INFLUENCE OF WIND-DRIVEN RAIN DATA ON HYGROTHERMAL PERFORMANCE

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ABSTRACT

The design choice for any wall system must be integrated with some moisture engineering analysis. Energy and durability analysis must go hand and hand to provide buildings with good service life performance.

Moisture engineering analysis has recently been performed to predict whether a particular wall system may survive repeated exterior or interior environmental loads, some of these loads may be intentional and some not. In wood elements mold growth may occur when high moisture content conditions are maintained within the material for a sufficient period of time favorable for biological activity. The appearance of mold in construction materials and the mechanics of mold growth are dependent on a multitude of factors, some not yet fully understood even among wood-durability experts. During the past few years better models have appeared that predict the transport of heat, air and moisture transfer. These models include the important transport processes which allow building envelope designers methods to predict the response of an envelope system to exterior and interior excitation. One of the most important of the exterior environmental loads are those imposed due to wind-driven rain. Indeed, these loads may be many times more important than those due to vapor and air convection transport. To date the wind-driven rain loads are possibly the least understood and they can influence the moisture and energy performance the building envelope the most.

In this preliminary study, the influence of time-averaging of the exterior wind-driven rain loading will be examined using advanced hygothermal modeling. The influence of one weather location was examined to determine the effect of local climate on the time-averaging effects on the envelope performance. Experimental data will be analyzed to provide the effect of rain profiling on the transient wetting dynamics of porous facades. Four time averaging step were employed at 5 min, 15 min, 30 min and 1 hour, and these were obtained from experiments. The response of the envelope wall system was evaluated by determining the hygrothermal performance of the structure to dry out as a function of various wind-driven rain profiles.

It is expected that the preliminary results from this critical parametric analysis will provide a very useful and fair approach for assessing building envelope wind-driven loads. For the wall cases examined, the choice of hourly weather data is an acceptable time scale for hygrothermal simulation in a defect free wall structure.

INTRODUCTION

In all climates, moisture plays an important role in the durability and performance of building enclosures. The design of moisture tolerant enclosures should involve the simulataneous consideration and balancing of the potentials for wetting, storage and drying.

Many recent, moisture-related failures of wood frame construction in low-rise residential buildings and steel frame construction in high-rise residential and commercial buildings have created 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 all simultaneously present. A new approach has emerged to assist in the design of building envelope durability assessment, which employs a combination of experiments and advanced modeling to predict the long-term performance of building envelope systems. This approach that employs the use of advanced modeling with state of the art inputs such as material level and sub-system level material layer in addition to interior and exterior environmental loads is termed as *Moisture Engineering* (Karagiozis, 2001 ASTM). This integrated approach is visually depicted in Figure 1.
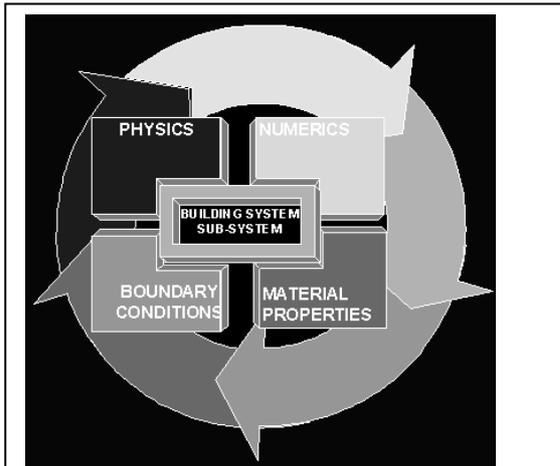
Figure 1: Integrated Moisture Engineering Approach

In a recent ASTM publication (Karagiozis, 2001: Treschel Editor), a elaborate classification of numerical tools used to simulate the transport of Heat-Air-Moisture (HAM) in buildings was presented. A critical element in the design of wall systems is prescribing the exterior and interior environmental loads. Exterior hygrothermal environmental loads are those that directly influence the transport of moisture and are:

