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Overview of Hygrothermal (HAM) Analysis Methods

by John Straube[1] *and Eric Burnett*[2]

IN THE DESIGN of modern engineered buildings it is customary to use a variety of mathematical models to simulate the performance of the structural system and the service (HVAC) systems. Structural, mechanical, and electrical engineers use various different mathematical models to analyze the response of the modeled system or subsystem and then improve, adjust, or revise the system as needed until a final design is arrived at. Analysis, even crude analysis and, perhaps, with more than one model, is necessary to design a new facility or subsystem as well as to assess an existing building or part thereof.

The building industry is moving toward a similar situation with building enclosures. However, we in North America still have some way to go in developing a professional consensus on which models are to be preferred, what analysis procedures are cost and qualitatively effective, and how to develop the necessary experience to use these models properly. Rapidly changing technologies, e.g., materials and interior building environments, combined with higher expectations of performance for both the enclosure and the building, have created a very real need for the development and use of practical hygrothermal analysis methods.

This chapter will provide some background and a brief overview of the various building hygrothermal analysis methods. The objective is to provide a framework to identify the different needs, to list and compare analytical procedures and models, and to give some direction to those who would like to match need and HAM (heat, air, and moisture) analysis methods. The intent and limitations of the various hygrothermal analysis procedures, the factors that affect the value of the results, and the nature and amount of information required are also outlined.

The intent of this chapter is not to reproduce the excellent and detailed state-of-the-art report authored by Hugo Hens as part of the IEA Annex 24 project. This document should be referred to for more detailed information on heat, air, and moisture physics and for a more comprehensive listing of models.

THE NEED FOR ANALYSIS

The general goal of hygrothermal analysis is the evaluation of the temperature and moisture conditions that might prevail across and within a portion of any building enclosure over time. Different individuals or groups may have different needs for HAM analysis. Three general needs for analysis can be identified: design, assessment, and study (Fig. 1). Design professionals such as architects and engineers generate the first two needs. Researchers and students have a need to study enclosure performance.

Probably the most important and also the most basic need is to learn how to conduct a HAM analysis and thereby to develop the experience necessary to undertake design and then to utilize the more sophisticated analysis tools. Research is an extension of this basic need in that, for the purposes of research, development, or demonstration, more accurate and more complex mathematical models may be necessary. The need for assessment of an enclosure whether for the purpose of a condition assessment, forensic investigation, conversion, or space conditioning energy calculation usually involves an existing building. Of course the process of design involves choices, repetition, and judgment and requires much more than analysis. Figure 2 is an attempt to demonstrate the procedural and other differences between design needs and assessment or study needs. Note that one important decision that has to be made is whether a formal analysis is even necessary; prior experience may obviate any need for an analysis.

The purpose of most hygrothermal analysis is usually to provide sufficient and appropriate information needed for decision-making. The three most common reasons for conducting of a hygrothermal analysis can be listed as:

1. Develop an appropriate level of understanding of enclosure response, e.g., does condensation occur and how much; is thermal bridging significant; where and when will decay occur?
2. Identification and/or avoidance of a performance problem, e.g., excessive condensation; stud ghosting; decay.
3. Quantify energy flow through the enclosure as well as its impact on comfort and mechanical systems.

Depending on the need, an appropriate analysis technique should be chosen. The quality and quantity of information required must be consistent with the analysis technique chosen. For example, consider the case where one needs to avoid a specific enclosure problem. This problem may require only a one-dimensional, steady-state analysis of one extreme set of climatic data and material properties. Although a simple analysis technique may provide neither absolutely correct or accurate results, so long as a satisfactory decision can be made (i.e., a safe design) with this information, the technique fills the need. Consider also the situ-

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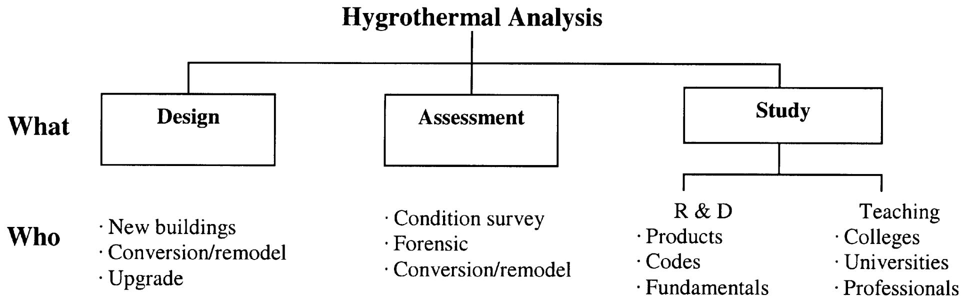


FIG. 1—General need for hygrothermal analysis and user groups.

