Integrated Hygrothermal Performance of Building Envelopes and Systems

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ABSTRACT

Many recent, moisture-originated failures in low-rise residential and high-rise residential/commercial buildings have put a significant pressure to change construction codes in North America and Europe. However, solutions to moisture induced problems may be difficult when several interacting mechanisms of moisture transport are present. Recently, a new approach to building envelope durability assessment has been introduced in North America. The approach employs moisture engineering, which requires system information about the wall systems as constructed or with aging characteristics coupled with advanced modeling to predict the long-term performances of building envelope systems. This permits the comparison and ranking of individual building envelope systems with respect to total hygrothermal performance.

While critical information can be obtained by investigating the one to one relationships of a building envelope to interior and exterior environments, the total behavior of the actual whole building is not accounted for. This paper goes one step further, by incorporating the individual hygrothermal performances of all walls, roof, floor and mechanical systems. The direct and indirect coupling of the building envelope and indoor environment with HVAC system are included in the analysis. The full house hygrothermal performance of an aerated concrete wall system are examined for a hot and humid climate. The hour by hour drying potential of each system was then numerically analyzed using real weather conditions of Miami. The results clearly demonstrated the limited drying potential for the wall system in that climate. Furthermore, the selected exterior thermal insulation strategies and interior vapor control strategies in this study clearly show the critical behavior of the full house with respect to drying initial construction moisture. The results show the importance of the total hygrothermal behavior of the whole house to the coupling between the various envelope parts, interior and exterior environments and HVAC system. From these results moisture control strategies are identified for the whole house hygrothermal performance.

1. INTRODUCTION

Moisture transport through a building envelope influences not only the durability, indoor air quality, health and safety of the inhabitants, but also the energy efficiency of the envelope system. The influences of moisture transport are experienced differently in lightweight (hygroscopic) or heavy weight (moisture massive) building envelope systems. Many recent, moisture-related failures of wood frame construction in low-rise residential and steel frame in high-rise residential / commercial buildings have put a significant pressure to change construction codes in North America. Indeed a recent failure of a moisture massive envelope systems (School Building) (Gu, 1998) (composed of aerated concrete blocks in Florida, clearly demonstrates the need for proper moisture control analysis of building systems. However, solutions to moisture induced problems may be difficult to achieve when several interacting mechanisms of moisture transport are present. Moisture can exist in three phases, vapor, liquid and solid phase (ice). During transition moisture can change phases by evaporation, condensation, sublimation, freeze and thawing transport mechanisms. Research is continuously upgrading existing understanding on these complicated issues.

Recently, a new approach to building envelope durability assessment has been introduced, and is becoming an acceptable norm in North America. The approach employs experimental and advanced modeling analysis to predict the long-term performances of building envelope systems to various levels of interior and exterior environmental loading. This permits the comparison and ranking of wall systems with respect to an overall hygrothermal performance. Elaborate experiments are conducted to measure the various hygrothermal properties such as sorption and suction isotherms, vapor permeabilities, liquid diffusivities, and drainage which are then complimented with full scale laboratory building envelope testing to determine system and sub-system performances. Modeling is then initiated to predict the hygrothermal performances of the individual building envelope part. This approach has been termed as Moisture Engineering (Trechel 1998, Karagiozis, 1997b).

Further advances in the area of moisture engineering are currently been achieved by taking a broader wholistic approach to moisture design. In most applications, building envelope designers attempt to predict the hygrothermal performance of an individual building envelope, for example a wall, roof or basement by uncoupling the system not only to the interior environment but the interactions of the other envelope components to both the exterior and interior environments. This one to one interaction of a small part (section of a wall system perhaps) of a building is termed today as state-of-the-art. The stand-alone analysis of specific envelope parts is important in understanding the influences of various controlling elements (vapor retarder, air barriers, building papers) in terms of their effect on the hygrothermal performance of the envelope, but provide limited performance information on the overall heat and mass transfer of a building.

