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A Complete Analysis of the Heat, Air and Moisture Transfer on Building Performance

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Abstract

The simulation of combined heat, air and moisture (HAM) is important to predict the indoor air quality and thermal comfort. Moreover, inappropriate levels of indoor humidity and temperature can contribute to a high movement of water vapor through the building walls, causing deterioration and reduction of the thermal insulation which leads to higher energy demand. The simulation of the buildings behavior can help to optimize the design of new or existing building, help better control the HVAC system and therefore results in energy efficient buildings.

In this work, an in-house modular object-oriented tool (NEST) for the multiphysics simulation of buildings is presented. The whole building is modeled as a collection of basic elements (e.g., walls, rooms, openings, occupancy, HVAC system, solar radiation distributor, etc.). These elements can be modeled using different physical models and scales. A combined heat, air and moisture transfer model for the building envelopes and rooms have been implemented and validated with different benchmark cases. The in-house simulation tool has been used for the simulation of hygrothermal behavior of rooms inside different public buildings (residential apartments, hospital rooms, universities and school plants). The simulations allowed as the analysis of the humidity effect on thermal comfort and energy performance of the rooms.

Keywords - energy efficiency in buildings;indoor air quality;HAM

1. Introduction

Buildings account about 40% of the global CO2 emissions which are directly related to the energy consumed for maintaining the building usability. [4] Building energy consumption has increased from 20% to 40% in developed countries exceeding the industrial and transportation [5]. It is estimated that almost 50% of the global energy demand is due to buildings. Hence, engineering solutions and tools are needed in current times in order to analyze and optimize energy efficiency in buildings. This involves the use of eco-friendly and less energy intensive building materials, incorporation of passive solar principles in building design, operation including day-lighting features and use of energy efficient appliances in buildings.

In this paper, NEST-Buildings tool, an in-house, modular, object-oriented and parallel methodology tool for the multiphysics simulation of buildings is presented. The tool models the whole building as a collection of basic elements (e.g., walls, rooms, outdoor, people, ventilation, solar radiation distributor, HVAC, etc.). These elements are capable of solving themselves for given boundary conditions that are given by the connected elements. They can be modeled with different physical models and scales (ranging from global, 1D, 2D, 3D to CFD&HT models) which gives the flexibility in modeling a system of many elements with different level of details in the same simulation.

Most building materials are porous. In the pores, moisture can exist and cause significant effects in material durability, thermal performance and indoor air quality. So first, mathematical models for the coupled heat and moisture transfer through walls and inside room are presented. These models were implemented inside the NEST-Buildings code. Simulations are first verified with some reference cases in the literature: isothermal moisture transfer, heat and moisture transfer through three materials used in building construction (brick, concrete and hemp concrete) and moisture transfer inside room under isothermal conditions.

After verification, NEST-Buildings tool has been used in the framework of the EU project RESSEEPE. The main idea of the RESSEEPE project is to technically advance, adapt, demonstrate and assess a number of innovative retrofit technologies in public buildings. In a first stage of the project, the NEST-Buildings tool has been used to simulate and analyze the hygrothermal behavior of various existing characteristic rooms of three different public buildings (hospital, university and school) located in distinct locations of Europe (Spain, England and Sweden). Simulations allow the analysis of energy performance and thermal comfort inside different characteristic rooms of these demosites.

In this paper two characteristic rooms from the EU project are studied and presented: a hospital room in Terrassa, Spain and a class room in Coventry, UK. Simulations are run for a period of one year and two situations are studied. Situation 1: closed rooms just taking into account buffering from walls due to external weather conditions. No heating, ventilation or occupants are considered. Situation 2: the same rooms are simulated with considering heating, ventilation and occupants inside.

2. Mathematical Model

The mathematical model for heat, air and moisture (HAM) transfer through building hygrothermal material walls and inside rooms are described in this section.

Heat and moisture transfer through wall

The moisture is transported through the porous wall under liquid and vapor phases. The liquid is sucked due to capillary pressure gradient while the water vapor is diffused due to partial vapor pressure gradient. By applying the Fick's law for vapor diffusion and Darcy's law for liquid transport, the moisture transport equation through a wall [6] can be written as:

$$\frac{\partial \theta}{\partial t} = D_\theta \frac{\partial^2 \theta}{\partial x^2} + D_T \frac{\partial^2 T}{\partial x^2} \tag{1}$$