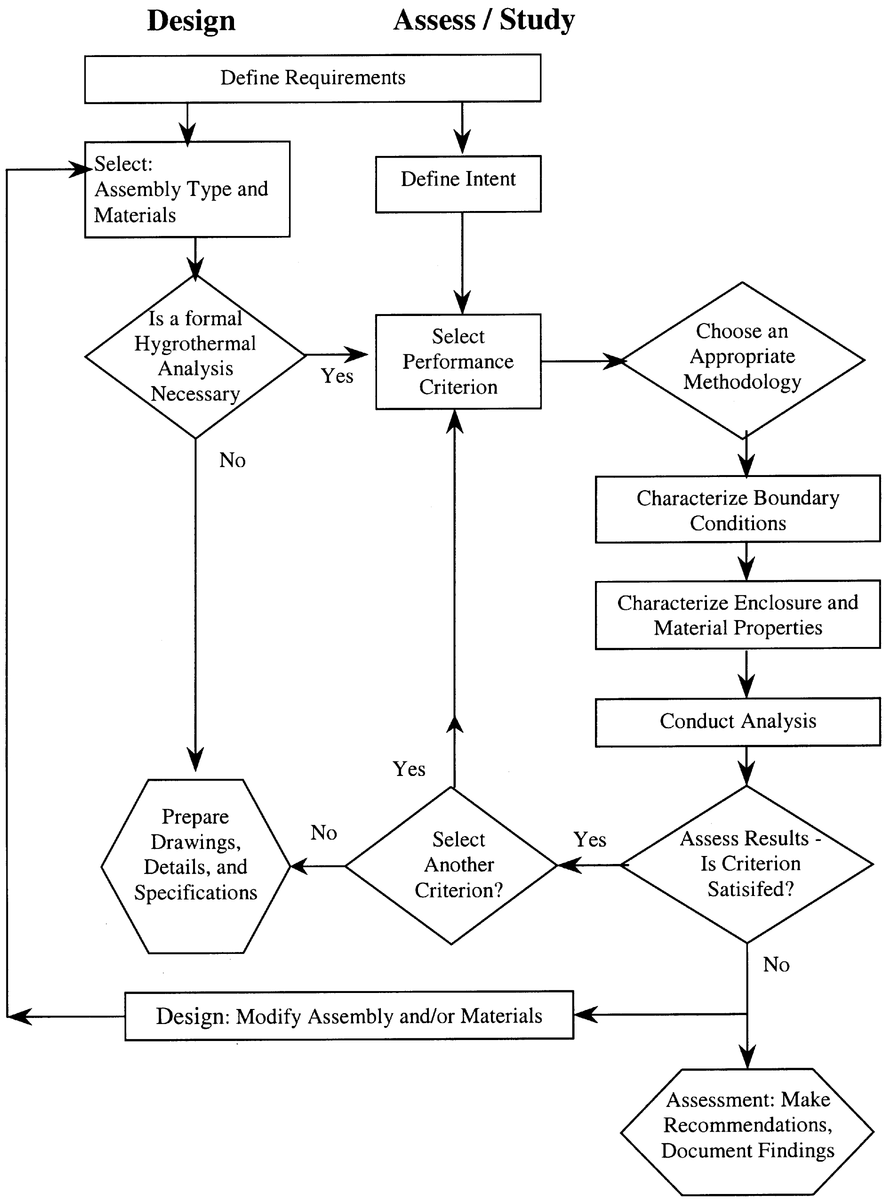


FIG. 2—General hygrothermal enclosure design or assessment procedure.

ation when conducting a parametric analysis where the accuracy of the difference between results (relative results) may be much more accurate than the absolute value of any particular result. Indeed, in many buildings no analysis is required because of long and successful experience with that specific assembly in that specific climate.

More detailed, and more accurate, analysis is often required when the potential cost of a problem is high, a new and untried product is to be used, or to demonstrate conformance to regulatory bodies. A detailed analysis, however, requires a much higher level of experience on the part of the analyst, more and more detailed material and boundary condition information, more powerful computers, and above all, more time.

