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Dynamic coupling between vapour and heat transfer in wall assemblies: Analysis of measurements achieved under real climate

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ABSTRACT

An experimental wooden-frame house was designed, instrumented and tested to provide measurements suitable for the study of coupled vapour and heat transfer under real climate conditions. In this paper, six different wall assemblies were tested under complex temperature and humidity boundary conditions over more than 3 years. The main objective is to take advantage of the strong outdoor and indoor stresses to emphasise the dynamic coupling between vapour and heat transfer for different wall assemblies. Measurements showed that the heat flux crossing the vertical walls was significantly influenced when a vapour flow crossed insulating materials with high hygroscopic inertia. To further explain this result, a classical numerical model was selected. It was designed to compute coupled transfer at the building scale. A good agreement was obtained for temperature measurements, while higher differences were observed with humidity measurement. An uncertainty analysis was achieved on both experimental and numerical results. It appeared that the uncertainty of the simulation results was one order of magnitude lower than the experimental uncertainty. Finally, the numerical model was used to break down the coupling of vapour and heat transfers. The latent heat effect occurred as the most sizeable effect, which was consistent with the experimental observations.

1. Introduction

In response to the issues raised by coupled transfer in construction materials, several numerical models have been developed over the last few decades and today are well established. Some were first dedicated to the estimation of the energy consumption at the whole building scale – the so-called BES (Building Energy Simulations) models – [45]; ESP-r [3,9]; etc.), while others were specifically designed to study coupled transfer at the envelope or at the whole building scale – the so-called HAM-model, (WUFI and WUFI-Plus [1,14,19], HAM-Tools [16], HAM-BE [25], HAM Fit Plus [44], etc.). A classification that highlights the models' specificities was proposed in Ref. [49]. Differences are related to granularity, simplifying assumptions, the way material properties are handled and the governing potential for moisture transfer. This illustrates that there is no single way to model coupled transfer in buildings.

To validate different models, experimental results are still needed to enrich the existing data for various materials, wall assemblies and conditions. Many set-ups have been designed and instrumented to this end. For example [43], present a data set specifically designed for benchmarking one-dimensional heat and moisture transfer models. Measurements were taken on spruce plywood and cellulose insulation samples.Ref. [34] proposed an experimental set-up to study vapour transfer in the insulating materials more specifically.Ref. [46] designed a test facility to study the behaviour of calcium silicate samples under controlled conditions. The set-up was designed to validate a coupled HAM-CFD (Computational Fluid Dynamic) model. Consequently, there is already a large amount of data on coupled transfer in building materials and numerous modelling approaches. However, these studies focus on material samples placed in controlled conditions and data concerning full-scale experimental investigations are still

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Nomenclature

Latin symbols

Cp	specific heat capacity (J kg^{-1} K^{-1})
e	thickness (m)
g_V	vapour flux (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
H	enthalpy (J)
h_{Vap}	mass transfer coefficient (s m)
AH	absolute humidity (kg_V kg_{DryAir}^{-1})
m	mass (kg)
p	pressure (Pa)
q	heat flux (W m^{-2})
R	resistance (m^2 K.W^{-1})
T	temperature (K or °C)
u	uncertainty (–)
V	volume (m^3)
W	moisture content (kg m^{-3})
x	variable (–)

Greek symbols

δ	vapour permeability (s)
Δ	variation (–)
λ	thermal conductivity (mW m^{-1} K^{-1})
λ_W	humid thermal conductivity (W m^{-1} K^{-1} kg^{-1} m^3)
ρ	density (kg.m^{-3})
Φ	relative humidity (–)

Subscripts

App	apparent
C	convective
Cond	conductive
Dry	measured on dry material
Exp	experimental
In	indoor
Irr	irradiative
Mdl	model
Out	outdoor
R	ratio
Sat	saturated vapour
V	vapour

