Assessment Method for Combined Heat, Air and Moisture Transfer in Building Components

Bojan Milovanović*
Faculty of Civil Engineering
University of Zagreb
e–mail: bmilovanovic@grad.hr

Dunja Mikulić
Faculty of Civil Engineering
University of Zagreb
e–mail: dmikulic@grad.hr

ABSTRACT

The present state of knowledge, concerning heat, air and moisture (HAM) transfer through construction elements demands updating. The standardized Glaser method for calculation, prediction and evaluation of moisture performance is frequently used to assess the moisture safety of structures but is considered as rarely applicable. The method has a lot of limitations and as a result, construction elements that are qualified as good moisture design may in reality, due to built-in moisture, precipitation and air exfiltration face many problems. With the recent advances in analytical and experimental knowledge, the prediction of the HAM response of structure has come closer to reality. In this article a review of the acceptable tools based on HAM transfer is made.

KEYWORDS

Moisture flow, Glaser method, HAM model, WUFI, internal insulation, moisture control,

INTRODUCTION

Despite advances in material science, computers and building technology, building failures related to building physics continue to occur. When regarding only the building envelope it is estimated that about 75 – 90 % of all damages are caused by moisture [1]. These failures range from a building not meeting its energy use target to a building causing people to become ill from exposure to various chemicals or biological organisms. These failures cost society considerable amounts of money each year and many of these failures are preventable already during the design stage of the building process.

Ignoring building physics principles during the design and construction phases can lead to a number of problems during the operation phase such high energy usage, health problems, physical building damage and a host of other problems related to these. Many surveys have reported that most envelope failures are caused by

* Corresponding author

moisture accumulation [2-4]. These investigations indicate that no practical wall system can completely prevent moisture penetration at all times.

Problems, such as preventing the deterioration of historical buildings, the improvement of heating insulation, as well as the retrofitting of the outer parts of existing buildings, are strongly linked to questions concerning moisture behaviour. Moisture behaviour has to be predicted in design stage in order to avoid moisture problems because often, small mistakes in the design phase have great influence on running costs and risk for failures. It is therefore important to have good, reliable prediction tools.

EXTERNAL AND INTERNAL INSULATION

Frequently used method of thermal envelope retrofit of existing buildings is to construct the thermal insulation layer on the external side of the building component. The advantages of external thermal insulation systems are protection of the load bearing structure from great temperature gradients and different external loads, wind driven rain, freezing and thawing cycles. By using this method of insulation, effect of thermal bridges can be minimised and also the simplicity of installation work needed has to be mentioned. Drying capacity of the walls constructed with external insulation is very good if nonhygroscopic materials are used.

In short, it can be said that building elements with external insulation are unproblematic regarding building physics principles, advisable for realisation and application.

On the other hand, there are a lot of old buildings that are protected as a cultural heritage, whose facades cannot be changed and should be kept in original state. This kind of building envelopes can be insulated only by applying internal insulation.

Applying internal insulation is regarded as potentially hazardous method because by doing this, one is significantly affecting hygrothermal behaviour of existing load bearing materials. This can lead to lower drying capacity of the building element and higher annual moisture content of the materials and consequently to moisture related problems.

MOISTURE FLOW MECHANISMS

Water vapour and liquid water migrate by a variety of transport mechanisms:

- Water vapour diffusion by partial water vapour pressure gradients
- Displacement of water vapour by air movement
- Capillary suction of liquid water in porous building materials
- Liquid flow by gravity or air pressure gradients

Water vapour diffusion

Water vapour flow by diffusion is important in application like cold storage facilities, build-in refrigerators, or in buildings where a high inside partial water vapour pressure is needed and the building is extremely airtight.

The equation used to calculate water vapour flux $\boldsymbol{m_v}$ by diffusion through building materials is based on Fick´s law for diffusion of a dilute gas.

$$m_v = -\mu \cdot \text{grad } p \qquad (1)$$

Where:

μ **-** water vapour permeability
grad (p) – gradient of partial water vapour pressure

Water vapour permeability should not be constant number but a function of relative humidity and temperature, and could also vary spatially because of variations in the material's porous system.