MODELING HYGROTHERMAL PERFORMANCE

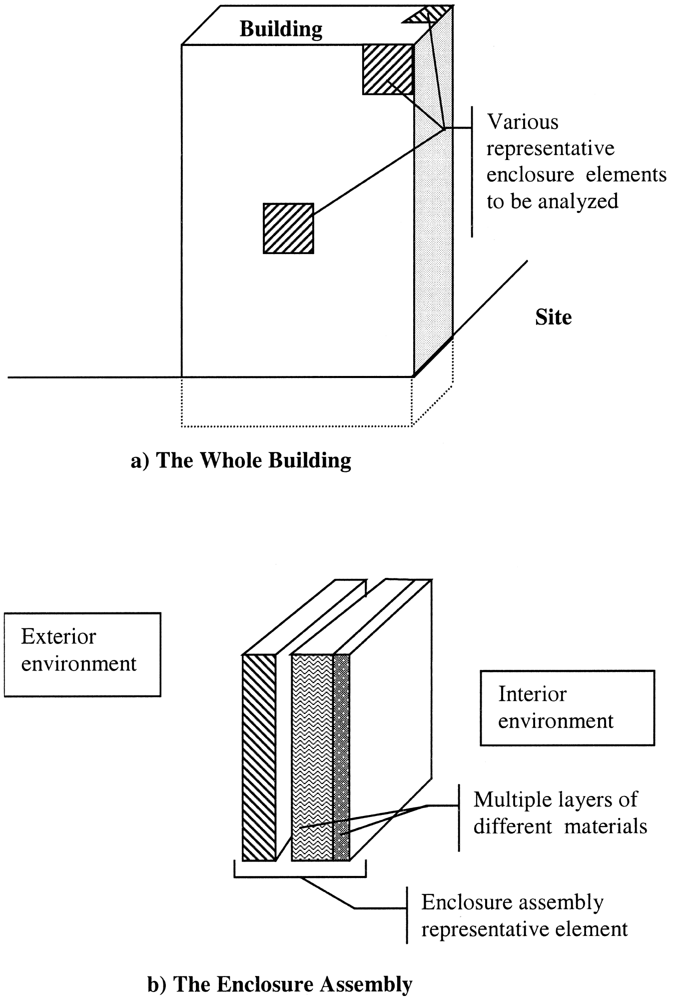
Although the physics of moisture storage and transport are reasonably well understood, predicting the moisture and temperature conditions inside building enclosures is seldom a simple task. The prediction of the hygrothermal performance of the building enclosure typically requires some knowledge of:

1. *Geometry of the enclosure*—including all macro building details (e.g., building shape and height), enclosure assembly details, and micro-details (e.g., cracks) (as shown in Fig. 3, the building enclosure is usually discretized into smaller representative elements).
2. Boundary Conditions
   - (i) interior environment, including the interaction of the enclosure with the interior environment, and
   - (ii) exterior environment, including the interaction of the building with the exterior environment.
   - (iii) boundary conditions between elements (Fig. 3).
3. Material properties and their variation with temperature, moisture content, and age, as well as their chemical interaction with other materials.
4. Physics, chemistry, thermodynamics, and mathematics of combined heat, air, and moisture transport.

These four categories are sufficient to conduct an analysis. However, analysis cannot or should not be done in a vacuum; there must be both context and limitations. In any enclosure problem, one must know the general performance conditions as well as the important performance thresholds. This could constitute the fifth category of information required for a hygrothermal analysis:

5. Performance thresholds (that is, the conditions under which a material or assembly will cease to perform as intended).

Five major categories of required knowledge and information have been listed above. Each of these five categories involves some mathematical representation. Representation requires assumptions and approximations. Therefore, whatever the model used (no matter how complex), it will, to some degree, be incorrect. At present, one is often forced to make gross assumptions because of a lack of information and knowledge. In practical situations, such as a design problem, the constraints of time and money will also have an impact on which approximations and assumptions are made.



a) The Whole Building

b) The Enclosure Assembly

FIG. 3—Aspects of the enclosure.

Most champions of complex HAM models emphasize the accuracy of the modeling of the building physics or the number of dimensions, etc. For example, in the recent Annex 24 review of HAM models [*1*], the models were differentiated on the basis of how well the physics was modeled. The ability of a model to match real performance, however, depends on the collective, possibly accumulative, influence of all the other aspects as well.

To illustrate the scale and complexity of the problem of accurately modeling HAM, consider that each one of the five required categories of information listed above is also dependent on the consideration of:

1. Dimension—one, two, or three dimensional.
2. Time—steady-state, quasi-static, or dynamic.
3. Quality and availability of information.
4. Stochastic nature of each data set (e.g., material properties, weather, construction quality).

