the solid wall simulation, the heating load increases by 18.5%, the cooling load by 29.6% and the total load by 20.2%. In the cavity wall simulation, the heating load increased by 6.5% and the cooling load by 11.8%, for a total increase of 7.3%.

Also, in the case of the solid wall simulations affected by capillary water, the design heating power and cooling power increased by 23.6% and 6.8% respectively. In the case of cavity walls, the design heating and cooling power increased by 8.5% and 3.3% respectively.

From the above analysis, it can be seen that the wet area at the base of the wall has a significant impact on the building energy consumption in the shallow groundwater area, numerically it has a greater impact on the heating energy consumption in winter, but due to the smaller heating load base in the dry state in summer, the proportional increase in cooling compliance in summer is greater. In addition, if the effect of capillary water rise is not taken into account, the selection of air conditioning may result in the selection of insufficient power; the real energy consumption will be higher than the simulated energy consumption without taking into account the effect of capillary water. Finally, the rise in heating and cooling loads also demonstrates the importance of suppressing capillary water rise from an energy saving perspective.

It should be noted that the simulations developed in this study are based on a purely heat transfer and aim to assess the energy impact of the difference in heat transfer performance of the wet wall base; the effects of moisture transfer and the evaporation of water are not taken into account.

5. Conclusion
In this study real-scale water uplift and heat transfer experiments were carried out on two traditional Chinese blue brick solid walls and cavity walls. The measured heat transfer coefficients can approximate the change in heat transfer performance of the walls under the influence of rising capillary water at the wall base. In addition, the energy simulation of the Zhu’s ancient house of traditional brick construction was used as an example to analyse the possible energy simulation errors caused by whether capillary water uplift was considered. The combined experiments and analyses lead to the following conclusions. In the dry state, similar heat transfer coefficients exist between cavity walls and solid walls. 240mm cavity walls have an average heat transfer coefficient of approximately 2.13 W/m²·K, while solid walls are approximately 1.97 W/m²·K.

In the cases of a wall with capillary water rise, the heat transfer coefficients of the different parts of the wall can vary significantly. The average heat transfer coefficients of the damped parts of the experimental 240mm thick wall rise to 3.61 W/m²·K and 3.67 W/m²·K respectively. In the simulations for this experiment, considering only the effect of capillary water on the envelope, the annual heating load rises by 18.5% and 6.5% in the solid and cavity walls respectively, the annual cooling load increases by 29.6% and 11.8% respectively, and the total load rises by 20.2% and 7.3%, so the rise in capillary water should be considered in the energy consumption simulations.
In the retrofit of existing historic buildings, blocking capillary water rise or increasing internal insulation can be effective to reduce building energy consumption, since the heat transfer coefficient of the single brick wall is large.

Finally, the outstanding aspect of this experiment is that during the heat transfer phase, the use of the heating box device does not allow for one-dimension heat transfer. The heat from the heated portion of the wall is transferred vertically to the bottom tank and the upper wall, which has a greater effect in wet conditions, thus causing a large difference in heat flow between the two sides of the measurement and resulting in a small thermal resistance of the wall in the results. The latent heat flow of the evaporation on the surface also needs to be investigated in next research. Nevertheless, the lower part of the wall of a single-story historic building will also be in contact with the surrounding soil, so the results of this study are closed with the real heat transfer of a historic building in its natural environment.

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