Heat and moisture transfer in wall-to-floor thermal bridges and its influences on the insulation performance

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Abstract. The moisture modifies the characteristics of heat transfer in building envelopes. Multiple factors, including the distinct hygric properties of various material, gravity, etc., affect the moisture content, resulting in a non-uniform distribution of water vapour in different parts of the envelope (e.g. column, beam, the main part of exterior walls). Usually, the more water vapour in a material, the higher the thermal conductivity, resulting in more heat transfers here. Moreover, condensation easily occurs where there is wet, marking such parts have risks both on structural safety and mould growth. The wall-to-floor thermal bridge (WFTB) occupies the largest area among all kinds of thermal bridges that formed by frame structures. In this study, we aimed to quantify the influence on heat loss through WFTB when the moisture transfer in envelopes is considered. The average apparent thermal resistance of WFTB (R_{TB,ave}) was defined to access the insulation performance of WFTB in practical application. The results of transient numerical simulation indicated that when the moisture transfer is considered, the insulation performance of building envelopes decreases significantly, while the adverse effect of WFTB on heat insulation becomes less pronounced. The results indicated that the measures of insulation for WFTB should be reconsidered when the moisture transfer is considered.

1. Introduction
The hot summer and cold winter climate (HSCW) zone covers a vast area in China, including all the urban agglomerations in the middle and lower reaches of the Yangtze River, and sharing almost half of China’s gross domestic product. To reduce energy use and realize the target for peaking carbon dioxide emissions before 2030, lightweight aggregate materials with low thermal conductivity is promoted by the Chinese government in the HSCW zone. However, as the climate in this zone is characterized by high humidity all year round, the heat transfer in building envelopes are significantly modified by the moisture content in such porous building material [1, 2]. Mendes et al. showed that the influence of moisture on the heating/cooling load is more significant in a humid climate [1]. Liu et al. simulated the heat transfer in a one-dimensional wall in Changsha and indicated that the peak cooling loads of the HVAC system were overestimated, while the total load were underestimated when the effects of moisture transfer (MT) is neglected [2]. However, building envelopes are composed of various materials. The heat flow and moisture distribution in complex structures (e.g., thermal bridges) can be not fully revealed by the existing study, which is in urgent need of further research.

2. Methodology
2.1. Coupled heat and moisture transfer (HAMT) model

Depending on the mass and energy conservation law, the change of moisture content and enthalpy in the controlled element can be written as equation (1).

\[
\begin{aligned}
\rho c_p \left[ \frac{\partial T}{\partial t} + \nabla \cdot (\rho \nabla \phi) \right] &= \nabla \cdot \left( k \nabla T \right) + q_v \nabla \cdot (\nabla \phi) \nabla \phi
\end{aligned}
\]

The moisture flux \( g \) and heat flux \( q \) through the surface of the wall can be described by equation (2).

\[
q = h(T_{air} - T_{surf}) + h_p g + \alpha I,
\]

\[
g = \beta (\varphi_{air} - \varphi_{surf})
\]

In the study case, the heat transfer coefficient \( h \) on the interior and the exterior surface is set as 8.7 and 23.0 W·m⁻²·K⁻¹, and the vapour transfer coefficient \( \beta \) are calculated through the Lewis analogy. The outdoor conditions (solar radiation, air temperature and relative humidity) in Hangzhou, a typical city in the HSCW zone, are taken from typical meteorological year data. The indoor conditions are set according to ASHRAE Standard [3]. The solar absorptivity of the surface \( \alpha \) is 0.7.

2.2. Geometry and index for evaluation

Among all kinds of thermal bridges that formed by frame structures, wall-to-floor thermal bridges (WFTB) occupy the largest area with the maximum heat flux. Figure 1 gives the geometry of a WFTB and hygrothermal properties in detail [4, 5].

**Figure 1.** The geometry of a typical wall-to-floor thermal bridge and hygrothermal properties.

Apparent thermal resistance (denoted as \( R_{TB} \)) has been used to access the resistance of heat flowing through thermal bridges in practical application, which is calculated based on the heat transfer caused by thermal bridges \( (Q_{TB}) \), the physical area of the thermal bridge \( (A_{TB}) \), the temperature gradient, and convective heat transfer coefficient \( (h) \) (see Ge et al. 2020 for detailed information [5]). To well evaluate the overall thermal performance of WFTB in the cooling/heating season, the average apparent thermal resistance \( (R_{TB,ave}) \) is proposed in this study, which can be calculated according to equation (3).

\[
R_{TB,ave} = \frac{1}{\sum_{i=1}^{n} R_{TB,i}} \sum_{i=1}^{n} \left( \frac{A_{TB,i} \left( T_{air,in} - T_{air,out} \right)}{Q_{TB,i}} - \frac{1}{h_{in}} - \frac{1}{h_{out}} \right)
\]

3. Results and discussion

3.1. Validation results

The commercial software COMSOL Multiphysics (5.5.0.359, COMSOL, Inc., Stockholm, Sweden) was adopted to perform the presented HAMT model, which has been validated by comparing with the benchmark cases of the HAMSTAD project [4]. The comparisons indicate that the results of the presented HAMT model agree well with the benchmark cases. The heat transfer (HT) model, in which the MT has been neglected, was validated by an on-site experiment [5].
3.2. Case study
The exterior surface temperature of WFTB and its surrounding areas is displayed in figure 2, in which it can be found that the temperature of the exterior surface was higher in the heating season with the simulation of the HAMT model. This phenomenon indicates that more heat flows out through the envelope when the HT was considered, i.e., the insulation performance became weaker. This is because the thermal conductivity increased when building materials get wet. During summer, a similar result can be found, i.e., the exterior-surface temperature was lower in the HAMT case.

When the MT was considered, the thermal insulation performance becomes better. Under the HT condition, the calculated $R_{TB,ave}$ were only 0.88 and 1.96 m²·K·W⁻¹ during the summer and the winter, respectively, which increased to 1.19 and 2.22 m²·K·W⁻¹ under the HAMT condition. This is because the thermal conductivity of the lightweight aggregate material increased. The heat dissipation caused by WFTB, therefore, becomes less marked.

Moreover, the bimodal profile (see literature [5] for detailed information) under the condition of HAMT, as shown in figure 2, results in a risk of damage caused by thermal stress. Moreover, the relative humidity in the area of WFTB is higher than its surrounding areas (the orange part in figure 3(a)). While the absolute humidity at the interface is significantly high (red circles in figure 3(b)), resulting in a high risk of condensation when a sudden drop in outside temperature occurs.

4. Conclusion
This study investigated the thermal performance of WFTB under the HAMT analysis. It can be concluded that the insulation performance of the envelope, including WFTB and the main part of the walls, decreases when MT is considered. The heat dissipation caused by WFTB becomes relatively less pronounced. During the heating season, the risk of structural safety and condensation at the interface between WFTB and its surrounding was also found in this study.

References
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