The degree to which these factors are taken into account is usually considered to be the measure of the sophistication of the model. For example, a three-dimensional, dynamic model that uses measured material and boundary condition data and accounts for their variation with time could be considered to be a reasonably comprehensive and therefore sophisticated model. However, regardless of the sophistication, the accuracy of other input data (boundary conditions, material properties, and geometry) and the performance thresholds will limit the accuracy and utility of the results. Furthermore, from a practical point of view, the value of the results should be consistent with the effort, time, computational resources, and cost entailed.

INFORMATION REQUIRED FOR ANALYSIS

Each of the five categories of information required for a HAM analysis is briefly reviewed below. It should be emphasized that the study of each of these topics is a significant undertaking in itself and only the most important points can be discussed.

Enclosure Geometry

The actual enclosure geometry must be modeled before any hygrothermal analysis can begin. In simple methods the geometry is almost always reduced to a series of one-dimensional layers. Note that it is rare to ever have a detailed and comprehensive knowledge of the three-dimensional enclosure. Gaps and discontinuities are important as they usually create a contact resistance or break for capillary flow, cracks, and punctures allow airflow, etc. In fact, most analyses are conducted on ideal walls. The reason for most performance problems is unknown or unpredictable imperfections in the enclosure. The ability to model the actual enclosure geometry, including the inevitable imperfections, may in fact often be the most important factor for the accurate prediction of true, three-dimensional hygrothermal enclosure performance. The shape of the enclosure may change with time, for example due to wind pressures, shrinkage, etc.

Boundary Conditions

The boundary conditions imposed on a mathematical model are often as critical to its accuracy as the proper modeling of the moisture physics. In general, both the internal and external environments need to be known (see Chapter 2). For instance, both driving rain and solar radiation must be properly accounted for. Few of the models deal with driving rain, partly because there are little data available. There are some practical situations where driving rain need not be accounted for, namely enclosures with functional fully sealed perfect barrier or non-absorbent claddings systems. However, the practical value of models that do not account for driving rain deposition is curtailed, especially if the tolerance of an assembly to imperfections in construction is to be assessed.

For models that include air flow, accurate and detailed knowledge of wind pressure variations and building stack effect pressures is required, but are only very rarely available. Interior and exterior temperatures are known with a much greater degree of accuracy than any of the other boundary conditions, but their precise knowledge is usually not that important to the results. The magnitude and variation of interior humidity, which can be critical to the success or failure of a given enclosure in service, is more poorly known, although recent research has improved the quality and quantity of the information available.

The time-domain is also important. Almost all computer models employ hourly time steps, since most weather data are available in this form. Simple analysis methods employ monthly averages, binned data, or even seasonal averages. The choice of time step is not critical for most models: a 15-min time step provides no increase in accuracy over a 1 h time step that is not overwhelmed by the uncertainties of the input data.

Material Properties

The material properties required for hygrothermal analysis depend on the type of problem that needs to be solved and the analysis tool chosen to assist in the solution. Simple models often require only a single value for the vapor permeability and thermal conductivity. Such data are tabulated in various references for many materials (see Chapter 3), but it is sometimes difficult to find and is often inaccurate and out of date.

More detailed analysis requires more detailed and higher quality material property data. Detailed models will require air and vapor permeability, moisture diffusivity, and thermal conductivity values, all as a function of temperature, moisture content (RH), and age. Such complete detailed material property data sets are exceedingly rare. While this detailed information exists for a limited number of material samples [*2*], almost no studies have been conducted to quantify the variability of ostensibly similar materials. It is known that some materials (e.g., wood, concrete) can exhibit very wide variations in properties depending on source, manufacturing technique, etc. (See also Chapter 3.)

Modeling the Physics

Several comprehensive and informative review papers from chemical engineering [*3*] and soil science [*4*] appear to provide a more comprehensive view of moisture transport physics than the building science literature. Some of the more recent mathematical models proposed [*5,6*] improve upon the more limited models of Philip and de Vries [*7*] and Luikov [*8*], which have often been used as the basis for building enclosure hygrothermal performance models. The work of Imakoma et al. [*9*] also suggests that great improvements can be made. Building science applications, however, are more dynamic than soil problems, boundary conditions are less accurately known than in chemical process engineering, and, unlike most other disciplines, multi-layer assemblies must be dealt with.

Despite the difficulties, many models have been developed, ranging from the very simple to the most complex practical with the computer resources and knowledge available.

Each detailed model is based on a particular means of modeling the moisture physics. One approach is to choose a driving potential and lump all mechanisms into one total moisture diffusivity function. Another approach is to separate vapor diffusion from liquid transport. In the latter case, one can model the flow as either a parallel process (vapor diffusion and capillary transport) or series (i.e., vapor diffusion functions to a certain moisture content, then capillary conduction takes over). In reality the flow is parallel, although the series approach may be sufficiently accurate in some cases.