1) Ambient Temperature,
2) Ambient Relative Humidity
3) Solar Diffuse
4) Solar Direct
5) Cloud Index
6) Wind Speed
7) Wind Orientation
8) Horizontal Rain Precipitation

All of the these exterior loads affect the transport of heat and moisture in building enevlopes. However, in more than 90 % percent of building envelope wall cases the combination of wind-driven rain, that happens when rain precipitation co-exists with the presence of wind is always much more critical than most of the other exterior environmental loads. While this has always been the case, not until fairly recently with the ability to predict the transport of liquid wind driven rain in hygrothermal models such as TRATMO2 [Salonvaara, 1991], LATENITE [Salonvaara and Karagiozis, 1994], WUFI [Kuenzel, 1995] and MOISTURE-EXPERT [Karagiozis, 2001] did it receive the attention it deserved. An earlier application demonstrating the importance of including wind-driven rain analysis for brick veneer systems in Vancouver, B.C. is presented in Figure 2. Here the effect of including the exterior rain load in the hygrothermal analysis is

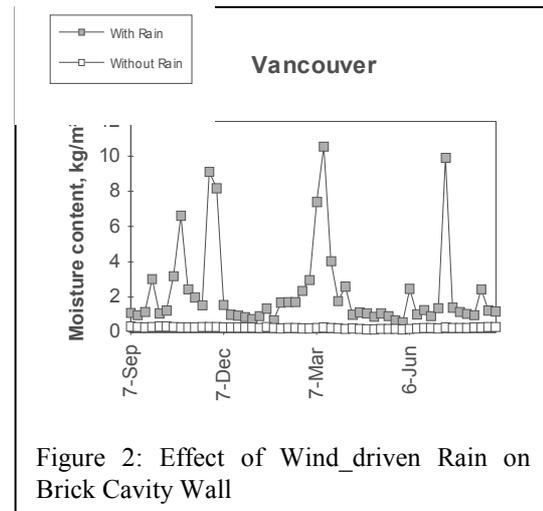clearly depicted by [Salonvaara and Karagiozis, 1996].

Figure 2: Effect of Wind_driven Rain on Brick Cavity Wall

Limited work has appeared in the literature to examine the effects of time averaging of wind driven rain loads. KORONTHÁLYOVÁ and MATIAŠOVSKÝ [2001], recently presented a study to determine the effect of time averaging, looking a larger intervals that a time step of 1 hr. In their study, they found that for an aerated concrete wall system, time step of 8 hours gave good agreement with experimental data.

The main reason for this particular investigation is to determine whether data from a longer or shorter time averaging period may be used to simulate the hygrothermal performance of building envelope systems. Currently almost all hygrothermal models employ wind-driven rain data at intervals of 1 hr, coinciding with the same time-step for all other weather parameters (temperature, relative humidity, cloud index etc.). Some of the questions that this preliminary paper will address are: Is a 1 hour time step acceptable for hygrothermal simulations ? Should a smaller one be used ? .
In this paper, the authors will first introduce a methodology for calculating the wind driven load, examine the magnitude of this load and then determine the influence of time-averaging for two constructions.

DESIGN RAIN LOADS ON WALLS
Previous research by Lacy [1965], Sanders [1996], Kuenzel [1994], Karagiozis and Hadjisophocleous [1998], and Straube [1998] have all developed approaches to determine the wind driven rain loads on building facades as a function of geometry, terrain, height of building, wind speed, wind direction and horizontal precipitation. These different approaches on averaged surfaces areas (not localized conditions) give results that vary up to 25 %. This difference at present is acceptable as

even the uncertainty of the experimental method methods for rain gauge measurement of wall impinging wind-driven rain can be more than -/+ 60 % [Hugo Hens Student, 2002].