Further advances (the subject of this paper) in the area of moisture engineering are currently been achieved by taking a broader wholistic approach to moisture design. An iterative open loop approach of complete hygrothermal analysis of a building is demonstrated which requires the direct coupling of all building envelope systems with the interior environment and mechanical systems (HVAC) and the exterior environmental loads.

In this paper, the authors present a new model and approach to wholistic moisture engineering analysis. This paper demonstrates this approach by employing advanced moisture engineering modeling. An application of this wholistic moisture engineering approach is performed to quantify the drying performance of an aerated concrete block building. All building elements, such as the walls, roofs are included in the analysis. The source of water considered is due to the initial construction moisture in the aerated concrete block. The study will attempt to shed some light in some of the issues present in the integrated moisture performance of a complete building.

2. OBJECTIVES OF PRESENT STUDY

The present work is concerned with the hygrothermal performance (drying potential) of a particular aerated concrete block home subjected to two selected vapor diffusion control strategies. The objective of the work was to determine the long-term hygrothermal performance of the building to various vapor control and thermal insulation strategies while subjecting the exterior boundary to real weather data (including temperature, vapor pressure, wind speed and orientation, solar radiation, sky radiation, cloud indexes and rain). A wholistic approach is employed by using moisture engineering principles that integrate, intensive numerical analysis and accurately defined material property measurements. The weather data used in this study analysis are representative of a hot and humid-climate found in the south east coast of United States (FL).

3. VAPOR CONTROL THEORY

Moisture entry into the wall structure can be caused mainly by five processes: initial construction moisture, vapor diffusion, liquid diffusion, water leakage and moist air leaking inward or outward (being more important for cold climates) through the building envelope. The present study is concerned with moisture transport due to vapor and liquid diffusion throughout the wall. Moisture transport by diffusion occurs under the influence of a vapor pressure or moisture content (capillary suction pressure) gradient acting across the wall structure. The rate of moisture flow is dependent upon the magnitude of the vapor pressure gradient and the vapor permeances as well as suction pressure and hydraulic conductivity of the component layers of the wall assembly. Additional factors of significant importance are the overall integrity of the building material (i.e. cracks and openings), the interface contact and surface moisture resistances, but have not been included in this analysis. In general, for a given permeable structure the greater the vapor pressure difference across a wall assembly, the greater will be the rate of diffusion. To control this moisture flow into the wall structure, vapor barriers have been devised. Vapor barriers are materials or systems which adequately retard the transmission of water vapor across the wall assembly, offering a high resistance to the diffusion of water vapor. Due to the higher indoor relative humidities, especially in hot and humid climates, de-humidifiers are used for increased levels of human comfort and vapor barriers are incorporated near the warm side of the wall structure. It is generally advocated as a safe design principle since the entry of moisture is restricted closer to the source over a longer period of time during the year , which is the exterior in this study. This is generally true for climates that are designated as hot and humid. The application, location and selection of the vapor retarders is strongly dependent on wall design (whether or not special buffer zones have been provided) and on climatic conditions. However, only a limited number of studies exist that have integrated both the vapor and liquid transport performance of building systems including the effects of wind-driven rain see [Salonvaara and Karagiozis, 1998].

4.MATERIAL-PROPERTY DETERMINATION

Hygrothermal material properties for aerated concrete and interior and exterior stucco were extracted from a paper presented by one of the authors [Karagiozis, 1997a].

Water Vapor Permeance and Liquid Diffusivity

The water vapor transmission characteristics of aerated concrete, and interior and exterior stucco layers were determined according to the modified ASTM E96 Test Method for Water Vapor Transmission of Materials [Karagiozis, 1997a]. Four different sets of relative humidities were used as boundary conditions in order to determine the dependence of vapor transmission characteristics as a function of relative humidity. The properties for the liquid diffusivity were also measured using a gamma-ray spectrometric method [Karagiozis, 1997a], and these were included in the numerical analysis.