Almost all models use an average moisture storage function that does not exhibit hysteresis. Some models only deal with the hygroscopic region.

There is a range of possible moisture driving potentials: vapor pressure, relative humidity, capillary suction stress, or moisture content. (Chemical potential is another little used potential). The argument against vapor pressure is that it drives only vapor diffusion, and hence is not typically used alone. The disadvantage of using moisture content, while physically valid, is that it is discontinuous at material interfaces and hence its use adds mathematical difficulties to the calculations. Capillary suction is likewise a discontinuous function. Relative humidity does not actually drive liquid or vapor flow but is continuous across an assembly. All of the potentials can be related to one another and can be used with the proper transformations (i.e., via Kelvin's equation and the sorption isotherm/moisture storage function).

Vapor diffusion is supposedly a well-understood transport mechanism, although the measurement and understanding of different vapor flow enhancement mechanisms requires more work before a consensus can be reached. Knudsen diffusion (effusion) is explicitly ignored by all building models, but is usually implicitly included in the vapor permeability. Few computer models account for the different temperature dependencies of Fickian and Knudsen diffusion, likely because the differences are small in comparison to the variability of the measured vapor permeability.

Surface diffusion is discussed as a transport mechanism in many of the model developments. Few models explicitly deal with the fact that the adsorbed moisture density gradient is the driving force. Surface diffusion may be implicitly included in models that use measured total moisture diffusivities, but temperature effects must be accounted for and many models use material properties that include only capillary flow driven by suction. In fact, it is important to understand that moisture flow cannot simply be driven by vapor diffusion or capillary suction, but that surface diffusion also acts and all three mechanisms may be acting at some times.

Liquid conductivity is included in most of the detailed models described later, although some of the earlier and simple models use constant diffusivity (even though it usually varies by several orders of magnitude with changing moisture content). One model includes different functions for wetting, drying, and redistribution, although this may be possible to implement in models with multiple sets of data for each material. This is worrying since Karagiozis et al. [*10*] have shown, through parametric modeling, that the use of the proper liquid diffusivity is very important for accurate predictions in some applications. If water content is used as a driving potential, it must be coupled to the suction curve to avoid the erroneous calculation of liquid flow in the supersaturated region (a fictitious liquid diffusivity might also be used).

Gravity-driven liquid flow (i.e., drainage) may be important for the accurate modeling of some types of walls and some conditions (rain penetration). Liquid water not absorbed in the pores of capillary active materials will cling to surfaces until gravity forces overcome surface tension and drainage flow begins. The amount of moisture that clings is a function of the surface on which it is deposited. This surface water can be modeled by assuming a surface material layer with certain moisture storage properties. Most of the models that consider drainage assume perfect drainage (e.g., the water is removed from the enclosure) after a certain amount of moisture is deposited on a surface. Note, however, that liquid water transport is similar to air leakage in that both occur at unknown locations with unknown intensity.

Convective vapor transport, i.e., air leakage, is accounted for in some of the most comprehensive models. The proper modeling of convective airflow and its moisture transport is important to some types of buildings (especially lightweight framed enclosures with incorrectly installed or low-density insulation). Unfortunately, convection is even more difficult to model than diffusive and capillary moisture transport. In practice, most building enclosures are designed as if they are perfect air barriers; in reality, they are not. In order to model air leakage, one must have some knowledge of the flaws. Any models that do include air leakage effects must deal with the fact that the results are only as accurate as the estimate of the flaw in the air barrier. With these limitations in mind, several of the models that do include air leakage have been shown to be quite useful as research tools.

Performance Thresholds

The temperature and moisture conditions at which performance is lost are covered in much greater depth in Chapter 4 of this manual.

The threshold moisture content level that corresponds to most moisture-related damage mechanisms is often equivalent to that material's moisture content when that material is in equilibrium with an environment of approximately 80% RH [*11–13*]. At this relative humidity, both fungal growth and corrosion can be sustained, provided temperature conditions are favorable. This is a first-order estimate, since wood may require higher RH levels for decay fungi to act, and steel may corrode at lower RH levels. Although it may be reasonable and conservative to use the moisture content of a material at 80% RH as a threshold level for performance problems, the actual performance threshold varies with time, temperature, type of deterioration, etc. Liquid water is required for freeze thaw damage and high rates of deterioration. Much more work is required to define the conditions under which most materials will deteriorate.

