IMPACT OF COUPLED HEAT AND MOISTURE TRANSFER EFFECTS ON BUILDINGS ENERGY CONSUMPTION

by

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Coupled heat, air, and moisture transfers through building envelope have an important effect on prediction of building energy requirements. Several works were conducted in order to integrate hygrothermal transfers in dynamic buildings simulations codes. However, the incorporation of multidirectional hygrothermal transfer analysis in the envelope into building simulation tools is rarely considered. In this work, coupled heat, air, and moisture (HAM) transfer model in multilayer walls was established. Thereafter, the HAM model is coupled dynamically to a building behavior code (BES).The coupling concerns a co-simulation between COMSOL Multiphysics and TRNSYS software. Afterward, the HAM-BES co-simulation accuracy was verified. Then, HAM-BES co-simulation platform was applied to a case study with various types of climates (temperate, hot and humid, cold and humid). Three simulations cases were carried out. The first simulation case consists of the TRNSYS model without HAM transfer model. The second simulation case, 1-D HAM model for the envelope was integrated in TRNSYS code. For the third one, 1-D HAM model for the wall and 2-D HAM model for thermal bridges were coupled to the thermal building model of TRNSYS. Analysis of the results confirms the significant impact of 2-D envelope hygrothermal transfers on the indoor thermal and moisture behavior of building as well as on the energy building assessment. These conclusions are shown for different studied climates.

Key words: *hygrothermal transfer, HAM-BES co-simulation, multidimensional effect, energy performance.*

Introduction

Nowadays, economic and environmental issues related to the reduction of energy consumption in buildings are increasingly important. Indeed, the construction sector is one of the highest energy consumption sectors with almost 45% of the world energy consumption and responsible of 36.1 billion of tons of CO_2 emission. In order to reduce energy costs and environmental impacts related to buildings, several organizations and research laboratories have focused on the physical study of the building and its energy behavior. Today these studies around the world were under-taken according to the creation of several standards and modeling tools in the construction field.

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The good estimation of thermal loads (sensible and latent) requires an accurate assessment of the coupled HAM transfer through envelope as well as a dynamic hygrothermal interaction between both the envelope and the building's indoor air.

Although, in the majority of building energy analysis codes, calculation of heat transfer through envelope neglects both: moisture storage in a porous material constituting the wall and multidimensional effect related to thermal bridges problems.

Further that thermal effect, an excessive moisture accumulation causes structural damage to the envelope and affects indoor air quality. Indeed, high levels of ambient humidity lead to a microbial growth that can severely affect human health. At the same time, this environment promotes fungal development and condensation appearance in the wall.

Nevertheless, detailed envelope hygrothermal transfer modeling and its dynamic interaction with indoor air are rarely explored in the actual state of the art. In particular, thermal bridges problems where the modeling is complex owing to the strong coupling of hygrothermal transfer phenomena with properties highly depending on material water states. As well as, multidirectional effect that makes the non-linear hygrothermal system equations more difficult to resolve.

In order to study the multidimensional thermal bridge effect on building energy consumption, several works have been carried out. Such as, Narowski *et al.* [1] who developed a simple approach defining corrector factors in building dynamic simulation. These coefficients express an equivalent thermal conduction flow due to thermal bridge. In the same sense, Martin *et al.* [2] summarized in their work the various problems related to assessment of heat transfer through thermal bridge and its integration in building dynamic simulation tools. Two methods were investigated: simplified stationary approach and dynamic approach. Results indicated that the dynamic method is more appropriate for real studies evaluation.

In another study, Theodosiou and Papadopoulous [3] studied the influence of thermal bridge on energy consumption of old buildings in Greece. In their conclusion, the authors shown that using the international standards [4] for heat transfer evaluation trough thermal bridges can lead to an underestimation of the real building energy requirements.