5. DESCRIPTION OF THE MODEL

A new model, developed by the authors provided a structured framework allowing the integration the individual heat, air and moisture performances of various oriented walls systems and roof assemblies, by lumping the building dependent geometries to the interior and exterior environment as well as the mechanical equipment of the building. The open modular structure of this building envelope moisture engineering model allows outputs of any hygrothermal model to be assembled and incorporates a feedback loop control, such that thermal and moisture fluxes are directly included in the indoor air conditioning model. Moisture models such as MOIST [Burch, 1993] WUFI, [Kunezel 1995] and LATENITE, [Salonvaara and Karagiozis, 1994] can be included in the analysis.

6. PROBLEM DESCRIPTION

The hygrothermal performance (drying potential) of an aerated concrete block home as depicted in Figure 1 was analyzed with two different interior vapor control strategies. The house was rectangular in cross section (15 x 20 m) and the roof was inclined at 20 degrees. Windows and doors occupied the approximately 20 % of the exterior building surface, and were represented with U-value thermal performances of 2.0 W/m^{2}K. The roof consisted of 300 mm mineral wool insulation with polyethylene vapor/air retarder and gypsum board on the interior side.

Two additional cases were simulated; one with 25 mm expanded polystyrene installed on the exterior of the building and the other without the insulation. This was conducted to determine the influence of exterior insulation (thermal performance) on the drying performance of the building.

The walls were composed of the following layers starting from the exterior to interior: a 12.5 mm exterior grade acrylic stucco, a 198.4 mm aerated concrete block and a 6.35 mm interior gypsum plaster. The inside surface of the gypsum plaster was coated with a vapor open paint (permeance approximately 200 ng/m^{2}sPa or 4 perms). Variations of this wall consisted of the cases with a 6-mil polyethylene membrane installed in the interior side of the wall and without this vapor control. The aerated concrete was initially assumed at 22 % moisture content. This represents a very wet initial moisture condition in the aerated concrete layer. All other layers in the wall system were assumed to be in equilibrium at 80 % relative humidity.

Wind driven rain water was included in the analysis, the exterior surfaces were exposed to the amount of rain that typically hits a vertical wall. This amount depends on the intensity of precipitation, wind speed and wind direction as well as the location on the wall surface [Karagiozis and Hadjisophocleos, 1995].

The wall was exposed to outside air temperature, relative humidity, wind speed and orientation and rain precipitation that varied hourly according to the weather data from the selected location (Miami). The simulations were carried out for a three year exposure starting on the 1st of August. The solar radiation and long wave radiation from the outer surfaces of the wall were included in the analysis. In this study, no air infiltrating or exfiltrating was considered; therefore the primary mode of water transmission is due to diffusion processes, both vapor and liquid transport. For the simulations of the wall and roof assemblies the LATENITE 3.0 VTT [Salonvaara, 1998] version was employed for all simulations, and LATENITE simulations were performed at VTT.

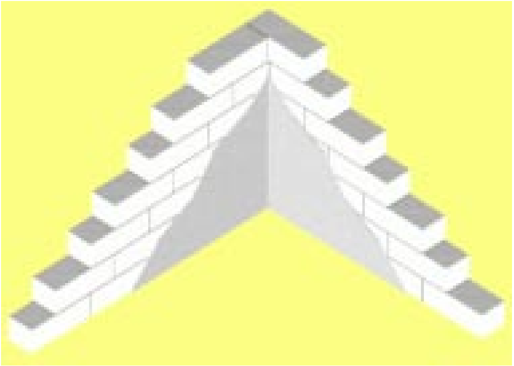
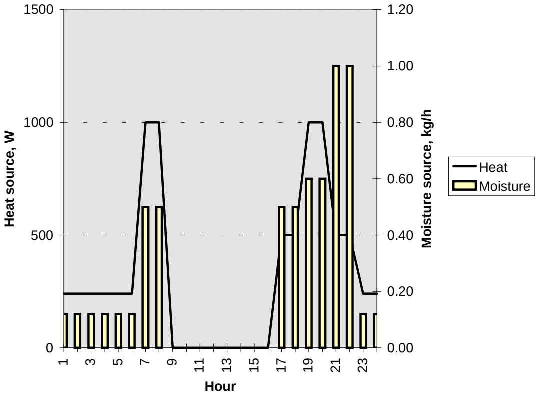