AVAILABLE ANALYSIS TOOLS

Since all models are simplifications of real behavior, it is difficult to define a demarcation point between simple and detailed models based on their modeling parameters alone. It may instead be more useful to differentiate between models based on the need they are intended to fill. This chapter assumes that the differentiation is based on the intent of the model: detailed models aim to predict actual performance, while the purpose of simplified models is primarily to provide sufficient information to allow designers and analysts to make decisions.

In many design or assessment situations, the results of an analysis must provide sufficient information to accept or reject a particular assembly or material. The relative performance of several assemblies is far more important to a designer with a choice to make than the actual performance of each. A great deal can be learned from "what-if" analysis, especially when tracking the influence of a single variable. In any case, the designer often does not have the resources (time, knowledge, material properties, etc.) to conduct a more detailed analysis. Simple models have been developed to fill this need.

Simple models are not necessarily intended to predict performance accurately, but to provide predictions of sufficient accuracy for the purpose of decision making. Such models must include information from all five of the basic data sets, but simplifying the data significantly. For example, monthly average conditions can be used to represent boundary conditions; three-dimensional airflow can be simplified to one-dimensional steady state; material properties are assumed to be constant, etc.

It is often useful or necessary to conduct a detailed analysis for research, product development, litigation, and historic renovation work. Detailed models have undergone dramatic development in recent years. They are briefly reviewed below.

Heat Flow Models

Heat and moisture flow through building enclosures are inextricably coupled. However, knowledge of only the temperature conditions in an enclosure can still be very useful to the analyst. Numerous computer models exist for the prediction of heat flow through buildings. These programs can be differentiated by the number of dimensions that can be modeled, whether dynamic analysis is possible, and on how they handle radiation and convection at surfaces and in cavities. The most widely used programs in North America, FRAME 4.0 and Therm 2.0, are two-dimensional steady-state models that are especially useful for assessing the thermal performance of windows and other lightweight assemblies. Both of these programs allow for fast analysis of the temperature conditions in an existing or proposed enclosure. The Swedish programs HEAT2 and HEAT3 provide even more information by allowing for the dynamic analysis of two- and three-dimensional structures. All four of these programs are commercially available. HEAT7.2, developed at Oak Ridge National Laboratory (ORNL), has been used widely to solve complex three-dimensional thermal bridging and dynamic heat loss problems [*14*].

Simplified HAM Models

One of the first, and most widely referenced, simple models is Glaser's method [*15,16*], originally published in 1958–59 as a graphical method. This model assumes the building enclosure is one-dimensional and that all moisture transport is driven by vapor diffusion. The *ASHRAE Handbook of Fundamentals* has included a cursory example of this method since the 1981 version. Typically Glaser analysis assumes steady-state boundary conditions for periods ranging from a few days to a few months, and invariant material properties. (See also Chapter 7.)

Several European codes accept the use of Glaser's method for supporting an enclosure design. The German moisture standard, DIN 4108 [*17*], for example, provides the thermal conductivity and vapor permeance of a range of materials, defines the boundary conditions and period of time to be used for both wetting and drying, and even recommends acceptable performance thresholds (e.g., by giving maximum safe moisture contents for various materials). Most North American publications describing Glaser's method assume only one set of boundary conditions (wetting) and even consider any condensation as failure.

While diffusion may be an important moisture transport mechanism in enclosures made of solid, capillary active materials (such as the plaster-finished masonry walls often used in Europe), exfiltration condensation is more important for both energy consumption and moisture tolerance of the lightweight framed assemblies used widely in North America. A simple extension of Glaser's diffusion method can be made that adds simple convection in parallel with diffusion. Such a model considers air leakage to be a diffusive process, uncoupled from heat flow, with no account for latent heat effects. By the further expedient of ignoring hygroscopic adsorption and convective heat flow, several simple models have been developed.

Stewart [*18*] was probably the first to develop such a model. His model used hourly weather data and included solar radiation effects, but it did not gain acceptance likely because it was proprietary. TenWolde [*19*] reported the development of a computer model based on one-dimensional convection and diffusion with no capillary transport but using monthly average temperature and humidity values.

Handegord [*20,21*] developed EMPTIED, Envelope Moisture Performance Through Infiltration Exfiltration and Diffusion for Canada Mortgage and Housing Corporation. It uses monthly bin temperature data (e.g., it does not consider heat storage) and outputs plots of the monthly amount of condensation, drainage, and evaporation. EMPTIED is available free from CMHC, is very easy to operate, and provides fast, generally conservative, results.