However, in the majority of work carried out on this subject, coupling heat and moisture transfer is not taken into account. Among rare studies, in this way, dos Santos and Mendes [5] developed a 2-D coupled HAM transfer to investigate hygrothermal behavior of upper and lower thermal bridges. In this work, internal boundary conditions were imposed without dynamic interaction with inside air building and its systems (ventilation, heating, and air conditioning). These authors highlighted the importance of a detailed hygrothermal analysis (*i. e.* the temperature and the relative humidity distributions, the water vapour, and heat flows) to predict correctly both the energy consumption and the risk of mold growth and building material degradation caused by the excess of indoor humidity.

In the current work, a coupled HAM transfer model in multilayer walls was established where hygrothermal properties of material represent the input parameter of this model. They were measured function of their water content. In order to study the building energy consumption, an integrated analysis of dynamic moisture behavior of the envelope (with coupled HAM transfer) within a BES was undertaken. This integration process was achieved by developing a HAM-BES co-simulation platform where two simulation tools were implemented: one for building dynamic simulation (TRNSYS) and the other for wall hydrothermal transfer modeling (1-D for wall and 2-D for thermal bridge) (COMSOL). This developed HAM-BES co-simulation platform was conducted for a case study to analyze the influence of 1-D and 2-D coupled HAM transfer through wall on indoor air hygrothermal situation and building energy consumption. For that, various types of climates were studied.

Coupled HAM transfer modeling in the building envelope

In order to have an accurate prediction of the hygrothermal behavior at building envelope, we have opted for a model based on the Luikov theory in [6, 7], with the following assumptions:
– local thermodynamic equilibrium between all present phases,
– gaseous phase complies to the ideal gas law,
– hysterises and chemical reactions between phase were not taken into account,
– radiative heat transfer is neglected,
– humidity storage capacity variation with temperature change was neglected, and
– solid medium was undeformable.

The developed model, consider the temperature as driving potential for heat transfer, the total pressure for air transfer, and the water vapor pressure for the hydric transfer. This allows us to avoid discontinuity problems at the wall layers interfaces, which is not the case with the water content. Moreover, the water vapor pressure is in direct relation with the relative humidity which is a useful parameter with a simple and direct signification, particularly when using the experimentation [8].

To realize an accurate and detailed study, we took into account in this approach, the variation of hygrothermal material properties depending on the water content. This concern especially: the moisture permeability, k_m, and the storage moisture capacity, C_m, for hydric transfer, and the thermal conductivity, λ, for heat transfer.

Equations (1) and (2) represent both moisture and gaseous balances phases, eq. (3) expresses the heat balance by taking into account the heat conduction and advection due to moisture and total pressure gradients:

$$C_{m_i}\left(\omega\right)\rho_{s_i}\frac{\partial P_v}{\partial t}=\mathrm{div}\left[k_{m_i}(\omega)\nabla P_v+k_{T_i}\nabla T+k_{p_i}\nabla P\right] \tag{1}$$

$$C_{a_i}\frac{\partial P}{\partial t}=\mathrm{div}\left(k_{p_i}\nabla P\right) \tag{2}$$

$$C_{p_i}\rho_{s_i}\frac{\partial T}{\partial t}=\mathrm{div}\left[\lambda_i\left(\omega\right)\nabla T+\alpha_i\nabla P_v+\gamma_i\nabla P\right]+L_v\rho_{s_i}\sigma_i C_{m_i}\left(\omega\right)\frac{\partial P_v}{\partial t} \tag{3}$$

where $i = 1, 2, \ldots, n$ is wall's layer position (from the outside to inside), $C_m = (1/P_{vsat})(\partial\omega/\partial\varphi)$ [kgkg^{-1}Pa^{-1}] – the moisture storage capacity, λ [Wm^{-1}K^{-1}] – the thermal conductivity, C_a [s^{2}m^{-2}] – the humid air storage capacity, k_m [kgm^{-1}s^{-1}Pa^{-1}] – the total moisture permeability, k_T [kgm^{-1}s^{-1}K^{-1}] – the liquid water conductivity caused by temperature gradient, k_p [kgm^{-1}s^{-1}Pa^{-1}] – the moisture infiltration coefficient, $\gamma = h_l k_{m,\ \alpha\ =\ h_l k_p}$ [m^{2}s^{-1}], h_l [Jkg^{-1}] – the liquid specific enthalpy, and $\sigma = \mathrm{div}(j_v)/\mathrm{div}(j_m)$ [–].