The moisture transport equation can be expressed using various driving forces massive moisture content, ω, volumetric moisture content, θ, capilary pressure, ψ, or relative humidity, ϕ. The use of the moisture volumetric content, θ, has been chosen as it gives a direct physical meaning by presenting the quantity of water in [m^3] contained in a [m^3] of material. The moisture flux in the surface is calculated from the water vapor gradient between the air and the surface pore, boundary condition for both external and internal sides is:

$$\rho_l \left(D_\theta \frac{\partial \theta}{\partial x} + D_T \frac{\partial T}{\partial x} \right) = h_m (\rho_{v\_Amb} - \rho_{v\_Surf}) \tag{2}$$

The energy transport equation takes into account the condensation/evaporation within the material [7] [8], can be written as:

$$\rho_0 C_p \frac{\partial T}{\partial t} = (\lambda + L_v \rho_l D_{T,v}) \frac{\partial^2 T}{\partial x^2} + D_{\theta,v} \frac{\partial^2 \theta}{\partial x^2} \tag{3}$$

The boundary condition for both external and internal sides takes into account convection with the ambient air, condensation/evaporation and solar irradiation:

$$\left((\lambda + L_v \rho_l D_{T,v}) \frac{\partial T}{\partial x} + D_{\theta,v} \frac{\partial \theta}{\partial x} \right) = h_T (T_{Amb} - T_{Surf}) + L_v h_m (\rho_{v\_Amb} - \rho_{v\_Surf}) + \Phi_{rad} \tag{4}$$

Room model

The room model considers the transient indoor temperature and humidity based on the heat and moisture balance in the room, by involving all the heat and moisture fluxes coming from the walls and also the internal heat and moisture generation due to occupant and building operation (lighting, air conditioning…). The room is assumed to be a perfectly mixed zone and can be presented by a single node characterized by a pressure, a temperature and a relative humidity. Under this assumption, the heat and moisture balances are:

- Heat balance: $$\rho V C p \frac{\partial T}{\partial t} = \sum_{i=1}^{Nwalls} \dot{Q}_{wall\_i} + \dot{Q}_{source} + \dot{Q}_{Ventilation} \tag{5}$$

Where $\dot{Q}_{wall\ i}$ is the convective heat transfer between the walls and the air inside the room, computed as:

$$\dot{Q}_{wall\ i} = A_i\ h_i\ (T_{wall\ i} - T_{room}) \tag{6}$$

$\dot{Q}_{Ventilation}$ is the heat produced or released inside the room due to the ventilation:

$$\dot{Q}_{Ventilation} = \dot{m}\, C_p (T_{SetTemperature} - T_{room}) \tag{7}$$

$\dot{Q}_{source}$ is the heat generated due to occupant activities, whose values are tabulated and depend on the gender and activities of the occupants [11].

- Moisture balance:

$$V \frac{\partial \rho_v}{\partial t} = \sum_{i=1}^{Nwalls} \dot{Q}_{mwall\_i} + \dot{Q}_{mSource} + \dot{Q}_{mVentilation} \tag{8}$$

Where $\dot{Q}_{mwall\_i}$ is the moisture absorption/desorption of the building envelope, defined as:

$$\dot{Q}_{mwall\_i} = A_i h_{mi} \left(\rho_{v\_surf\_i} - \rho_v\right) \tag{9}$$

$\dot{Q}_{mVentilation}$ is the moisture supply and removal from the zone by airflow:

$$\dot{Q}_{mVentilation} = \dot{m}\left(\rho_{v\_surf\_i} - \rho_v\right) \tag{10}$$

$\dot{Q}_{mSource}$ is the moisture generated due to occupant activities and are tabulated in [2].

3. Numerical Resolution

The numerical simulations of the above hygro-thermal models for envelop and rooms are performed using NEST-Buildings code (Nest Element Specialization Toolkit). It is a modular, object-oriented and parallel methodology tool for the multiphysics simulation. The building can be modeled as a collection of basic elements (walls, rooms, windows, outdoor, etc.). Every element is capable of solving itself when subjected to boundary conditions which are taken from the neighboring elements. The advantages of such a modular approach are that: *i)* each element can be modeled with different physical models and scales (1D, 2D, 3D to CFD&HT models) and gives the flexibility in modeling a system of many elements with different level of details in the same simulation: *ii)* the code is parallel, i.e. the numerical calculations can be easily done in several parallel processes as the models are uncoupled to each other at code level, saving computational time and making possible the simulation of big systems; *iii)* new physical phenomena and methods can be easily implemented without changing the basic structure of the code which leads to sustainable source code; *iv)* it is easy to integrate new elements, elements can be reused and represented in any form depend on the application which makes the source code highly versatile.

4. Verification and Validation

The simulation tool has been tested and verified with analytical and reference results in the literature, these cases are: isothermal moisture transfer through the wall, heat and moisture transfer through the different wall materials used in building construction and isothermal moisture transfer inside the room.