DeGraauw [*22*] documented a Simplified Hygrothermal Analysis Method (SHAM) that extended EMPTIED's simple diffusion/convection model by adding guidance for assessing the impact of driving rain, solar radiation, built-in moisture, coupling of convective heat and vapor flow, etc. Although the method typically uses computer spreadsheets and can be easily implemented in a simple computer program, it was developed for use as a pedagogical tool and for designers with an understanding of building science.

Review of Detailed Computer Models

A comprehensive review of available heat, air, and moisture models can be found in the Task 1 Report of the International Energy Agency's Annex 24 [*1*]. This review emphasizes the models that are either available to North American practitioners or have been used in important research.

The models that are discussed below have each been implemented in computer programs that use various finite-element or finite-volume schemes. The numerical virtues and difficulties of each approach are not the primary interest here (although this topic is critical for practical computer models).

Cunningham [*23*] took a simplified approach and used vapor pressure as the only driving potential, as vapor diffusion and convection are assumed to be the only moisture-transport mechanisms in this model. The model used the sorption isotherm to couple moisture content to vapor pressure and a linearly varying vapor diffusion coefficient. Despite the extensive simplifications, the model was validated by simple lab tests [*24*] and extensive in-service monitoring [*25*] of wood-framed roof structures. The limitations of the model are that it cannot deal with rain absorption, situations where capillary active materials are above the critical moisture content, or complex airflows.

WALLDRY [*26,27*] is a simple model that attempts to model the drying of framed wall assemblies by decoupling heat, moisture, and airflow. Moisture transport is considered to be exclusively by vapor diffusion, since capillary transport in wood is a rather slow process. In field validation trials, the model was unable to capture finer details of the drying process, although in some situations it was able to model some features of the moisture transport process. It is a public-domain package available from the Canada Mortgage and Housing Corporation. It is presently being upgraded to better model the drying of walls, especially those that incorporate ventilation behind the cladding.

TRATMO (Transient Analysis Code for Thermal and Moisture Physical Behaviours of Constructions), developed by Kohonen [*28*], was one of the first relatively complete and useful computerized building enclosure models. It used vapor pressure (calculated from the moisture isotherm) and temperature as driving potentials. However, as initially implemented, the moisture diffusivity and vapor permeability were constant, and surface diffusion was included as part of the vapor diffusion term.

Carsten Rode (formerly Pedersen) [*29,30*] used both the sorption and suction curves to define the moisture storage function in his one-dimensional model, MATCH. In the hygroscopic regime the sorption isotherm (defined by an equation that allows hysteresis) is used, and moisture transport is assumed to be by vapor flow only, driven by vapor pressure differences and defined by the vapor permeability of the material. In the capillary regime the suction curve is used together with the hydraulic conductivity to model moisture transport. The more recent research-only version accounts for diffuse air leakage, enthalpy flow, and latent heat. Some validation has been carried out through the use of his own [*31*] and other researcher's [*32*] lab results, although none of the work has involved driving rain deposition or similar natural exposure. MATCH, like the similar MOIST, can probably be used successfully for the approximate analysis and design of protected membrane roofs and walls with non-absorbent cladding.

Burch's MOIST model [*33*] (see Chapter 8) is similar in many respects to Rode's earliest MATCH model. Moisture transport is modeled as vapor flow driven by vapor pressure gradients and capillary transport driven by capillary pressure gradients. The vapor permeability and hydraulic conductivity are both given as functions of moisture content. The latent heat of phase changes is accounted for, as is the increased heat capacity provided by wet materials. Fibrous insulations are assumed to have no moisture storage capacity. No attempt is made to model air leakage, but a useful indoor climate model aids the development of realistic indoor climate data. Simple lab validation tests have been conducted in the hygroscopic range [*34*], with good results, and field comparisons [*35*] (without solar exposure, although it can calculate solar effects) have shown reasonable comparison, so long as the moisture content remained in the hygroscopic range and rain deposition was not involved. It is a public-domain package.

Ojanen et al. built on Kohonen's work to produce TCCD2, (Transient Coupled Convection and Diffusion 2 Dimensional) [*36–38*], a two-dimensional program developed primarily for the analysis of framed building walls. The model uses the same basic physics and mathematical formulation as used in Kohonen's model. A major improvement made over Kohonen's model is the use of moisture content dependent diffusivity. Convection airflow is accounted for as well as condensation (and frost formation) and evaporation, but capillary transport and surface diffusion must be lumped into the vapor diffusion process. It has been validated with laboratory experiments and has been shown to provide useful information regarding the impact of convective flows on hygrothermal performance [*39*].