Envelope-ambience interaction and boundary conditions

In the present study, convective heat and mass exchanges, related to the internal and external environmental excitations, are taken into consideration. Concerning the total pressure, Dirichlet boundary conditions are imposed.

The boundary conditions are summarized in the following equation:

$$k_m(\omega)\nabla P_v + k_T\nabla T + k_p\nabla P = h_m\left(P_{v\text{amb}} - P_{v\text{surf}}\right) \tag{4}$$

$$\lambda\nabla T + \alpha\nabla P_v + \gamma\nabla P = h_c\left(T_{\text{amb}} - T_{\text{surf}}\right) + \left(1-\sigma\right)L_v h_m\left(P_{v\text{amb}} - P_{v\text{surf}}\right) \tag{5}$$

where amb index represents internal and external ambiances, surf index is the surface of the wall. The h_m [kgm^{-2}s^{-1}Pa^{-1}] and h_c [Wm^{-2}K^{-1}] represent the heat and mass convective exchange coefficients, respectively. The used driving potentials are assumed continuous at the interfaces between the n layers of different materials constituting the wall.

The HAM-BES co-simulation approach

The HAM-BES co-simulation approach consists of coupling a dynamic building simulation tool (TRNSYS) with a coupled HAM transfer model for envelope implemented in COMSOL. The coupling was carried out in MATLAB that represents an integrator tool ensuring the data exchange and time synchronization between TRNSYS and COMSOL.

The COMSOL/MATLAB connection is provided through the LiveLink interface based on a client/server system where MATLAB is the client. MATLAB commands are performed on COMSOL server. Thus, the HAM model is defined in MATLAB, and differential equations system is solved by the COMSOL solver. Concerning the TRNSYS/MATLAB link, it is established using the type 155, who allows to create a dynamic connection between both tools.

The COMSOL-TRNSYS co-simulation implementation

In order to develop a performing tool for HAM-BES co-simulation, and ensure a reliable coupling between COMSOL and TRNSYS softwares, a strategy for data exchange and time synchronization between the two tools was developed.

In our approach, the control of the time step was provided by the BES model (TRNSYS). Consequently, the data exchange between the two coupled softwares is made in the post-convergence to the current BES model time step during which the HAM model is solved in COMSOL with a finer time step. The diagram in fig. 1 summarizes the temporal synchronization approach between the BES model in TRNSYS and the HAM model in COMSOL. The difference of the time step between the two models is justified by the different of hygrothermal transfer kinetic in wall and internal ambience that directly affects the dynamic behavior of coupled models. The time step Δt_{BES} used in TRNSYS is 1 hour. This value is common in buildings dynamic simulation. Furthermore, the time step used in the HAM model implemented in COMSOL, was determined according to the studied wall type and composition agreeing to heat and mass transfers kinetics in the wall under the imposed thermal and hydric solicitations.

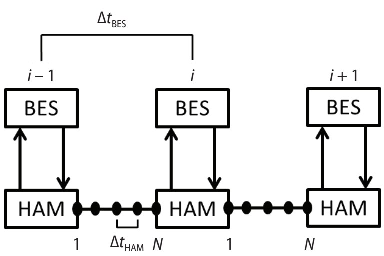

Figure 1. Temporal synchronization strategy

The transferred data from the BES model (TRNSYS) to the HAM model (COMSOL) correspond to external and internal boundaries conditions of the envelope. These boundary conditions are the outside weather data and the ambient hygrothermal conditions of the building inside. The initial conditions of the HAM model correspond to temperature and moisture profiles stored by the integrator tool (MATLAB) for current BES time step at the end of the previous BES time step.