One option of the empirical calculation approaches that can been used by various hygrothermal models such as WUFI [Kuenzel and Holm, 2000], WUFI-ORNL/IBP [Karagiozis, Kuenzel and Holm, 2001] MOISTURE-EXPERT [Karagiozis, 2001] and LATENITE-VTT [Salonvaara, 2001] is given below. This approach calculates the amount of wind-driven rain on a vertical wall surface using the equation:

$$Rain_{vertical}= FE \cdot FD \cdot FH \cdot 0.2 \cdot V\cos\theta \cdot rh$$

where: FE= exposure factor
FD= deposition factor
FH= height factor
V = hourly average wind speed at 10 m, m/s
θ = angle between wind direction and normal to the wall (Figure 3)
rh= rainfall intensity, horizontal surface, mm/h
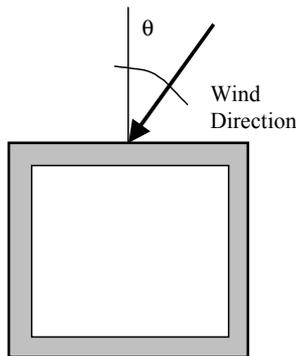$Rain_{vertical}$ = rain deposition on vertical wall, kg/m2·h

Figure 3. Plan view of building with definition of wind angle.

The exposure factor for angle of incidence is influenced by the topography surrounding the building and recommended values are given by Table 1:

Table 1: Recommended values for exposure factor

Exposure Class	Exposure Factor
Normal	1.0
Exposed (e.g. coastal, hill top, funneled wind)	1.3
Sheltered (e.g. trees, neighboring buildings, depression)	0.7

For buildings of less than 10 m (33 ft) The height factor can be calculated from
$$FH= (z/10)\alpha$$

where α is the gradient exponent and z is the height (m) above grade. The gradient exponent typically is 0.1 for open coastal areas, 0.2 to 0.25 for suburban areas and as much as 0.4 for urban areas. Table 2 provides the values to be used for design calculations for building less than 50 m (164 ft). For buildings over 50 m tall more detailed calculations should be made.

Table 2: Recommended values for height factors for buildings less than 50 m tall.

Terrain:	Open	Suburban	Urban
Height (m)		0.25	0.4
<10	1.0	1.0	1.0
15	1.0	1.1	1.2
20	1.1	1.2	1.3
30	1.1	1.3	1.6
40	1.1	1.4	1.7
50	1.2	1.5	1.9

The rain deposition factor depends on the shape of the building. Values for the rain deposition factor for rectangular buildings are shown in Figure 4.
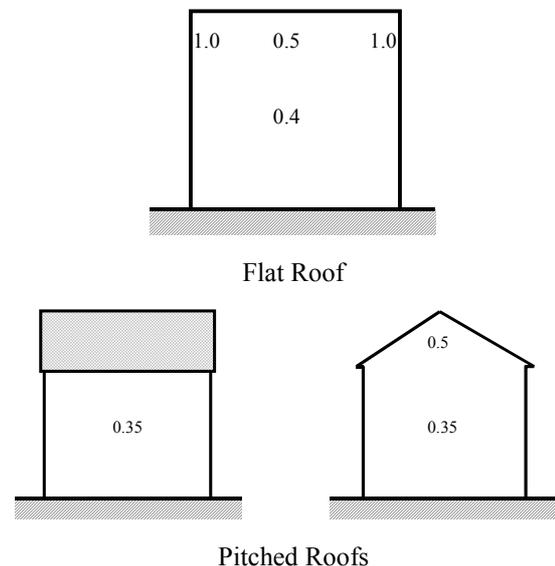

Flat Roof

Pitched Roofs

Figure 4: Recommended values for deposition factors for walls of rectangular buildings