Figure 1--The analyzed wall structure in detail 12.5 mm exterior grade acrylic stucco, a 198.4 mm aerated concrete block and a 6.35 mm interior gypsum plaster. The inside surface of the gypsum plaster was coated with a vapor open paint (permeance approximately 200 ng/m^{2}sPa or 4 perms). (Courtesy of Jan Kosny [1999])

7. BOUNDARY CONDITIONS

Internal conditions were analytically resolved by the transport of moisture and heat through the wall systems and the mechanical heating and air conditioning controls. The interior inhabitants were also modelled as heat and moisture sources and sinks, by allowing daily variations of thermal and moisture production and dissipation (allowing the inhabitant to open a window when a certain set-point interior temperature was reached (24 C). A typical 24 hour schedule is depicted in Figure 2 for a 2 adult and 2 children household [Salonvaara, 1998a]. The interior space was dehumidified, and a 0.3 air change per hour was assumed for air quality purposes. The US National Climatic Weather Center [1995] data for Miami during the years 1961-1963 were used in the simulations. The 1961 yearly average temperature and vapor pressure in Miami is 24.2 °C, and 2225 Pa, respectively.

A rectangular building (15 x 20 m) was modeled, the heat and mass transfer coefficients for external and internal surfaces were variable depending on the temperature, the wind speed and orientation (only the for the exterior surfaces). The Lewis relationship between heat and mass transfer was assumed. The heat and mass transfer coefficients for the exterior were assigned values that varied from hour to hour depending on the exterior weather conditions



.Figure 2. Heat and moisture sources in the building at various times of day. Daily heat and moisture sources total 7.9 kWh and 6.1 kg.

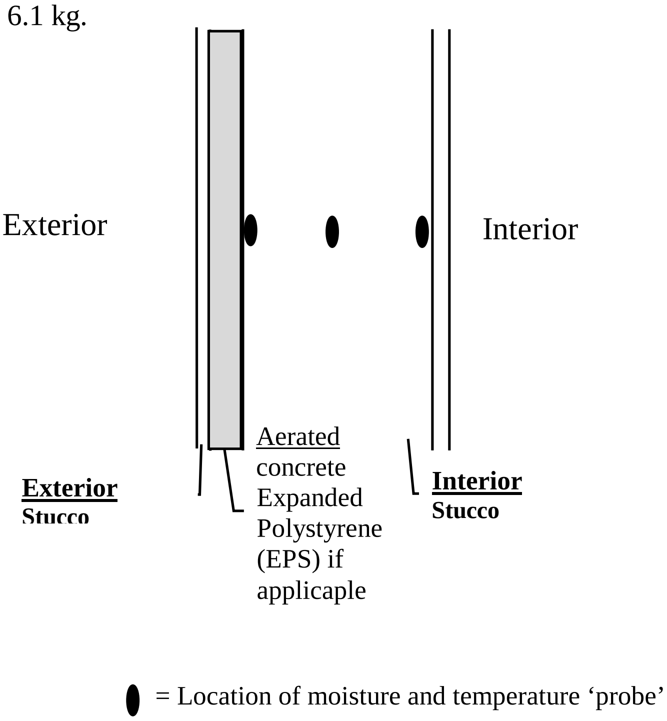


Figure 3.—The graphical layout of the parametric cases (Positioning of numerical moisture and temperature probes)

8. SIMULATION RESULTS

Figures 4 and 5 show the heating , cooling and dehumidifying behavior of the building for various conditions. The building was equipped with a heating and cooling system that turned on heating if the temperature fell below 20°C and cooling if the temperature rose above 22°C. Naturally in the climate of Miami the cooling demand is more prevalent. As the amount of cooling hours required in Miami is higher than that of heating, the cooling system had a drying effect on the indoor air if the relative humidity was above 50%. The dehumidifying effect was relative to the difference between vapor pressures in the indoor air and the reference vapor pressure (50% at room temperature). Figure 5 shows the significant effect of dehumidification required for various interior temperatures and vapor pressures, it becomes evident that the climate of Miami is both hot and humid.