Moreover, at each time step convergence, Δt_{BES}, heat and moisture flux transported by the envelope to the inner ambience and calculated by the HAM model are transferred to the BES model. These flows are identified in TRNSYS as thermal and moisture gains. It is noted that the transmitted heat gain used in the BES model is corrected upstream, in the integrator tool (MATLAB). This is done to take into account the conduction heat gain of the wall already calculated in TRNSYS. Figure 2 shows the data exchange strategy between the two BES and HAM models each global time step Δt_{BES}.

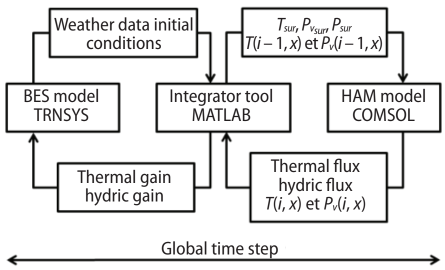

Figure 2. Data exchange strategy

Figure 3 illustrates the established co-simulation process and developed coupling strategy between BES model represented by TRNSYS and HAM model implemented in COMSOL.

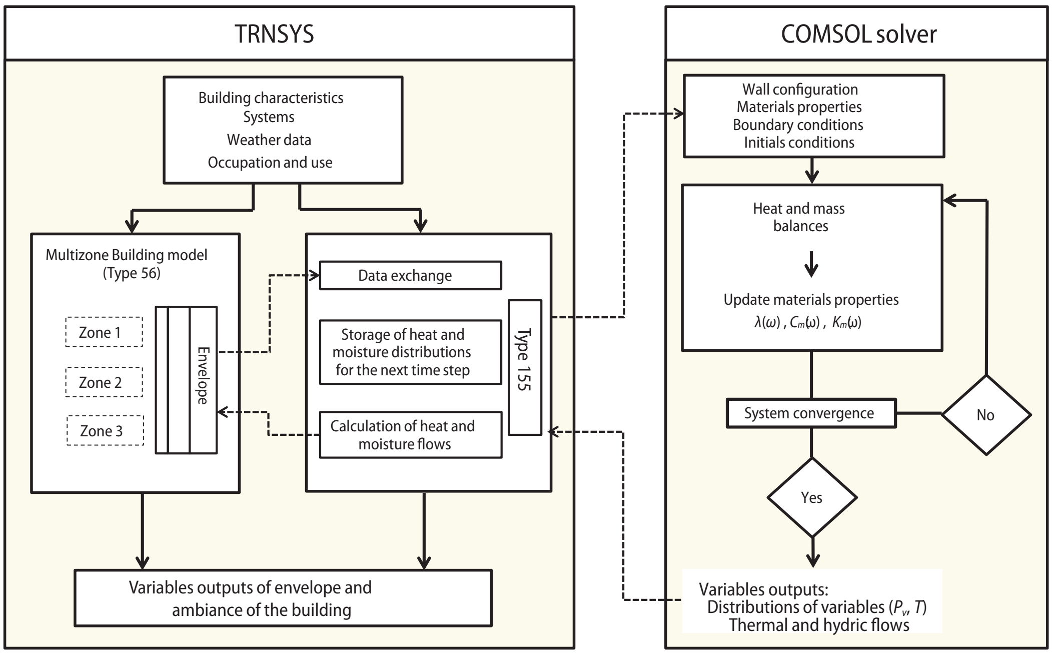

Figure 3. Diagram of HAM-BES co-simulation process

The HAM-BES co-simulation validation

In order to verify the correct functioning of the HAM-BES co-simulation in a realistic configuration, an experimental validation was conducted by comparing the HAM-BES coupled model with experimental data extracted from the test results published by the International Energy Agency – IEA, Paris, as part of Annex 41.