Water vapour flow by air movement

The water vapour flux is represented by

$$m_v = W \cdot m_a \approx \frac{0,62}{P_a} \cdot m_a \cdot p \qquad (2)$$

Where:

W – humidity ratio of moving air
$\boldsymbol{m_a}$ – air flux
p – partial water vapour pressure in air
$\boldsymbol{P_a}$ – atmospheric air pressure

Water flow by capillary suction

Capillary water movement is governed by the gradient in capillary suction

$$m_m = -k_m \cdot \text{grad}\left(\frac{2\sigma \cos\theta}{r}\right) \qquad (3)$$

Where

$\boldsymbol{m_m}$ – moisture flux
$\boldsymbol{k_m}$ – water permeability
σ – surface tension of water
r – equivalent radius of capillary
θ **-** contact wetting angle

it is important to note that the term "moisture" includes both water vapour and liquid

GLASER METHOD

Standard method of moisture performance evaluation of building exterior walls used by civil engineering practitioners in Croatia is based on the standard Glaser method [5].

This method is based on the following basic assumptions:

- thermal and moist transports are independent, 1D and steady state,
- moisture is transported purely by vapour diffusion according to Fick's law,
- heat is transported exclusively by heat conduction according to Fourier's law,
- there is no sorption and no migration of liquid water in the wall,

- liquid moisture in the wall is due to condensation of water vapour, which takes place on interstitial surfaces where water vapour pressure is equal to saturated vapour pressure or higher.
- the method does not consider the moisture capacity of building materials

The Glaser method [6] is based on three basic equations:

- a balance equation of heat,
- a balance equation of liquid water and
- a steady-state diffusion

It is also assumed that transport of heat is independent of moist transport and can therefore be solved separately.

Almost all construction materials are porous in nature and because of that they have the ability to store moisture to some extent, respectively.

It can be seen from above, that moisture control strategies are based solely on water vapour diffusion. Displacement of water vapour by air movement is treated superficially, and water vapour supplied by wind driven rain or soil moisture is being overlooked completely.

It is found by researchers [7] that, when present, above mentioned mechanisms can move far greater amounts of moisture than diffusion does. Air movement and liquid flow should have the highest priority in moisture control.

With the recent advances in analytical and experimental knowledge, the prediction of the Heat, Air and Moisture (HAM) response of structure has come closer to reality.

HEAT, AIR AND MOISTURE (HAM) TRANSFER MODEL

To accurately capture the influence of the building enclosure on the indoor environment and Heat, Ventilation and Air Condition systems (HVAC), a transient HAM transfer model that handles the coupled heat, air and moisture transfer phenomena through building enclosure is essential. The first physical models accounting for vapour diffusion, capillary water transport, initial moisture, latent heat of evaporation and transient conditions were published in [8,9].

Within the activities of the International Energy Agency, the first critical review of the existing hygrothermal models was presented [10] which led to a classification scheme that ranked models with respect to complexity of the transport physics it entailed. This classification was afterwards extended by introducing the concept of real envelope system and sub-system effects and durability assessment [11].

In summation, one using the advanced moisture engineering or HAM model has to pay particular attention to:

- Heat and mass transfer physics
- Definition of environmental loads
- Definition of the construction entity (workmanship, defects, system and sub-system effects, aging degradation)

- Hygrothermal material properties (structural – biological – mechanical)

Interactions that must be accounted for in advanced hear, air and moisture transfer models are shown schematically on figure 1.