Isothermal moisture transfer in a wall

The HAMSTAD benchmark exercise #2 [7] is a one dimensional case with isothermal moisture transfer in a single layer exposed to air with relative humidity of 65% on one side and 45% on the other side, while the temperature is held constant at 25ºC. Figure 1 shows how the numerical model is able to predict very well the transient moisture diffusion in the wall with the relative differences below 1.2 %.

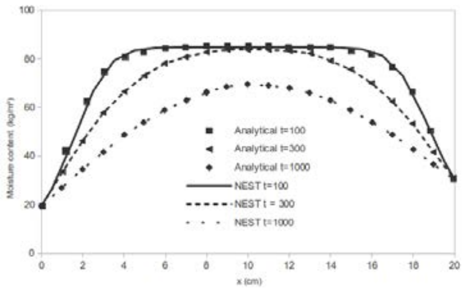


Figure 1 Moisture profiles of the layer at 100, 300 and 1000h.

Non-isothermal moisture transfer in different wall materials

In this section, the heat and moisture transfer through a single wall layer for different materials used in building construction (brick, normal concrete, hemp concrete), is studied and validated with results of [12]. A periodic variation of temperature and relative humidity are considered in the outdoor, similar to the summer weather condition. The external thermal convection coefficient is 25 W/m^2K while the indoor temperature, relative humidity and thermal convection coefficient are set to 24°C, 50% and 5 W/m^2K, respectively.

Simulations are run for a period of one year with a time step equal to 30 seconds, wall thickness is fixed to 20 cm and initial wall temperature and moisture content were considered to be 20ºC and 5.10^{-3} m^3/m^3, respectively. Figure 2 shows the temperature evolution at the inner and external surfaces of the concrete wall using the coupled heat and moisture model. compared with simulation results of just heat transfer model it can be observed that the temperature is slightly affected and increases with moisture presence in the wall. While moisture content on the internal and external surfaces reach a periodical state in few days, it needs about six months to reach a steady state at a depth of 10cm inside the concrete material (figure 3). A good agreement is observed comparing with results obtained [12].

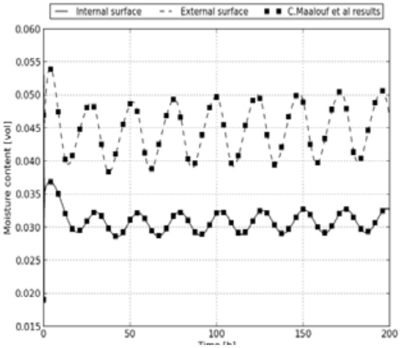


Figure 2 Moisture content in concrete surfaces

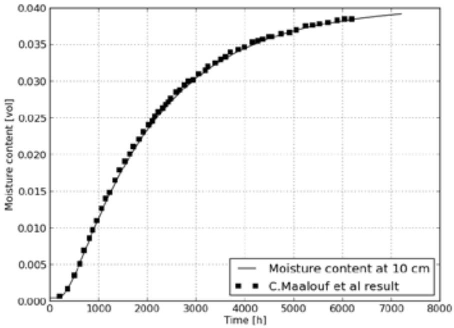


Figure 3 Moisture content in concrete centre

Figure 4 shows for two days after six months of simulation that the amplitude oscillation of temperature is lower for the hemp concrete than brick and concrete. The hemp concrete material isolates more the heat transfer coming from the external side. However, the brick material has the lowest moisture content at the inner side as it is observed in figure 5 it reduces more the moisture transfer through the wall.

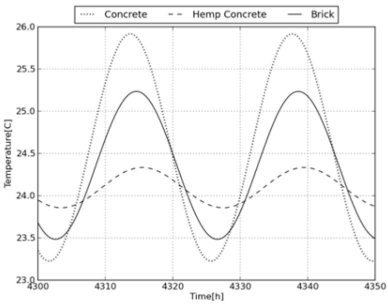


Figure 4 Internal temperature after 6 months

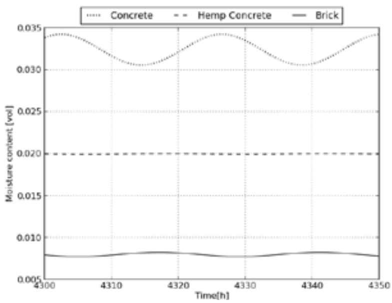


Figure 5 Internal moisture content after 6

Room and wall moisture transfer

A simplified building (a rectangular box shape) is presented for validation purpose [1] with walls made monolithic layer having a thickness of 150[mm] of aerated concrete is tested under isothermal conditions, but with moisture transfer until cyclic steady state is reached. The room envelope exchanges moisture with outdoor and internal moisture generation of 500 g/h between 9:00h and 17:00h is considered. Two different cases are studied: No heat and moisture is considered through the walls (case 0A); Heat and moisture transfer is considered only at the inner surfaces of the room (case 0B). Initial and boundary temperature is 20ºC while relative humidity is 30%. Figure 6 and figure 7 show the relative humidity over the length of the day for case 0A and case 0B, respectively. Good agreement with analytical solution with a maximum relative difference of 1.06% and 1.42 % for case 0A and case 0B is observed.