In this validation, the EC3 experimental test of Annex 41 was considered. This test was carried out by the Fraunhofer Institute for Building Physics in Germany [9]. The test was performed in a room with volume of 50 m^3 and a wall surface of 67 m^2 (without floor, door and window). The wall is constituted of 240 mm of brick with 70 mm of outer polystyrene insulation layer and 12 mm of plaster as an inner coating. A double glazed window with 1.41 × 1.94 m² dimension was included in the south wall. The room is equipped with a thermal control system, ventilation, and a humidity generator. This test was performed with a constant ventilation of 0.6 L/h air exchange rate. To simulate, a moisture production of three people in the room, a moisture supply scenario was imposed on a basic production of 25 g/h with a maximum of 400 g/h between 6 a. m. and 8 a. m. and 200 g/h between 16 hours and 22 hours, fig. 4. The details of the experiment are mentioned in the final report of Annex 4 [10].

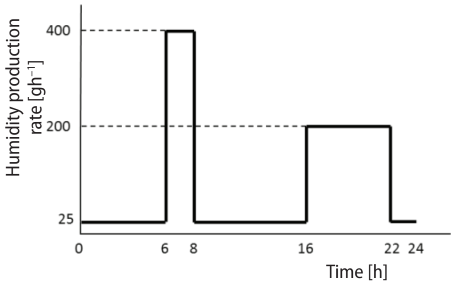

Figure 4. Humidity production scenario

To consolidate the validation process, the present model is also compared to the numerical simulation proposed by the model of Qin *et al.* [11].

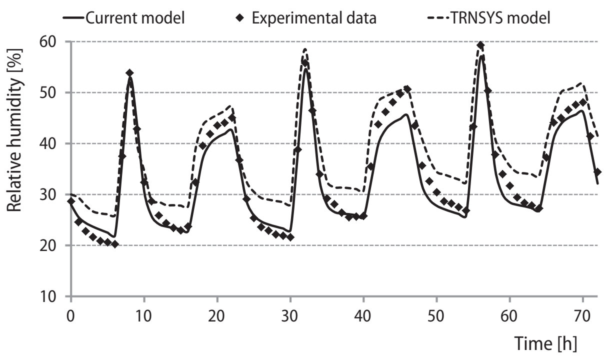

Figure 5. Comparison of numerical simulation of HAM-BES model and experimental data of annex 41 (January 17-19, 2005)

Figure 5 shows a comparison between experimental data and numerical simulations of the present model and that of Qin *et al.* [11] for the period of January 17-19, 2005. The confrontation shows a good agreement between the experimental results and the numerical prediction obtained by the coupled HAM-BES model. The difference between the present model and that of [11] is due to the resolution method. Indeed, Qin *et al.* [11] solve simultaneously the two models HAM and BES, whereas in the proposed model the numerical resolution is made separately.

Case study

After validation, the developed HAM-BES co-simulation platform was applied to analyze 1-D and 2-D wall hygrothermal transfer modeling on thermal and hydric behaviors of inside air building, as well as its energy consumption. For this purpose, a case study was carried out by considering experimental building test used for the HAM-BES co-simulation platform validation described in preceding paragraph.

To highlight the external condition effect, the case study was conducted for three different climates: oceanic climate of La Rochelle, hot and humid climate of Hong Kong, and cold humid climate of Berlin. In this study, three dynamic simulation approaches were considered, details of the simulation cases are summarized in tab. 1

Table 1. Description of simulation cases

Climate case	Simulation case
Case A. La Rochelle	1 – TRNSYS dynamic simulation model
Case B. Hong Kong	2 – TRNSYS model + 1-D HAM model for envelope
Case C. Berlin	3 – TRNSYS model + 1-D HAM model (envelope) + 2-D HAM model (thermal bridge)

The first simulation case is the dynamic building simulation model proposed by TRNSYS with a simple thermal conduction for the wall and a linear correction term to take into account of heat flux contribution of thermal bridge. This coefficient is determined according to European standards EN-ISO 14683 [4]. Concerning moisture transfer, effective capacitance humidity (ECH) model was considered. In this model, the buffering effect of adsorption and desorption of the envelope is represented by an effective moisture capacity defined as the product of air mass and a moisture capacity ratio. In this model temperature and humidity conditions at the surface of the buffer layer is identical to hygrothermal conditions in the inside air.