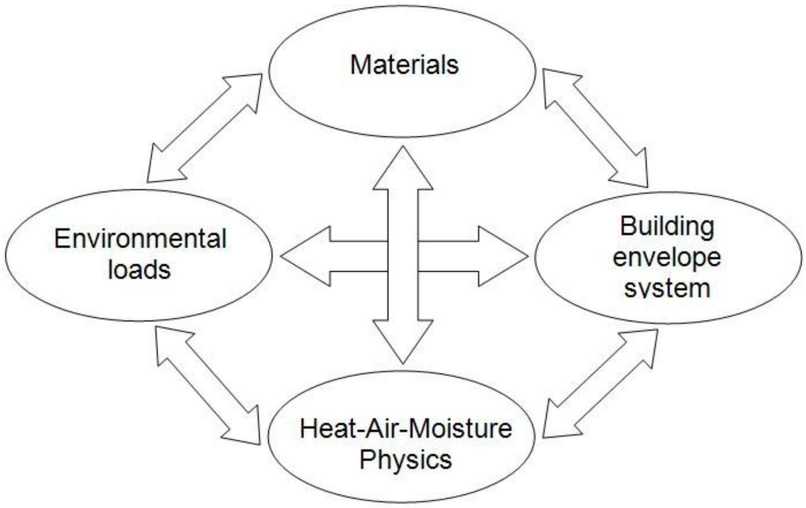

Figure 1. Interactions in HAM models

Among existing hygrothermal models, significant difference exists. Some of the models require not only a high level of knowledge about heat, air and moisture transfer, but also some knowledge in preparing the simulation and experimental data or experimental facilities to collect data [12]. A simple 2-D simulation may require significant time to collect material property data.

The validation, verification of advanced HAM models has been done by researchers [12, 13] and benchmarking cases have been created to assess the quality of the model [14]. Karagiozis [12] made a broad research between 12 most advanced HAM models, regarding 13 most important features that HAM models have to satisfy and his conclusion was that WUFI® model is the most advanced one.

WUFI® is developed by Fraunhofer Institute of Building Physics and is based on state-of-the art understanding of building physics regarding sorption and suction isotherms, vapour diffusion, liquid transport and phase changes:

This model is well documented and has been validated by many comparisons between calculated and field performance data.

The model requires a limited number of standard material properties data. Hourly weather data, such as temperature, relative humidity, wind, driving rain, and solar radiation are employed in the hygrothermal calculations. A WUFI® model flow chart is presented in figure 2.

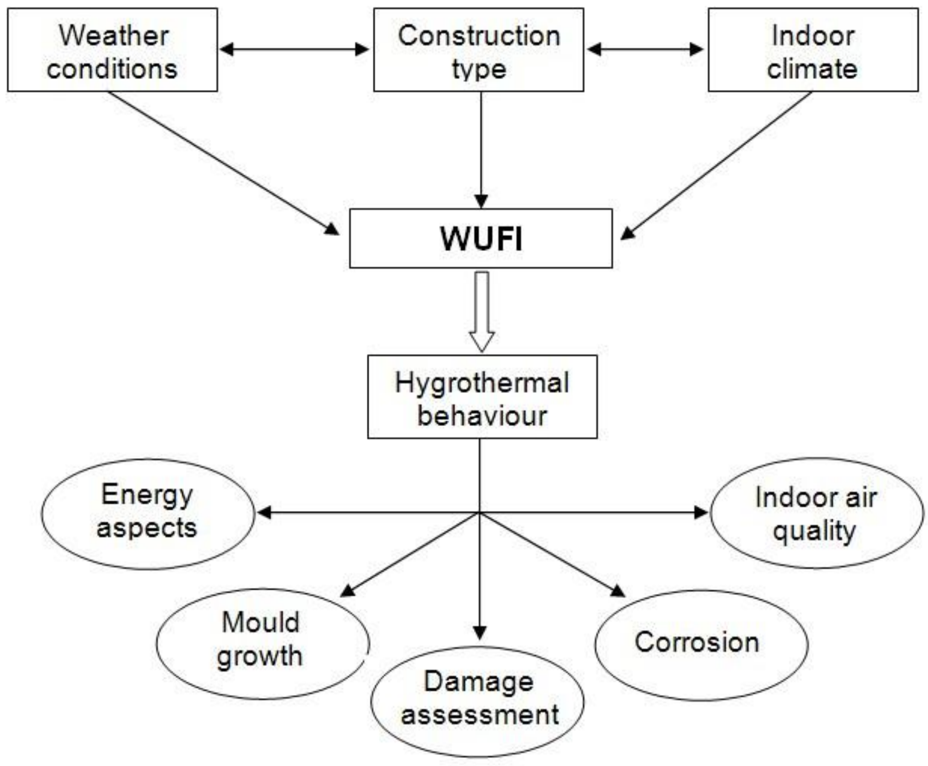

Figure 2. Software architecture of WUFI® [15]

Holistic hygrothermal analysis

Building envelope designers attempt to predict the hygrothermal performance of an individual building component, wall, roof, etc. thus uncoupling the system from the interior and exterior environment and from interactions among envelope components.

