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Impact of wind-driven rain on historic brick wall buildings in a moderately cold and humid climate: Numerical analyses of mould growth risk, indoor climate and energy consumption

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ABSTRACT

This paper gives an onset to whole building hygrothermal modelling in which the interaction between interior and exterior climates via building enclosures is simulated under a moderately cold and humid climate. The focus is particularly on the impact of wind-driven rain (WDR) on the hygrothermal response, mould growth at interior wall surfaces, indoor climate and energy consumption. First the WDR load on the facades of a 4 m × 4 m × 10 m tower is determined. Then the hygrothermal behaviour of the brick walls is analysed on a horizontal slice through the tower. The simulations demonstrate that the impact of WDR loads on the moisture contents in the walls is much larger near the edges of the walls than at the centre. The obtained relative humidity and temperature at the interior wall surfaces are combined with isopleths of generalised spore germination time of fungus mould. The results show that WDR loads can have a significant impact on mould growth especially at the edges of the walls. Finally, for the case analysed, the WDR load causes a significant increase of indoor relative humidity and energy consumption for heating.

1. Introduction

Building energy simulation (BES) models have been under development since the 1970s, for the numerical prediction of the thermal condition and energy performance of a building. Though most BES models nowadays also (partially) solve the hygric balance, moisture analysis is mainly limited to water vapour transport and its influence through latent heat effects and interior moisture buffering. The comprehensive hygrothermal interaction between the exterior and interior climates, as dealt with in building envelope models (e.g. [1–4]), is only incorporated to a limited extent. Recently, Nakhi [5], Holm et al. [6], Rode et al. [7] and Mendes et al. [8] have given an onset to whole building hygrothermal modelling by combining a model for heat, vapour and liquid transport in walls with a BES model. In these studies, the interactions between exterior and interior environments via heat and moisture transfers in building components were investigated as well as interior moisture buffering by building components.

Some of these interactions are not of great concern for recent wall configurations, such as well-insulated walls with air cavity and vapour retarder inside, walls with impermeable siding or sheathing, etc. On the other hand, in historic buildings in Europe, solid masonry systems have often been used for outer walls, without the installation of an adequate air space, insulation and/or vapour retarder, allowing a strong hygrothermal interaction between exterior and interior via the heat and moisture transfer in the walls. For such walls, the absorption of wind-driven rain (WDR) loads may result in a significant moisture flow towards the interior surface and environment, potentially yielding mould growth at inside wall surfaces, increased indoor humidity and/or increased heat transmission. The WDR load has however hardly been taken into account in previous whole building hygrothermal modelling. Therefore the influence of WDR loads on the whole building hygrothermal performance is particularly focused on in this paper.

Hall and Kalimeris [9,10] are perhaps the first case in which the impact of WDR loads on the moisture content in walls is

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Nomenclature

c	specific heat (J/kg K)
d	thickness of the wall (m)
g	flux (W/m^2 or kg/m^2 s)
I_h	horizontal rainfall intensity (mm/h)
I_{WDR}	wind-driven rain intensity on a building facade (mm/h)
k_h	heat conductivity (W/m K or W/m Pa)
k_m	moisture permeability (s or kg/m s K)
L_v	heat of vaporisation (J/kg)
p	vapour pressure (Pa)
p_c	capillary pressure (Pa)
S	radiative heat exchange (W/m^2)
T	temperature (K)
U	wind speed (m/s)
x, x', y', z'	coordinates (m)
x_i	distance from the corner (m)

Greek letters

α	surface film coefficient for heat transfer (W/m^2 K)
β	surface film coefficient for moisture transfer (s/m)
η	global catch ratio (–)
θ	wind direction (°)

Subscripts

c/t	convective/total
e/i	external/internal
h/m	heat/moisture
l/v	liquid/vapour
ref	reference
s	surface
WDR	wind-driven rain