Constants

L_V	latent heat of vapour condensation (2500·10^3 J kg^{-1})
p_{Tot}	total pressure (101,325 Pa)
r_{DryAir}	dry air constant (287 J kg^{-1} K^{-1})
r_V	vapour constant (462 J kg^{-1} K^{-1})

needed, as already underlined by several researchers experimenting hygrothermal simulations [38,42]. At the wall scale, an experimental apparatus presented in Ref. [12] and investigated further by Ref. [8] was designed to study the coupled transfers in the roofs. In Ref. [51], measurements obtained with 12 different wall assemblies were set against simulation results. In Ref. [10], a guarded hot box was presented. Its design allowed assessing the durability of a 30 m^2 wall assemblies based on the knowledge of its moisture content. A similar experimental work was presented in Refs. [28,29] and was designed to estimate the behaviour of various wall assemblies for humid conditions. Different wall assemblies were tested for realistic conditions by Ref. [17], then further described in Ref. [47]. Laboratory results obtained over 40 years for indoor finishing were presented in Ref. [39]. A lightweight building envelope wall exposed to real atmospheric conditions is reported in Ref. [4,6] have presented an experimental procedure developed to study inward vapour transport in wood-frame walls resulting from high-temperature gradients. At the building scale [11], have monitored heat and moisture transfer in various wall assemblies exposed to real climate for 3 years. A similar work was presented by Ref. [26] and [14] in Germany. To the best of the authors' knowledge however, these latest studies were mostly used for validation purposes and general conclusions could not be drawn. Consequently, the understanding of the overall hygrothermal behaviour of wall assemblies under real conditions appears to be incomplete and additional investigations are required to better illustrate the coupling between moisture and heat transfers.

Second, it requires a lot of time and efforts to precisely characterise the material properties and to include such results in the modelling. However, the heat and mass balances at the building scale are strongly influenced by other phenomena, which cannot be determined with a high level of confidence. It would be pointless to look after a high accuracy for some of the transfers and not for the others. For example, real outdoor conditions cannot be determined or modelled as accurately as laboratory conditions. Similarly, material properties can be precisely characterised for small samples, but substantial discrepancies may be obtained over an entire wall built with manufactured or locally prepared materials. The air change rate at the building scale is not precisely controlled, and may be significantly influenced by outdoor conditions [20]. It is also acknowledged that heat and vapour transfer at the wall scale are influenced to a large extent by the wall assembly [7]. Besides, despite the increase of computational power, saving computational time is still a concern. It was demonstrated in Ref. [30] that moisture transfer could be simplified without introducing strong biases. This illustrates the fact that a detailed knowledge of the material properties is not necessarily in line with the studies focusing at the building scale. Therefore, it would be useful to determine which phenomena are the most sizeable at the building scale.

In this context, a 20-m^2 wooden-frame test house was built in Grenoble, France. The set-up was designed to validate whole-building HAM simulation tools and to investigate different wall assemblies, so it was instrumented to collect temperature and relative humidity at different depths in the wall, as well as indoor and outdoor conditions. The monitoring has lasted more than 3 years and 6 different wall assemblies were tested. The detailed description of the experimental facility and the earliest results have been presented in Ref. [35]. In this paper, some of the measurements collected in the vertical walls will be discussed. The objective is to take advantage from the real outdoor conditions and the long term measurements to highlight further the coupling between heat and mass transfer. Specifically, the impact of vapour transfer on heat transfer will be evaluated for different light-wall assemblies. The second objective is to verify which modelling assumptions are relevant, regarding the observed phenomena. First, the experimental facility, the wall assemblies, the material properties and the instrumentation will be described. Then the experimental results will be used to compare the six wall assemblies. In the second part of this paper, coupled transfers in a single vertical wall will be simulated using HAM-Tools libraries. Two experimental sequences were selected because of the amplitude of the boundary conditions and the confirmed impact of materials on vapour transfer. A section will be devoted to the discussion of the measurement and modelling uncertainty. Finally, the preliminary conclusions drawn by the analysis of the experimental results will be examined in greater depth using the numerical tool.