This stand-alone analysis of specific envelope parts is important in understanding the influence of vapour retarder or air barrier on the hygrothermal performance of the envelope, but provides limited performance information on the overall heat and mass transfer of a building.

Holistic performance modelling couples all building envelope systems with the interior environment and HVAC systems and also with the exterior environmental loads.

Outputs from hygrothermal models

The results gained from advanced HAM models may be used to determine moisture tolerance of building envelope system subjected to various interior and exterior loads. Heat fluxes may be used to determine the thermal performance of the envelope under the influence of moisture and airflow. Drying times of materials which constitute building components from trapped or concealed construction moisture, investigate the danger of interstitial condensation and study the influence of driving rain on exterior building components.

Determination of output data may be used in post-processing in order to evaluate durability, mould growth, freeze and thaw.

Comparison between different repair and retrofit strategies with respect to total hygrothermal response and optimization of specific building element in question is possible.

BASIC GUIDELINES OF MOISTURE CONTROL

To minimize the risks related to inside insulation, it is recommended to follow several basic guidelines that aim at controlling exterior and interior humidity sources [16].

- *Minimize rain penetration into the wall assembly:* Rain penetration is a large potential source of water ingress within a wall assembly and is often reflective of the quality and condition of the masonry units and mortar joints. The addition of insulation must be combined with a detailed inspection and repairs of the exterior face of the masonry and mortar joints in order to minimize water intrusion.

- *Minimize penetration of indoor humidity into the wall assembly through diffusion, air infiltration and exfiltration:* In order to prevent humidity transfer, it is necessary to include a continuous vapor barrier within the wall assembly. The vapor drive and location and rate of condensation within a wall assembly depends on several factors, including the type of wall materials used and their order of installation, as well as the temperature and relative humidity conditions maintained inside the building during the heating season. Reduced air leakage also increases the level of occupant comfort and energy efficiency

- *Minimize the temperature drop within the wall assembly:* In considering occupant comfort and energy efficiency, it is often deemed necessary to increase the thermal resistance of the existing exterior walls. However, increasing the thermal resistance along the interior surface of solid masonry walls will also restrict indoor heat from warming the masonry wall during the winter season. As a result, the existing masonry will be subjected to greater cold temperatures than in its' past, increasing the potential for condensation and frost formation within the solid masonry wall. A balance must therefore be reached between objectives of durability and of thermal performance and comfort.

- *Minimize the air pressure differential across the exterior wall assembly:* It is the air pressure differential across the building envelope that is the driving force for exfiltration of warm, moist indoor air through the wall assembly (positive pressure in the building) and for rain penetration (negative pressure in the building). The air pressure differential across the exterior walls of a building is the result of stack effect, wind loads and the operation of the mechanical systems. Mechanical systems should ideally be balanced so that a relatively neutral air pressure exists across the building envelope.

By following the presented guidelines one should develop several possible strategies of building envelope retrofit which should then be systematically analysed by using HAM tools. A systematic method for hygrothermal analysis of building constructions using computer models was presented by Geving [17]. The method contains four main components:

- Problem definition

- Simulation set-up and input parameters
- HAM simulations
- Analysis of hygrothermal performance

Results gained from the analysis of hygrothermal performances of the retrofit strategy, respectively, are then used in the decision making and optimisation process.

CONCLUSIONS

Restoring heritage building envelopes by improving wall system performance is difficult task which often means introducing additional elements, including flashing, membranes, coatings, insulation, or over cladding, to improve the water shedding capabilities. Often this cannot be done discretely, without altering the character defining elements of the building and its heritage façade.

The main challenge with insulating solid masonry walls is to improve performance without compromising durability.

Potential wall system performance can be assessed using static temperature and vapor pressure gradient analysis (Glaser method) as well as dynamic hygrothermal analysis via computer simulation.

This paper presents the limitations of standardised Glaser method and identifies features required to make acceptable and fairly accurate heat, air and moisture analysis of the building components in order to reduce and avoid any moisture damages during exploitation of buildings.

Depending on the need, an appropriate analysis method should be chosen, for example, although a simple analysis method may provide neither absolutely correct nor accurate results, the method fills the need if it provides satisfactory results for decision making.