WIND-DRIVEN RAIN

As an exterior environmental load, wind-driven rain is a strong function of the orientation of the building. For many locations in North America a predominant wind-driven rain location exists. For

this predominant orientation the building envelope may receive the majority of the moisture load. In Figures 5 & 6, the wind driven load is shown for two locations, Seattle, WA and Miami FL. It is evident for Seattle that the predominant direction for wind-driven rain is the south side that receives more than 300 kg/m^2 of rain yearly. The north side only receives a small fraction approximately 20 kg/m^2. In Miami, the predominant direction is east, while the west side receives only a very small fraction of the rain load. The WeatherFileAnalyzer was developed at ORNL [Karagiozis and Koutsoubidis, 2002] to develop analysis such as those presented in Figure 4 as these are critical information to any building envelope designer.
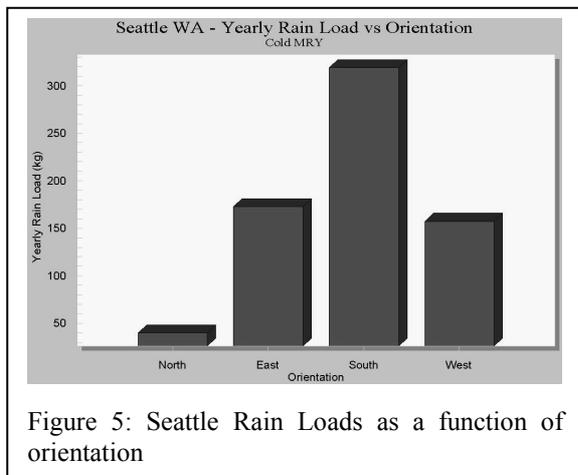

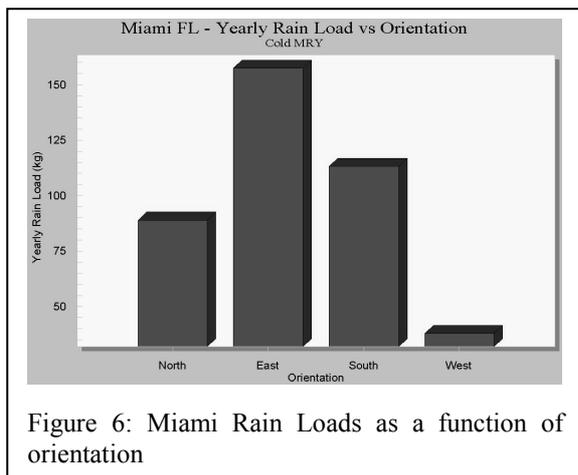
Figure 5: Seattle Rain Loads as a function of orientation

Figure 6: Miami Rain Loads as a function of orientation

Model Description

The WUFI-ORNL/IBP model is a Windows-based PC program for the hygrothermal (heat and moisture) analysis of building envelope constructions (ASTM MNL 40). Currently it is the most used transient hygrothermal model by building envelope designers and architects in North America. This advanced hygrothermal model has been specifically tailored to the needs of architects and building envelope designers. The model is a transient, one-dimensional heat and moisture transfer model, a two-dimensional model also is available that can be used to assess the hygrothermal behavior for a wide range of building material classes under climatic conditions found in North America. The model can be used to estimate the drying times of masonry and lightweight structures with trapped or concealed construction moisture, investigate the danger of interstitial condensation, or study the influence of driving rain on exterior building components. The program can also help to select repair and retrofit strategies with respect to the hygrothermal response of a particular wall assembly subjected to various climates. This design tool can aid in the development and optimization of innovative building materials and components. For example, WUFI simulations led to the development of the smart vapor retarder [i], a successful application of a software tool to a practical moisture control problem. Once the user supplies WUFI-ORNL/IBP with the data it needs, it will calculate the time evolution of the temperature and moisture fields in the building component. During or at the end of the simulation, the software gives distributions of results that describe the temporal evolution of thermal and moisture potentials, taken at specified locations or as mean values over specified layers.