For the second simulation case, the thermal conduction in the wall and ECH model proposed by TRNSYS were substituted by a 1-D coupled HAM transfer model developed in this work. For this case, main hygrothermal phenomena are considered: heat and moistures sources and sinks inside a building, thermal and hydric flows from the wall, water vapor adsorption/desorption at the inner and the outer envelope surfaces.

In the third model, in addition to 1-D hygrothermal transfer model for walls, multidimensional effects were considered by modeling hygrothermal transfer in 2-D with finer granularity, see fig. 6. This multidimensional modeling is applied to thermal bridges (upper corners of the building where materials with different hygrothermal properties are installed in non-parallel layers).

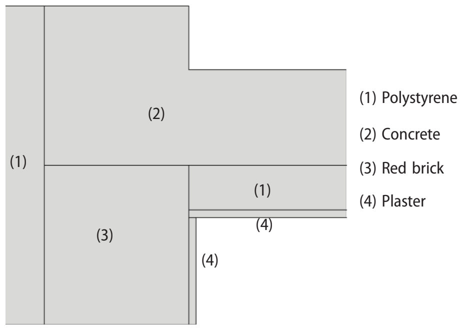

Figure 6. Composition of studied thermal bridge (vertical section through an exterior wall/floor deck intersection)

The simulation cases described in tab. 1 were conducted for both winter (January) and summer (August) periods with hygrothermal control systems (heating and cooling). The set point temperature was fixed at 18 °C in winter and 26 °C in summer. For the relative humidity, the comfort zone between 35% and 65% was imposed for the two seasons.

Effects of hygrothermal transfer on building energy consumption

The hygrothermal transfer at the envelope building (1-D for the wall and 2-D for thermal bridge) has a significant impact on the indoor building environment. In addition, consideration of this phenomenon in dynamic building simulation has a considerable effect on the prediction of the energy consumption. However, there is little work in this sense [12]. Among carried out studies, Qin *et al*. [13] who have analyzed the effect of hygrothermal air-flow transfer on building energy consumption. In this section, our study extends, in addition to hygrothermal transfer impact of envelope, to a multidimensional effect by modeling the hygrothermal transfer phenomenon in 2-D for thermal bridges.

The energy consumption was calculated for the studies climates carried out in the previous section for the three studied simulation cases, see tab. 1.

Figures 7, 9, and 11 summarize energy needs of heating (January) and cooling (August) for climates of La Rochelle, Hong Kong, and Berlin. The heat flow gains from the envelope to the internal air are represented for the three studied climates in fig. 8, 10 and 12.

In the heating season, the prediction of the energy consumption of TRNSYS model is lower than the two other models where hygrothermal transfer through envelope is included. The underestimation of heating needs is observed for different studied climates. Difference between

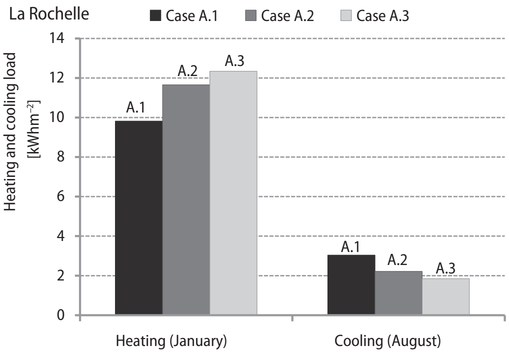

Figure 7. Energy consumption (heating and cooling) in the temperate climate of La Rochelle