Kerestecioglu et al. [*40,41*] have produced a comprehensive and flexible program called FSEC, which contains a library of differential equations, different finite elements, and various functional relationships for materials properties. This commercially available program can account for all of the moisture transport mechanisms, including convection, but in the implementation liquid and vapor flow are described by different sets of equations. Vapor is driven by vapor pressure differences, and liquid flow is driven by capillary suction. Surface diffusion is not explicitly handled. A great deal of user knowledge is required to operate the program.

The Windows-based WUFI [*42*] (see Chapter 9) was developed by Hartwig Kuenzel but is supported by the comprehensive work of Kiessl, Krus, and other workers at the Fraunhofer Institut fuer Bauphysik. This model uses a full moisture retention function, from the sorption isotherm and suction curve. Surface diffusion and liquid transport are driven by RH (and capillary suction via Kelvin's equation) and governed by a combined moisture diffusivity. Vapor diffusion is considered separately. All of the material properties can be defined arbitrarily as a function of moisture content (or RH) by entering a series of points (from, for example, measurements) or approximated from several important behavioral markers, like the absorption coefficient, capillary saturation, and dry-cup vapor permeance. Important features of this model are its ability to incorporate driving rain deposition as part of its boundary conditions, the use of different liquid moisture diffusivities for wetting and drying/redistribution processes, the ease of use, stability of the calculations, and the degree of field validation. The close fit between model predictions and many full-scale field validation exercises of a variety of walls and roofs over several years demonstrates the quality and robustness of this model. Its major limitations are its inability to handle air leakage and the associated energy and moisture flow. A two-dimensional version, WUFIZ, exists but has to date only been used as a research tool [*43*]. A version of WUFI ORNL/IBP for North America is enclosed in this manual.

LATENITE developed by Karagiozis and Salonvaara [*44–46*] is likely the most comprehensive heat, air, and moisture model available. Using a complete moisture storage function (e.g., sorption isotherm and suction curve), the model considers vapor and liquid transport separately, driven by vapor pressure and suction, respectively. The vapor permeability and liquid diffusivity vary with moisture content (surface diffusion is included in the liquid diffusivity) in an arbitrary way (defined by the user). Airflow, gravity drainage, driving rain deposition, moisture sources (e.g., leaks), wind, and stack pressures can all be incorporated into a simulation of up to three dimensions if desired. Driving rain can be comprehensively modeled through the use of a sophisticated commercially available CFD package as a pre-processor. Stochastic modeling can be used to assess the influence of inaccurate or variable material properties and boundary conditions. One, two, or three dimensions can be modeled, but only one- and two-dimensional calculation results [*47*] have been presented. Although this model has not been field verified, it was found to be reliable in the recent IEA Annex 24 comparison project.

CONCLUSIONS

In this chapter we have attempted to provide a general overview of a major technical field, namely, the building enclosure and its analysis and thus its design and performance. What is perhaps unique in this overview is the fact that need is used as the basis for assessment, i.e., whose need (designer, student, or researcher) and the nature of this need (money and time available, accuracy, intent, etc.). Implicit in this approach is the consideration of the experience and competence of the analyst—in fact, the critical element in the process is the ability of the analyst to define the problem correctly and to choose the appropriate methodology, data, and tool to resolve the problem. Furthermore, there is the fundamental need to learn and thus, conversely, to teach, and then gain experience. It follows that there is no single software or model that is best nor only one way to do things.

At the entry or most fundamental level, an essentially manual, relatively simple approach incorporating heat, water vapor, and airflow is recommended. With some experience this procedure can readily be adapted to a standard spreadsheet and thus computerized. At the next level, the analyst might want to learn to use software packages such as MOIST, and EMPTIED, which is useful in wetter and cooler climates, and WUFI ORNL/IBP. At the next level, one might wish to purchase a proprietary software package, such as the original WUFI, in order to expand one's capabilities. Beyond this level, the issue becomes problematic. At this time, programs such as Latenite are not available for general use. It is likely to be some time before this level of modeling is available or even needed for general design office use. First, the software has to be user friendly; second, the analyst has to be capable of making proper use of this level of analytical capability.

This brief overview of heat, air, and moisture analysis methods has emphasized the analysis needs of various groups. The review has shown that there are numerous computer models with a range of capabilities. More attention should be paid to developing a consensus about a simplified, manual methodology.

Wider use of hygrothermal analysis would foster the design and production of better buildings and building products. However, the largest user group, designers, are hampered more by the need for both education and training on how to conduct and interpret HAM analysis rather than the availability of sophisticated and accurate computer models. Researchers, code writers, and building product manufacturers often require better analysis tools than are presently available, preferably analysis tools with field and experimental validation.

REFERENCES

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