Governing Equations

The model solves the coupled heat and mass transfer for vapor, liquid flow and thermal transport. The governing equations employed in the WUFI model are as follows:

Moisture conservation

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot \left(D_\phi \nabla \phi + \delta_p \nabla \left(\phi\, p_{sat} \right) \right)$$

Energy conservation

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T \right) + h_v \nabla \cdot \left(\delta_p \nabla \left(\phi\, p_{sat} \right) \right)$$

(Eq. 2)

Where

ϕ =relative humidity, -

t   = time, s

T   =temperature, K

c   =specific heat, J/kgK

w   =moisture content, kg/m³

psat   =saturation vapor pressure, Pa

λ =thermal conductivity, W/(mK)

H   =total enthalpy, J/m³

$D\phi$ =liquid conduction coefficient, kg/ms

δp =vapor permeability, kg/(msPa)

hv   =latent heat of phase change, J/kg

On the left-hand side of equation (1) and (2) are the storage terms. The fluxes on the right-hand side in both equations are influenced by heat as well as moisture: the conductive heat flux and the enthalpy flux by vapor diffusion with phase changes in the energy equation strongly depend on the moisture fields and fluxes. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on $D\phi$. The vapor flux, however, is simultaneously governed by the temperature and the moisture field because of the exponential changes in the saturation vapor pressure with temperature.

SIMULATIONS

WALL1: Brick Veneer Wall System
A series of simulations were performed to investigate the effect of time averaging on typical brick veneer wall system consisting of the following layers (starting from the exterior to the interior:
- 104 mm brick veneer (old brick),
- 19 mm air space,
- kraft paper ($\mu = 328$),
- 12.5 mm exterior grade plywood,
- 89 mm mineral fiber insulation,
- 12.5 mm gypsum board.

Four different time steps for wind driven rain averaging were used (5 min, 15 min, 30 min and 1 hr). The rain data used was actual measured data at the Holzkirchen weather station site, for the horizontal rain precipitation as well as wind driven rain striking the vertical wall. Figure 7 shows the mass related precipitation frequency as a function of time for 20 hours. The normal and driving rain is plotted out.
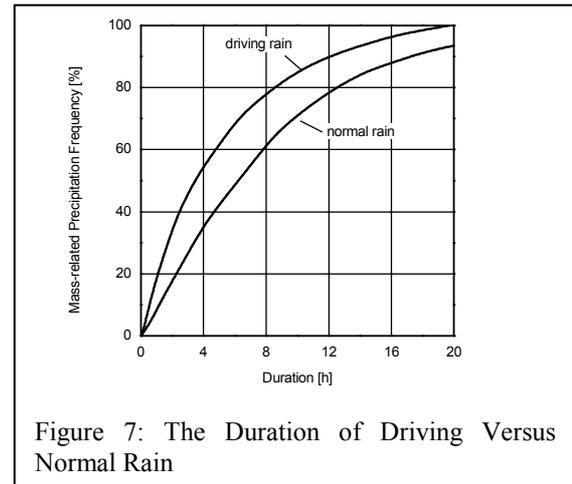

Figure 7: The Duration of Driving Versus Normal Rain

Figure 8 shows the driving rain as a function of month of the year for both measured and approximated quantities striking the wall. Here the agreement is very good allowing a high level of confidence in the hourly weather data and the empirical correlations used in the model
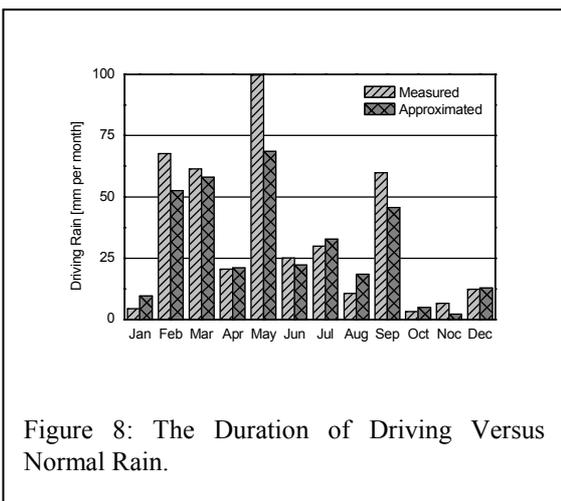

Figure 8: The Duration of Driving Versus Normal Rain.