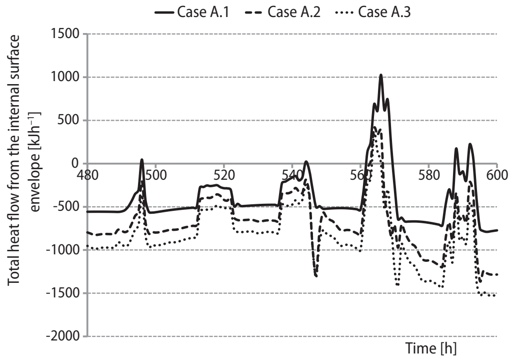

Figure 8. Total convective heat flow from the internal surface envelope for the winter period (January 20-25) for La Rochelle climate

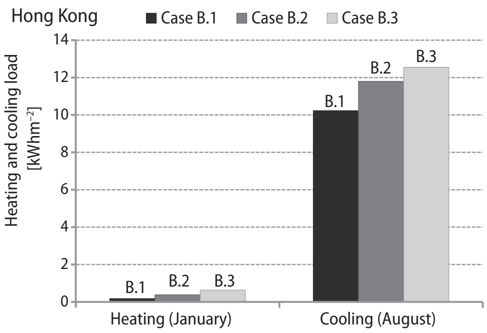

Figure 9. Energy consumption (heating and cooling) in hot and humid climate of Hong Kong

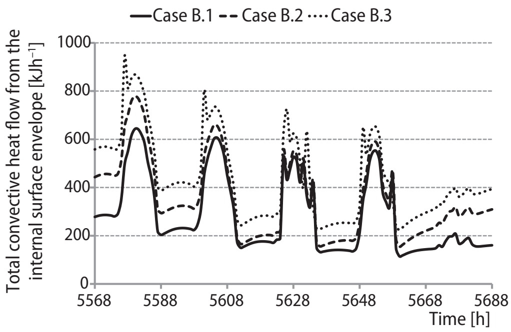

Figure 10. Total convective heat flow from the internal surface envelope for summer and winter periods for Hong Kong climate

TRNSYS model and the one that take into account of 1-D hygrothermal transfer reaches 28% for temperate climate of La Rochelle, 12% for Berlin, and 25% for Hong Kong.

This significant underestimation, in heating energy consumption for TRNSYS model, highlights the importance of considering coupled HAM transfer modeling in dynamic building simulation. Indeed, heat outflows from indoor (cold outdoor condition in winter) are more important, this phenomenon is clearly illustrated in figs. 8, 10, and 12 that show the important gap of heat less flow from the internal zone between TRNSYS model and the two other simulation cases. These results explain the difference in heating loads observed in this case study.

In fact, when the coupled HAM transfer is considered the variation of thermal conductivity according to material humidity state accelerates the heat flow kinetic. This phenomenon caused the heat loss that involved more direct energy consumption. When the hygrothermal transfer modeling is performed in 2-D for upper thermal bridges, the difference of heating load is more important compared to TRNSYS model.

The underestimation reached 36% in La Rochelle climate, 11% for Berlin, and 33% pour Hong Kong. This result is explained by consideration of the multidimensional effect of hygrothermal transfer in the thermal bridges modeling where heat losses become more important, see figs. 8, 10, and 12.