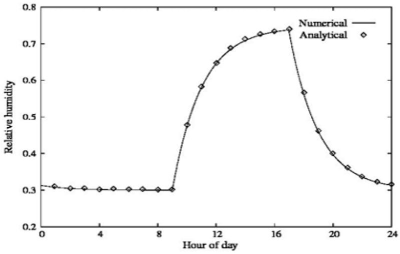


Figure 6 Relative humidity variation case 0A

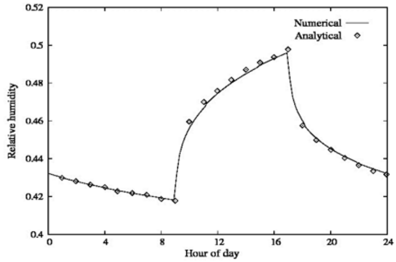


Figure 7 Relative humidity variation case 0B

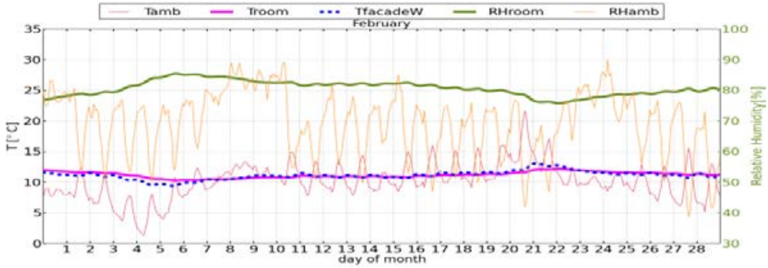
5. Study Cases

Once verified, The NEST-Buildings tool has been used to simulate different demosites rooms in Europe. However, for brevity only results for two rooms are presented: First, a hospital room in Terrassa, Spain, where the weather is relatively hot. Second, a class room in Coventry, UK where the weather is cold and humid. The simulations lead to study the hygrothermal behavior and comfort level for two rooms having different weather conditions. The ideal relative humidity (RH) of air for comfort is in the range of 30% to 70% in Spanish standard and from 40% to 70% in the UK standard. The simulations are run for different 2 situations: First envelope buffering where only heat and moisture transfer through walls is considered. Second, in addition to the first situation heating, ventilation and occupancy are considered inside the rooms.

Situation 1: Envelop buffering in a room

This simulation consists on predicting the temperature and the humidity inside the two demosites rooms during one year under real weather conditions, with just taking into account the heat and moisture buffering from walls due to weather conditions. It has been checked whether there is water condensation in the surface of the facades, where the temperature is below dew point, as it shown in the figure 8.

- Terrassa Room:



- Coventry Room:

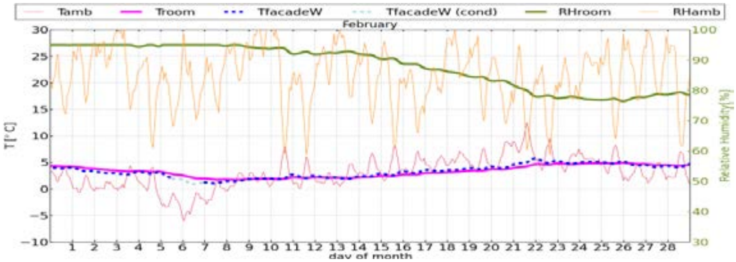


Figure 8 Temperature and relative humidity evolution inside rooms

The objective of this simulation was to study the heat and mass transfer through the room envelope. In this situation, the indoor temperature and humidity are basically influenced by the external weather and the material of the walls. Condensations take place in the inner façade of Coventry room in winter days (January, February, even March) which can cause the deterioration of wall material.

Relative humidity is temperature dependent; it reaches the maximum of 95 % in Coventry when the temperature is very low (close to zero). This means that the air in room is cooled and it can hold less moisture, therefore the air has a larger percentage of moisture relative to what it can hold. It has been observed that relative humidity is out of comfort ranges for many periods during the simulation of the two demosites rooms.