In Figure 6, the moisture content in the wall systems as a function of time is presented to show the relative hygrothermal performance of the aerated concrete walls for two orientations (North and South) using two different vapor control strategies (with and without and interior vapor retarder). Results are shown for the wall systems that employed an exterior insulation of 25 mm expanded polystyrene. The simulations start from the first day of August (1961) for a period of three years. The three monitor points within the aerated concrete as depicted in Figure 3 are plotted out. The slowest drying is exhibited by the wall that included the 6-mil polyethylene vapor retarder. Indeed the case that did not incorporate the vapor retarder dried to a moisture content of 0.05 nearly 8 times faster than the vapor retarder case. Minimal differences are observed between the south and north facing walls. As Miami is closer to the equator than say, Helsinki, north and south walls behave similarly because the solar angles (high), and the highest intensity of the sun per day comes to the east and west walls. From this figure, it becomes apparent that the preferred drying mode of this wall system in Miami is primarily towards the interior. However, for higher inside relative humidity, the drying potential of the overall wall system will be substantially reduced.

Figure 7, shows similar building conditions, but without any exterior insulation. The same three monitor points within the aerated concrete as depicted in Figure 3 are plotted out. The slowest drying is exhibited by the wall that included the 6-mil polyethylene vapor retarder. Indeed the case that did not incorporate the vapor retarder dried to a moisture content of 0.05 nearly 2.5 times faster than the vapor retarder case. Slightly higher differences are observed between the south and north facing walls, than the case with exterior insulation. As the building is exposed to larger exterior environmental loads, larger seasonal fluctuations are observed. Furthermore, as Miami is closer to the equation than say, Helsinki, north and south ways behave similarily because the solar angles (high), and the highest intensity of the sun per day comes to east and west walls. Comparing figures 6 and 7, it becomes apparent that exterior insulation retards the drying performance of the building envelopes.

Figure 8 depicts the transient total moisture mass present in the aerated concrete building as a function of time. Results are shown based on the wholistic moisture engineering approach described earlier in the paper. It is clear that the direct coupling of the interior environment and the building envelope parts can correctly represent the drying performance of the building. It is evident that interior vapor control and exterior insulation strategies for this particular building reduces the overall drying performance of the building. Furthermore, a significant amount of water is present in the building, which requires several years to dry out.

Figures 9 and 10 show the interior temperature and dehumidification requirements for the building for a period of one day. Daily diurnal cycles are clearly shown, and a peak load for cooling and dehumidifying the building is depicted. Humid fresh supply air drawn into the building from the exterior dominates in the dehumidifying scene which can be seen clearly by comparing the cases with and without vapor retarder in Figure 11. During the first month August) the demand for dehumidifying is increased by approximately 20% due to moisture diffusion from the building envelope (inward drying).

Figure 11 shows the dehumidification of indoor air, as a function of monthly amounts. Results show that the EPS insulation did not make any difference in the monthly averaged results. The simulation results for buildings that employed a vapor retarder are on top of each other, and similar results are demonstrated without the use of the vapor retarder.

9. CONCLUSIONS

Vapor diffusion control and insulation strategies have a significant effect on the hygrothermal performance (drying potential) of aerated concrete wall block buildings in hot and humid climates. This study, which included the effects of vapor transport, liquid transport found that the use of a tight interior vapor control may not be beneficial to drying the initial construction moisture in hot and humid climates. The results showed slow drying even for the no-retarder case as the drying potential for climatic conditions of Miami are not very favourable.

Exterior insulation strategies applied in aerated concrete wall systems, have some thermal benefit but significantly reduce the drying performance of aerated concrete buildings with high initial construction moisture. Indeed several years, 3 to 10 years depending on the parametric cases examined in this study may be required to dry out the initial moisture of the aerated concrete blocks in weather conditions of Miami. This may require that the interior finish (paint, wallpaper, wood, etc.) must have certain moisture properties or otherwise the interior surfaces may only be coated after the initial moisture has sufficiently dried out in order to avoid moisture related problems, such as mold growth for example, that may appear after some weeks or even later after several months. The processes leading to these problems may have been initiated by the initial moisture.

