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Hygrothermal bridge effects on the performance of buildings☆

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ABSTRACT

Although the thermal bridge effects on the building energy performance have been presented in the literature, the multidimensional hygrothermal analysis of the building envelope is still a challenge due to many difficulties such as modeling complexity, computer run time, numerical convergence and highly moisture-dependent properties. However, their effects are of paramount importance due to the local increase of heat and mass flux densities so that moisture can be easily accumulated around internal corners, increasing mold growth risk and causing structural damage. Therefore, for analyzing the effects of building lower and upper corners, a multidimensional model has been developed to calculate the coupled heat, air and moisture transfer through building envelopes. The algebraic equations are simultaneously solved for the three driving potentials — temperature, vapor pressure and gas pressure gradients — to improve the numerical stability of the discretized model. In the Results section, the coupling of the upper corner, wall, lower corner (with different types of foundations), ground and floor are analyzed in terms of temperature and relative humidity profiles, vapor flow and heat flux, showing the importance of a detailed hygrothermal analysis for accurately predicting building energy consumption, mold growth and structural damage risks.

1. Introduction

Most of the energy consumption and carbon emissions come from the way our buildings are heated or cooled, lit and utilized. In this context, to evaluate the building performance with thermal parameters, several codes have been developed. However, most of those codes do not take into account the moisture presence within building envelopes and the multidimensional effects. The moisture in building porous elements can imply an additional mechanism of transport, affecting the hygrothermal building performance and causing mold growth and structural damage risks. Moreover, those effects are magnified when the multidimensional geometry of the building envelope is considered.

The hygrothermal bridge is formed when there is a low thermal insulation between the external and internal faces of a wall, which encourages the formation of condensation. This can be a consequence of the geometric form, the structural junction or when materials with different coefficients of heat transmittance are installed in non-parallel layers, for example, foundations, parapets, concrete columns, corners, etc.

Beyond the thermal effect, the mass transport is also affected in the corner region, which is still barely explored in the literature due to modeling complexity, high computer run time, numerical divergence and highly moisture-dependent properties. Despite the effect due to both the multidimensional phenomenon and the high hygrothermal capacity of the concrete used in columns and beams, the low air speed near the internal corners also increases the mold growth (Fig. 1) and the structural damage (Fig. 2).

In order to analyze the thermal bridge effects on building energy performance, some authors in the 1990s — such as Hagentoft and Claesson [1], Anderson [2], Krarti [3] and Blomberg [4] — considered the heat losses to the ground and the effect of perimeter insulation for the case of regular slab-on-grade foundations, but no moisture transport was taken into account.

Narowski et al. [5] described a simple method that allows to model the conduction transfer functions for typical thermal bridges. This study was accomplished to improve building energy calculation results obtained from dynamic simulations by incorporating thermal bridge correction factors into building simulation codes. Asdrubali et al. [6] proposed a methodology to perform a quantitative analysis of some types of thermal bridges through the thermographic surveys. Al-Sanea and Zedan [7] used a computer model based on the finite-volume method to quantify the effects of mortar joint height on thermal performance of building walls under two-dimensional steady-periodic conditions.

However, when moisture effects on thermal bridges are taken into account, just a few research is found in the literature. Therefore,

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Nomenclature

c_0	specific heat capacity of the dry material (J/kg K)
c_m	specific heat of the structure (J/kg K)
c_{pa}	specific heat capacity at constant pressure of the dry air (J/kg K)
c_{pl}	specific heat capacity of the water liquid (J/kg K)
c_{pv}	specific heat capacity at constant pressure of the vapor (J/kg K)
g	gravity (m/s^2)
h	convective heat transfer coefficient (W/m^2 K)
j	density of moisture flow rate (kg/m^2 s)
j_1	density of liquid flow rate (kg/m^2 s)
j_v	density of vapor flow rate (kg/m^2 s)
j_a	density of dry air flow rate (kg/m^2 s)
j	density of moisture flow rate (kg/m^2 s)
L	vaporization latent heat (J/kg)
K	liquid water permeability (s)
P_{suc}	suction pressure (Pa)
P_v	partial vapor pressure (Pa)
P_g	gas pressure (dry air pressure plus vapor pressure) (Pa)
q	heat flowing into structure (external) (W/m^2)
T	temperature (K)
w	moisture content (kg/m^3)

Greeks

α	absorptivity (−)
β_v	surface coefficient of water vapor transfer (s/m)
δ_v	vapor diffusive permeability (s)
$\varnothing$	relative humidity (−)
k	absolute permeability (m^2)
$k_{\gamma g}$	vapor relative permeability (−)
λ	thermal conductivity (W/m K)
μ_g	dynamic viscosity (Pa s)
ρ_a	density of dry air (kg/m^3)
ρ_l	liquid water density (kg/m^3)
ρ_v	vapor density (kg/m^3)
ρ_0	density of the dry material (kg/m^3)

in order to analyze the heat and moisture transfer through building lower and upper hygrothermal bridges, a multidimensional model has been developed to calculate the coupled heat, air and moisture transfer.

The governing equations have been discretized using the finite-volume method for modeling the physical phenomena of heat and mass transfer in unsaturated porous media and they have been solved by using the MultiTriDiagonal-Matrix Algorithm [8], avoiding numerical instability-related problems due to the strong coupling between the mass and energy conservation equations.

Fig. 1. Mold growth around an upper corner edge.

Fig. 2. Structural damage at a lower corner surface due to rising damp effect.

In the Results section, the multidimensional effect transport in the lower hygrothermal bridges composed of soil, wall and floor are shown and analyzed in terms of temperature and relative humidity profiles and vapor and heat flux through the floor for different configurations of foundations. For the upper corner, the effects of the concrete beam on the temperature and relative humidity profiles are presented.

2. Mathematical model

The model has been elaborated considering the governing equations for moisture, air and energy balances. The transient terms of each governing equation have been written in terms of the driving potentials to take more advantage of the MTDMA solution algorithm. The following hypotheses have been assumed: no freezing/thawing, no deformable material, no chemical reactions and no free advection due to buoyant forces.

2.1. Moisture transport

The moisture transport has been divided into liquid and vapor flows as shown in Eq. (1):

$$j = j_l + j_v, \tag{1}$$

where j is the density of moisture flow rate (kg/m^2 s), j_l, the density of liquid flow rate (kg/m^2 s) and, j_v, the density of vapor flow rate (kg/m^2 s).

The liquid transport calculation is based on the Darcy equation:

$$j_l = K(\nabla P_{suc} - \rho_l g) \tag{2}$$

where K is the liquid water permeability (s); P_{suc}, the suction pressure (Pa); ρ_l, the liquid water density (kg/m^3); and g, the gravity (m/s^2).

The capillary suction pressure can be written as a function of temperature and moisture content in the following form:

$$\nabla P_{suc} = \frac{\partial P_{suc}}{\partial T}\nabla T + \frac{\partial P_{suc}}{\partial P_v}\nabla P_v. \tag{3}$$