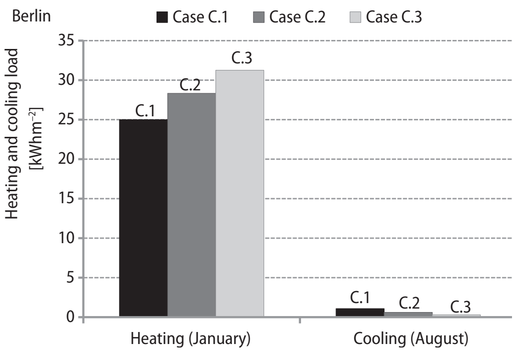

Figure 11. Energy consumption (heating and cooling) in cold and humid climate of Berlin

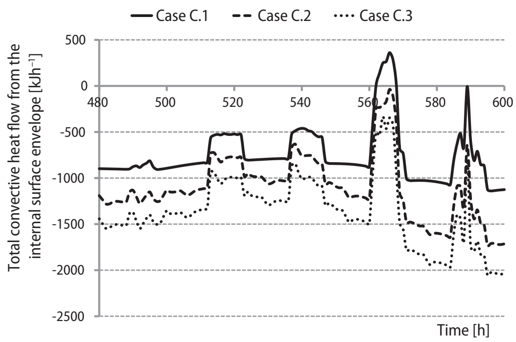

Figure 12. Total convective heat flow from the internal surface envelope for the winter period (January 20-25) for Berlin climate

Conclusions

The coupled HAM transfer through the envelope has a significant impact on the hygrothermal indoor behavior and energy consumption. In this work, hygrothermal transfer model in multilayer wall was established. This phenomenon is modeled in 1-D for the wall and 2-D for thermal bridges to take into account of multidimensional hygrothermal transfer effect of this envelope element.

In order to illustrate the influence of wall hygrothermal transfers consideration on prediction of building energy consumption, HAM-BES co-simulation platform was developed. This approach consists of combining two simulation tools: one for wall hygrothermal transfer modeling (COMSOL), the other for dynamic building simulation (TRNSYS). The advantage of this platform is a dynamic connection between both HAM and BES models. In this way, the continuous interaction between envelope and indoor hygrothermal environment is ensured.

After proceeding to an experimental validation of the HAM-BES dynamic co-simulation platform, a case study was carried out. In the simulations cases, studied building was exposed to three different climates. Results showed that the consideration of wall hygrothermal transfer has an important impact on prediction of building energy needs. Indeed, taking into account the wall hygrothermal transfer allows to introduce some phenomena (moisture diffusion, water vapor adsorption/desorption, thermal convection, and latent heat transfer) that are not considered in most dynamic building simulation tools.

Results showed as well the effect of hygrothermal multidimensional transfer modeling in thermal bridges which involve additional wall heat, and moisture flows in indoor mass and energy balances. For this reason, modification of the building energy demands is noted.

The case study conducted in this paper illustrates also the high influence of climatic condition on indoor hygrothermal behavior of buildings and its energy consumption.

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Nomenclature

C_a – humid air storage capacity, [s^{2}m^{-2}]
C_p – heat capacity, [Jkg^{-1}K^{-1}]
C_m – storage moisture capacity, [kgkg^{-1}Pa^{-1}]
h_c – heat convective exchange coefficient, [Wm^{-2}K^{-1}]
h_l – liquid specific enthalpy, [Jkg^{-1}]

h_m – mass convective exchange coefficient, [kgm^{-2}s^{-1}Pa^{-1}]
k_m – total moisture permeability, [kgm^{-1}s^{-1}Pa^{-1}]
k_T – non-isothermal moisture transfer coefficient, [kgm^{-1}s^{-1}K^{-1}]
k_p – moisture infiltration coefficient, [kgm^{-1}s^{-1}Pa^{-1}]
L_v – evaporation latent heat, [Jkg^{-1}]
P – total pressure, [Pa]
P_v – water vapor pressure, [Pa]
$P_{v_{sat}}$ – saturated vapor pressure, [Pa]
T – temperature, [K]
t – time, [s]

Greek symbols

λ – thermal conductivity, [Wm^{-1}K^{-1}]
φ – relative humidity, [%]
ρ_s – dry material density, [kgm^{-3}]
ω – moisture content, [kgkg^{-1}]

Subscripts

i – layer position in the wall from the outside to inside

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