In the following results, a series of simulations were performed using the 4 different time step averaging (5 minute, 15 minute, 30 minute and 1 hour time step). The simulations period was for a period of one year, starting out all simulations on January 1. Initial temperature and relative humidities were assigned at 80 % RH and 20 C. On the interior side a very vapor open coating was used (600 ng/m2 Pa s). In Figure 9, the effect of experimentally averaging rain data striking the exterior surface of the wall is shown. Data was collected at a time interval of 1 minute. It is evident that the peaks of the exterior rain load are smoothed considerably for the 1 hour time step. Data at 1 hr time step is used in hygrothermal simulations in North America.

Figure 9: The effect of experimental time averaging (5 min, 15 min, 30 min and 1 hr)
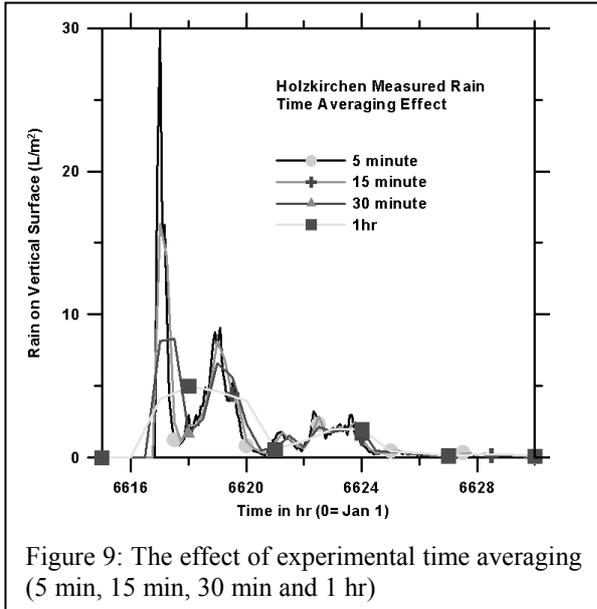
In Figure 10 the water content of the exterior brick veneer is plotted out. Results for all 4 time step are plotted out. No differences were observed for the storage of water due to time stepping.
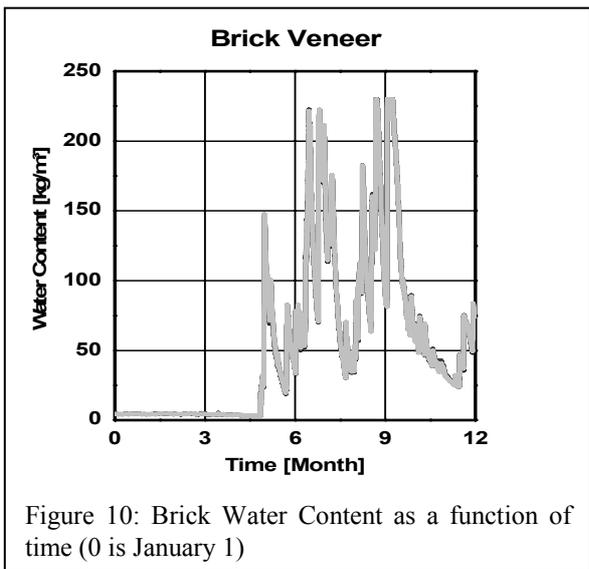

Figure 10: Brick Water Content as a function of time (0 is January 1)

Figure 11 shows the hygrothermal performance of the exterior sheathing board as a function of time. Here again the differences found were very small, indicating negligible effects in time averaging.