The proper combination of interior and exterior vapor control and insulation control must be employed, as demonstrated in this study. If buildings are equipped with air conditioning equipment, moisture transport from the interior can be regulated. Additional research is needed to determine the critical range of interior climatic conditions that owners of the building must adhere to. Buildings, must be designed to accommodate some form of synchronised moisture control that utilizes drying towards the interior as well as the exterior. Aerated concrete walls that incorporate such features can be developed with substantially higher moisture load tolerances for any climatic region, without necessarily requiring special cavities or other expensive changes in design.

Today, by effectively employing wholistic moisture engineering analysis, integrating material properties, system and sub-system performances (lab and field studies) and advanced modeling building envelope systems can be optimally designed. Advanced hygrothermal modeling is an efficient means to develop engineered construction products, similar to other high-tech industries such as aerodynamics, automotive and even the electronic fields.

The results provided in this paper are only applicable to the specific materials, wall specifications and weather conditions employed. Further work is needed to characterize the effects of defects in the exterior surface or possible moisture infiltration or exfiltration from the interior or exterior environments.

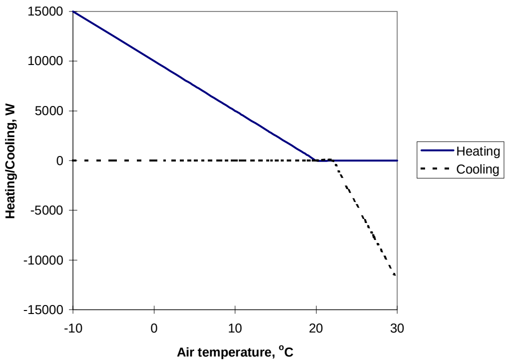


Figure 4. Maximum heating and cooling as a function of temperature. In x-axis outdoor air temperature for heating and indoor air for cooling. Heating is reduced linearly as indoor temperature rises from 20 to 22 °C.

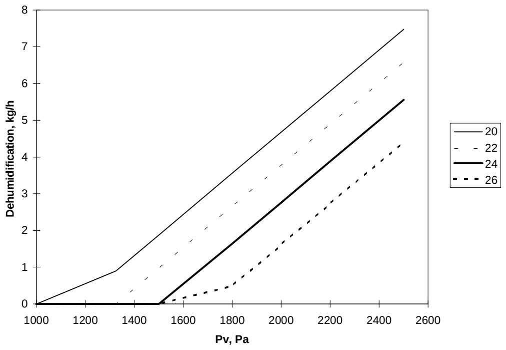


Figure 5. Dehumidification as a function of interior air vapor pressure (x-axis) and interior air temperature (various curves)

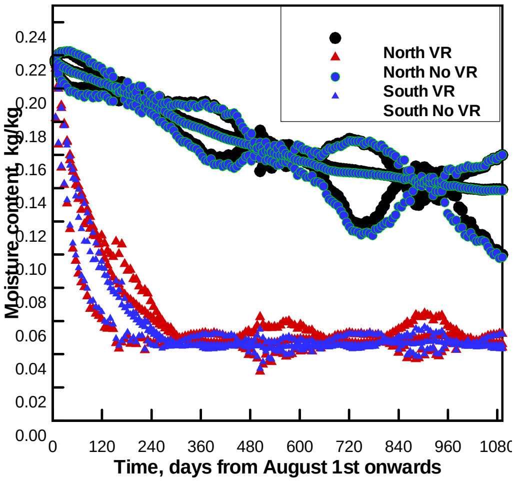


Figure 6. Moisture contents at three depths of aerated concrete layer for North and South facing walls. Walls with 25 mm exterior EPS insulation.