More detailed and more accurate method is needed when the potential cost of a problem is high, when there are no long term experiences of specific problem or when new products are to be used.

For many projects, the pace of design and construction and also the costs do not permit the assessment of masonry moisture levels over several seasons and in almost all cases there is no ongoing monitoring program to supply relevant data. In light of this challenge, hygrothermal simulation can be used to supplement or validate a truncated data set.

A new generation of models is expected to develop towards the probabilistic approach in HAM analysis, computing the probability and risk of moisture damage on the building component's surface or inside of the building component.

ACKNOWLEDGMENTS

Research presented was made within scientific project "From nano to macrostructure of concrete" (082-0822161-2990) funded by the Croatian Ministry of Science, Education and Sport.

REFERENCES

1. Trechsel, H.R.: Moisture control in buildings, ASTM Manual series, MNL 18, Philadelphia, USA, 1994.
2. Desjarlais, A.O.; Karagiozis, A.N.; Aoki-Kramer, M.: Wall moisture problems in Seattle. Performance of exterior envelopes of whole buildings VIII: Integration of building envelopes; 2002. pp. 1-8.
3. Barrett, D.: The renewal of trust in residential construction: an inquiry into the quality of condominium construction in British Columbia; Government of the Province of British Columbia; 1998.
4. Tsongas, G.A.; Govan, D.P.; McGillis, J.A.: Field observations and laboratory tests of water migration in walls with shiplap hardboard siding; Thermal envelopes VII / Moisture-practices; 1998. p. 469-483.
5. HRN EN ISO 13788: 2002. Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation, Calculating methods
6. Glaser H. Vereinfachte Berechnung der Dampfdiffusion durch geschichtete Wa¨nde bei Ausscheidung von Wasser und Eis. Ka¨ ltetechnik 1958;10(11):358–64 and (12) 386–90.
7. ASHRAE Handbook – Fundamentals: Chapter 23 – Thermal and Moisture Control in Insulated Assemblies, ASHRAE, 2005.
8. Philip, J. R., and D.A. de Vries., 1957. Moisture movement in porous materials under temperature gradients. Transactions, American Geophysical Union 38:222-232.
9. Luikov, A. V., 1966. Heat and mass transfer in capillary-porous bodies. London: Pergamon Press.
10. Hens, H.; Heat, Air and Moisture Transfer in Insulated Envelope Parts: (HAMTIE) Modeling, International Energy Agency Annex 24, Final Report, Vol. 1, Acco Leuven, 1996.
11. Karagiozis, A.N.; Porous Media Transport in Building Systems, CFD Society of Canada, Victoria, pp. 7-21 to 7-25, 1997.
12. Karagiozis, A.N.; Moisture Analysis and Condensation Control in Building Envelopes, Chapter 6, Advanced Numerical Models for Hygrothermal Research, ASTM International 2001.
13. Simonson, C.; Salonvaara, M.; Ojanen, T.; Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope: part II – verification and numerical studies; Journal of Thermal Envelope and Building Science; 28 (2); pp. 161 – 185; 2004.
14. Hagentoft, C.E.; Kalagasidis, A.; Adl Zarrabi, B; Roels, S; Carmeliet, J.; Hens, H.; Grunewald, J.; Funk, M.; Becker, R.; Shamir, D.; Adan, O.; Brocken, H.; Kumaran, K.; Djebbar, R.; Assessment method of numerical prediction models for combined heat, air and moisture transfer in building components: benchmarks for one-dimensional cases; Journal of Thermal Envelope and Building Science; 27 (4); pp. 327 – 352; 2004.
15. Kuenzel, H.M.; Karagiozis, A.N.; Holm, A.H.; Moisture Analysis and Condensation Control in Building Envelopes, Chapter 9, A Hygrothermal Design Tool for Architects and Engineers(WUFI), ASTM International 2001.
16. Gonçalves, M.D.; Insulating Solid Masonry Walls; Patenaude-JBK Inc., Varennes, Quebec, Email: m.goncalves@patenaude-jbk.com

17. Geving, S.; A systematic method for hygrothermal analysis of building constructions using computer models; Department of Building and Construction Engineering; The Norvegian University of Science and Technology (NTNU); Trondheim ; Norway