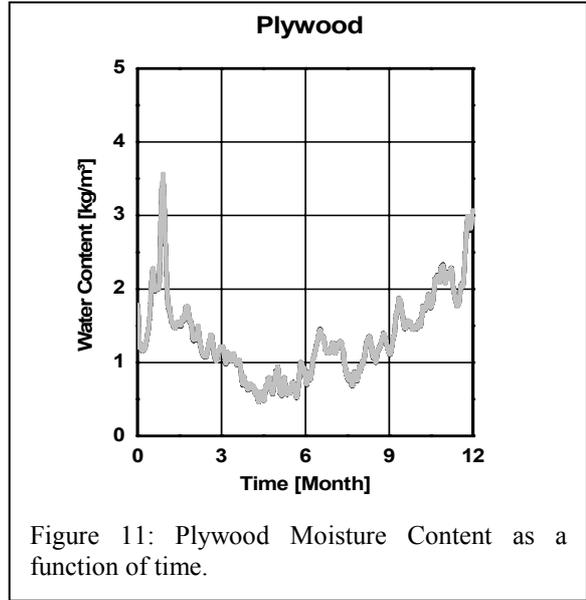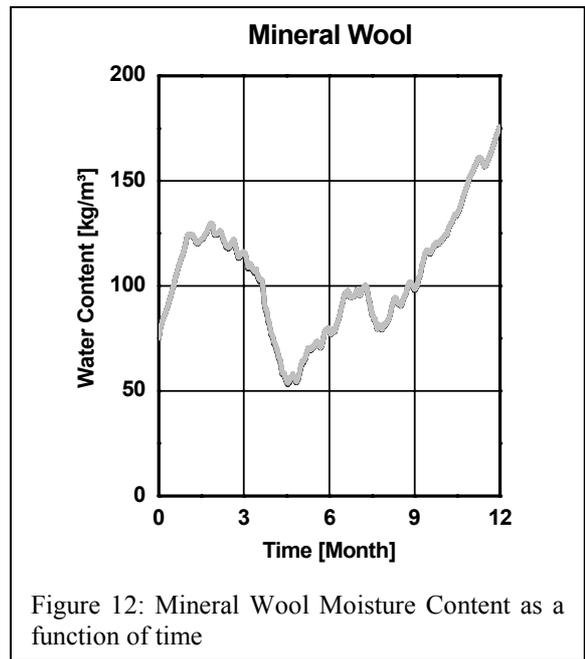Figure 11: Plywood Moisture Content as a function of time.

Figure 12 shows the transient moisture content behavior in the mineral wool. Again in this graph the differences between the different time scales are rather negligible.

Figure 12: Mineral Wool Moisture Content as a function of time

WALL2: Sandstone Wall System

Another series of simulations were performed to investigate the effect of time averaging on typical sandstone wall system consisting of the following layers (starting from the exterior to the interior:

- 104 mm sandstone,
- 19 mm air space,
- kraft paper (μ= 328),

- 12.5 mm exterior grade plywood,
- 89 mm mineral fiber insulation,
- 12.5 mm gypsum board.

In this simulation series the exterior facade is much more vapor and liquid absorbing that the previous case with the brick cladding.. The A-value (Sorptivity Value, $(kg/m^2.s^{1/2})$ of the sandstone used in these simulations is rather high at 0.167.

In Figure 13 the water content of the exterior sandstone is plotted out. Results for all 4 time step are plotted out. The results show maximum differences of less than 10 % in water content. The predictions indicate that the shorter the time step resulted in lower water content of the exterior facade.