Acronyms

BES	building energy simulation
CFD	computational fluid dynamics
RH	relative humidity
WDR	wind-driven rain

investigated numerically. Janssen et al. [4,11] and Blocken et al. [12] recently formulated the implementation of numerically determined WDR loads as boundary condition in the heat and moisture transfer analysis in building enclosures, based on advanced numerical techniques of Computational Fluid Dynamics (CFD) [13,14]. Also Häupl et al. [15] numerically investigated the impact of the rain on the hygrothermal performance of the facade of the 'Rijksmuseum' in Amsterdam, the Netherlands. Furthermore Kumaraperumal et al. [16] showed an experimental and numerical analysis of WDR loads and the hygric response of the walls for a Scottish castle. However several topics related to the response of a wall to the driving rain load still need further investigation. Examples are durability issues of building facades, algae formation at exterior surfaces, the possible impact on mould growth at inside wall surfaces, and the impact on indoor climate and energy consumption. The answers to these questions do not only depend on the composition of the wall and the outside climate, but also on the building configuration, moisture buffering capacity of the interior, heat and moisture sources in the building, ventilation rate, etc. Furthermore, although the distribution of the WDR load, with an intensity often highest near the upper edges and the sides of building facades [14], is considered to have an important role in the hygrothermal performance of buildings, so far no quantitative investigation of the impact of such distributed WDR load has been performed on the whole building scale. Such multicausal problems cannot be adequately dealt with via a component hygrothermal model, but do require whole building hygrothermal simulation. This paper presents an onset of such a study: the impact of the distributed WDR loads on the hygrothermal behaviour of the walls and the indoor environment of a tower building has been investigated.

In the first part of this paper, the methodology of the whole building simulation – with emphasis on the WDR simulation and the implementation of WDR loads in hygrothermal simulation of building components – is briefly presented. In the second part, the WDR load on the facade of a $4\,\text{m} \times 4\,\text{m} \times 10\,\text{m}$ tower is numerically determined. Then the heat and moisture transfer in the brick walls and the hygrothermal conditions in the room are numerically investigated on a horizontal slice through the walls and interior environment at half the tower height. Finally the impact of WDR on the hygrothermal performance, mould growth potential, indoor climate and energy consumption is discussed.

2. Methodology

2.1. Whole building modelling of heat and moisture transfer

In this paper a whole building simulation is defined as the numerical simulation of coupled heat, air and moisture transfer in building components and building zones, with the aim of comprehensively investigating the durability of the components, and the indoor climate and energy consumption of the zones. First, outdoor air conditions are often assumed to be uniform in this kind of simulations. Note that the distribution of outdoor conditions can sometimes get rather large especially e.g. in a street canyon under a hot climate due to combined effects of solar gain and wind [17,18]. In such situation, a more precise approach by CFD (e.g. [19]) can be useful. However because only a case study with a simple tower building under a cold climate is presented in this paper, such distribution is not considered. When "perfect mixing" of indoor air is also assumed, the whole building modelling of the interactions between exterior and interior climates via building components usually comprises: (1) the heat, air and moisture balance of the building zone(s); (2) the heat, air and moisture transfer in the building components; and (3) the boundary conditions for (1) and (2) and the coupling of (1) and (2). Because essential parts of the whole building simulation are widely known and used in this field and only simple case studies are presented in this paper, the reader is referred to e.g. [5–8] for a more general mathematical formulation of the whole building simulation. In this study, the heat and moisture balances for the zone are expressed as

$$\rho c V \frac{\partial T_i}{\partial t} = Q_{\text{wall}} + Q_{\text{vent}} + Q_{\text{internal}} \tag{1}$$

$$\rho V \frac{\partial X_i}{\partial t} = W_{\text{wall}} + W_{\text{vent}} \tag{2}$$

where ρ is the density of the indoor air (kg/m^3); c is the specific heat of the indoor air (J/kg); V is the volume of the room (m^3); t is the time (s); T_i is the temperature of the indoor air (K); X_i is the humidity ratio of the indoor air (kg/kg); Q_{wall} and W_{wall} are respectively the heat and moisture gain/loss (W and kg/s) of the entire wall surface; Q_{vent} and W_{vent} are respectively the heat and