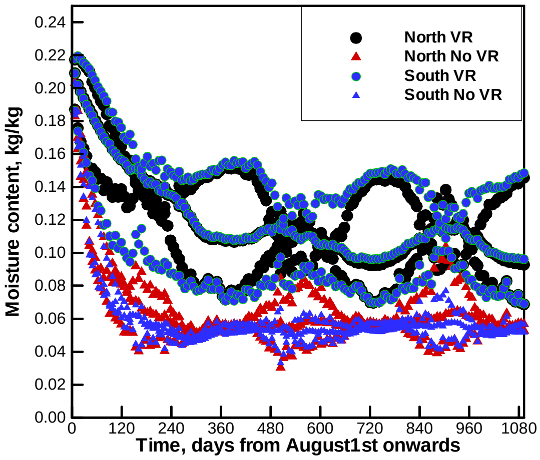


Figure 7. Moisture contents at three depths of aerated concrete layer for North and South facing walls. Walls without exterior EPS insulation.

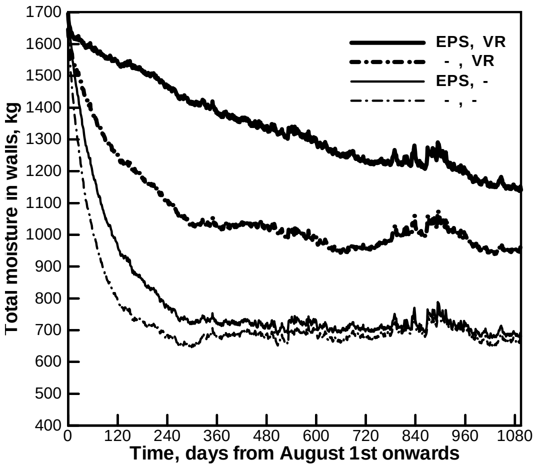


Figure 8. Total moisture content in the building envelope as a function of time (starting from August 1st).

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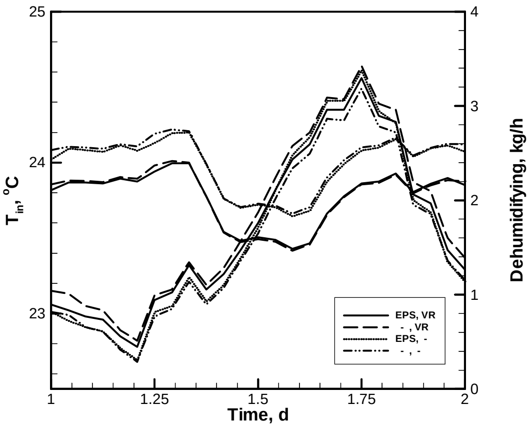

Figure 9. Indoor air temperature and dehumidification rate.

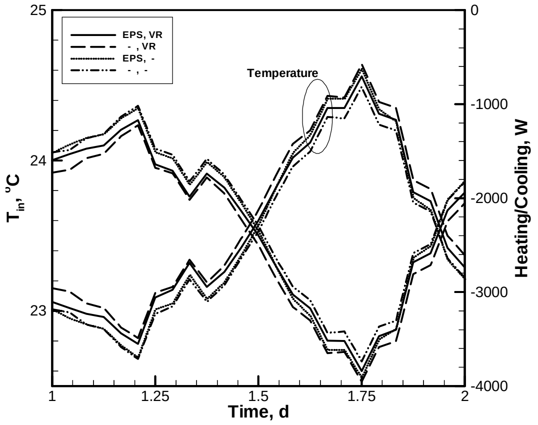

Figure 10. Indoor air temperature and heating/cooling

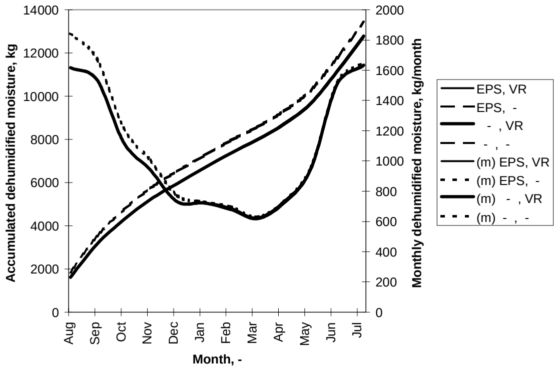

Figure 11. Dehumidification of indoor air: accumulated and monthly (m) dehumidified moisture.

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