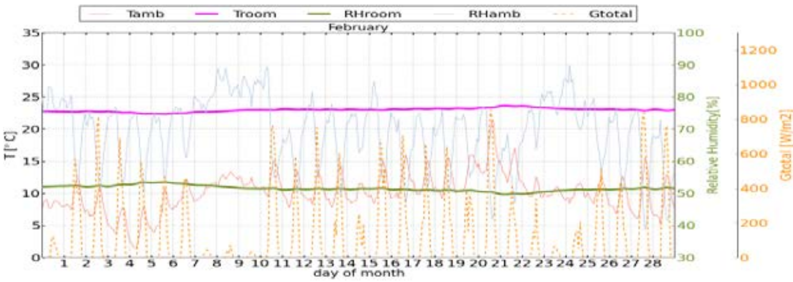
As it is a closed room, the air always have the same amount of water vapor, while the temperature increases during summer season, the amount of water vapor that air can hold increases and therefore the relative humidity decreases, so the comfort sensation improves.

Building envelope is not enough to isolate and conserve an appropriate comfort temperature for the demosites rooms, so a heating and ventilation system should be considered as it has been done for the next situation.

Situation 2: room with heating, ventilation and occupancy.

In this situation, a real ventilated room with occupants inside and heat and moisture transfer through the walls has been simulated. A fixed preheated air flow supply and heat and moisture generation rates due to occupants were considered at each demo site room according to the table1. For Terrassa, since it is a hospital, a permanent occupancy has been assumed.

- Terrassa room:



- Coventry Room:

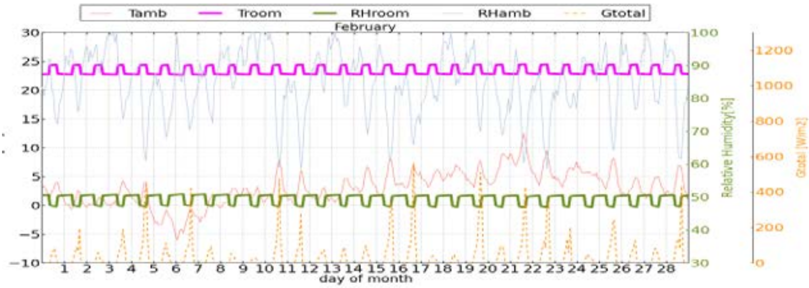


Figure 9 Temperature and relative humidity evolution inside rooms

For Terrassa, a permanent generation of moisture due to two occupants in the hospital room is considered; the relative humidity varies slightly around 50% in winter and 47% in summer. For Coventry, due to its educational use character, a daily generation of moisture from 8h to 16h due to 20 occupants is assumed. This generation implies a periodic evolution of relative humidity inside the room. The periodic evolution of humidity in Coventry is explained by the small volume of the room and the low ventilation rate. Although this wavy character of the relative humidity profiles, their values are always in comfort range.

Table 1Ventilation parameters and occupants behaviours for situation 2

	Air flow rate	Air flow rate [kg/s]	Inflow air Temperature [ºC]	Inflow air Humidity [%]	Number of occupants per room	Schedule	Activity	Moisture generation rate[g/h person]	Heat Generation rate[W/ person]
Terrassa	200 [m^3/h]	0.065	23	50	2	24h	Sleeping /relaxing	40	80
Coventry	0.8* [m^3/s]	1	23	50	20	From 8h to 16h	Studying	50	100

6. Conclusion

In this paper, a modular object-oriented tool with parallel infrastructure has been presented for the multiphysics simulation of buildings. The building is modeled as a collection of basic elements (walls, room, outdoor, occupant, ventilation,..). The simulation of coupled heat and moisture transfer is taken into account and implemented in the tool.

The simulation tool, NEST-Buildings, has been used to study and verify different reference cases: Isothermal heat transfer through wall, hygrothermal performance of three different materials used in building construction (brick, concrete and hemp concrete) and moisture balance inside room.

Finally, the NEST-Buildings tool has been used to analyze the hygrothermal performance of two illustrative cases. The heat and mass transfer at the buildings envelopes and rooms were used to analyze the hydrothermal behavior of building materials and indoor zone for a hospital in Spain and a university in UK under real weather conditions and taking into account the heat and moisture generation due to occupant activities.

It has been observed that building envelope isolate the indoor temperature but not good enough to maintain a comfort condition nor avoid condensations in cold days, so a heating and ventilation system is necessary. The simulations of conditioned rooms with occupants inside show acceptable ranges of temperature and humidity during the year inside the two test rooms.

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