In Figure 14 results show the water content as a function of time for the plywood sheathing board. Again negligible differences are observed, similar to those present in the brick veneer system.
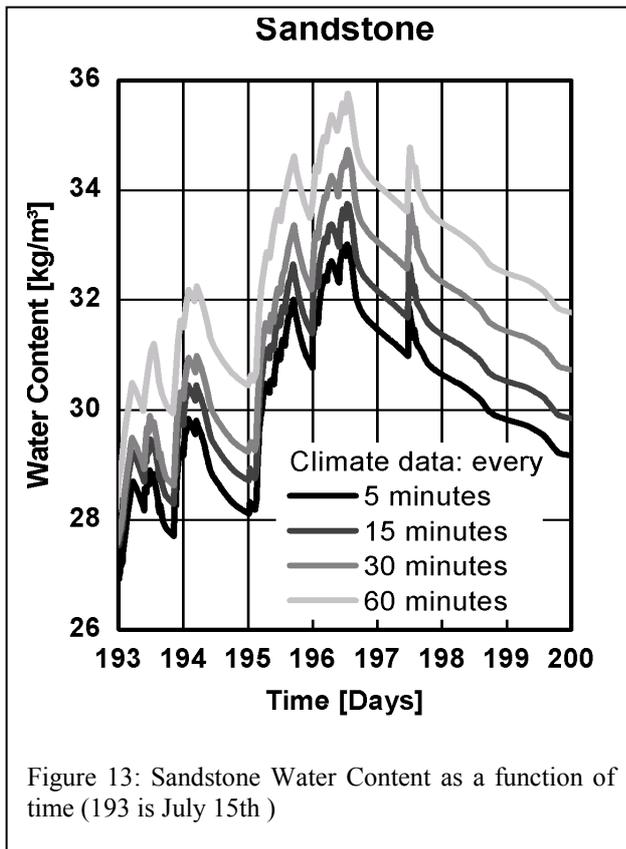
Figure 14: Sandstone Water Content as a function of time (0 is May)

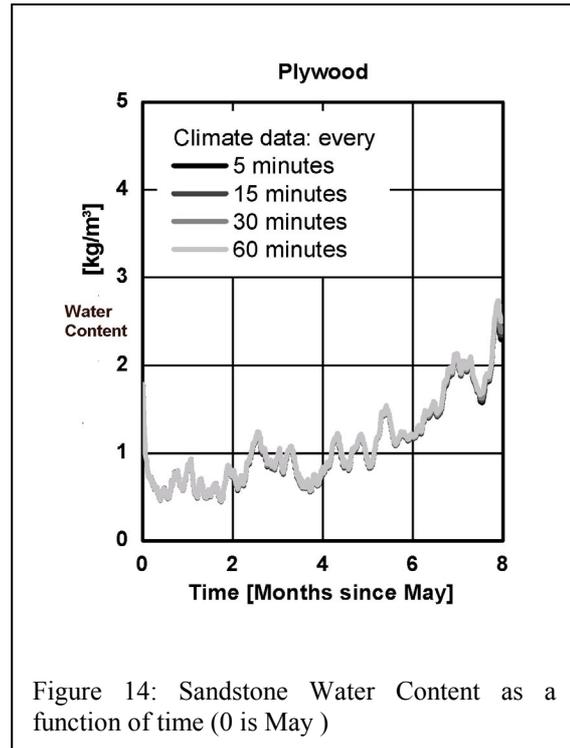Figure 13: Sandstone Water Content as a function of time (193 is July 15th)

CONCLUSIONS

The preliminary assessment of the effect of time averaging for wind-driven rain loads on the hygrothermal performance of a wall system was investigated for four different time averaging time steps and two wall systems. The wall systems were essentially identical, the only difference was the exterior cladding employed (brick versus sandstone).

Results show that small differences in the effect of time averaging of the experimental wind-driven rain data for the brick veneer wall systems. The moisture performance in all layers of the wall was not influenced by the choice of the time stepping.

For the more water absorbing wall system, the sandstone wall system, the results only show differences in the sandstone layer. Negligible differences were observed in all other layers of the wall.

As this only the beginning part of the study, several other important aspects have not been considered. The results of this study have not considered effects of water penetration, and the effects of local wind gusting in the terms of water intrusion. In addition, the run-off or splashing effects (different at different rain intensities and droplet sizes) were not simulated . Pressure equalization can not be evaluated with this model at the present time. Another aspect that may be important for future

work is investigating a frequency domain model of the wind driven rain data.

ACKNOWLEDGEMENTS

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