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Standard Guide for Characterization and Use of Hygrothermal Models for Moisture Control Design in Building Envelopes[1]

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1. Scope

1.1 This guide offers guidance for the characterization and use of hygrothermal models for moisture control design of building envelopes. In this context, "hygrothermal models" refers to the application of a mathematical model to the solution of a specific heat and moisture flow performance issue or problem. Hygrothermal models are used to predict and evaluate design considerations for the short-term and long-term thermal and moisture performance of building envelopes.

1.2 Each hygrothermal model has specific capabilities and limitations. Determining the most appropriate hygrothermal model for a particular application requires a thorough analysis of the problem at hand, understanding the required transport processes involved, and available resources to conduct the analysis. Users of this guide can describe the functionality of the hygrothermal model used in an analysis in a consistent manner.

1.3 This guide applies to hygrothermal models that range from complex research tools to simple design tools. This guide provides a protocol for matching the analysis needs and the capabilities of candidate models.

1.4 This guide applies to the use of models that include all or part of the following thermal and moisture storage and transport phenomena: *(1)* heat storage of dry and wet building materials, *(2)* heat transport by moisture-dependent thermal conduction, *(3)* phase change phenomena (for example, evaporation and condensation), *(4)* heat transport by air convection, *(5)* moisture retention by vapor adsorption and capillary forces, *(6)* moisture transport by vapor diffusion (molecular and effusion), *(7)* moisture transport by liquid transport (surface diffusion and capillary flow), and *(8)* moisture (vapor) transport by air convection.

1.5 This guide does not apply to cases requiring analysis of the following: *(1)* convection that occurs in a three-dimensional manner or through holes and cracks; *(2)* hydraulic, osmotic, or electrophoretic forces; *(3)* salt or other solute transport; or *(4)* material properties that change with age.

1.6 This guide intends to provide guidance regarding the reliability of input and how the corresponding results can be affected as well as a format for determining such information.

1.7 *Units*—The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system are not necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined.

1.8 *This guide offers an organized characterization of hygrothermal models and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM International consensus process.*

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the*

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Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C168 Terminology Relating to Thermal Insulation

E283/E283M Test Method for Determining Rate of Air Leakage Through Exterior Windows, Skylights, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen

E331 Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference

E631 Terminology of Building Constructions

E2273 Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies

E2357 Test Method for Determining Air Leakage Rate of Air Barrier Assemblies

2.2 *Other Standards:*

ANSI/ASHRAE 160-2009 Criteria for Moisture-Control Design Analysis in Buildings[3]

DIN EN 15026 Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation[4]

WTA Guideline 6-2-01 Simulation of Heat and Moisture Transfer[5]

3. Terminology

3.1 *Definitions:* For definitions of terms used in this guide, see Terminologies C168 and E631.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *air-leakage rate, n*—volume of air movement per unit time across the building envelope.

3.2.1.1 *Discussion*—this movement includes flow through joints, cracks, and porous surfaces, or a combination thereof. The driving force for such an air leakage in service can be mechanical pressurization and depressurization, natural wind pressures, or air temperature differentials between the building interior and the outdoors, or a combination thereof.

3.2.2 *analytical model, n*—model that uses closed-form solutions to the governing equations applicable to hygrothermal flow and transport processes.

3.2.3 *building envelope, n*—boundary or barrier separating the interior volume of a building from the outside environment or different interior environment.

3.2.3.1 *Discussion*—For the purpose of this guide, the interior volume is the deliberately conditioned space within a building, generally not including attics, basements, and attached structures, for example, garages, unless such spaces are connected to the heating and air conditioning system, such as a crawl space plenum. The outside environment may be weather conditions or any other known conditions that the exterior of the building envelope is exposed to. An interior partition that separates two dissimilar environments such as a cold storage facility adjacent to an occupied office can be treated as a building envelope element for modeling purposes.

3.2.4 *building envelope model, n*—portion of the building envelope, such as a wall, roof, floor, window, or door, or a combination thereof. The building envelope model comprises all of the components and materials as they are configured within the building envelope assembly (for example, the wall or roof assembly) at a given location.

3.2.5 *computer code (computer program), n*—assembly of numerical techniques, bookkeeping, and control language that represents the model from acceptance of input data and instructions to delivery of output.

3.2.6 *conceptual model, n*—interpretation or working description of the characteristics and dynamics of the physical system.

3.2.7 *finite difference model, n*—type of approximate, numerical model that uses a discretization technique to linearize the governing partial differential equations (PDE) consisting of replacing the continuous domain of interest by a finite array of spaced mesh or grid points (that is, nodes) spaced along the coordinate direction(s) of the one-, two-, or three-dimensional geometric coordinate system. The grid points define a set of control volumes representing volume-averaged subdomain properties. The derivatives of the PDE for each of these points are approximated using finite differences. The resulting set of linear or nonlinear algebraic equations are solved using direct or iterative matrix-solving techniques.

3.2.8 *finite element model, n*—type of approximate, numerical model that uses a discrete technique for solving the governing PDE wherein the domain of interest is represented by a finite number of mesh or grid points (that is, nodes), information between these points is obtained by interpolation using piecewise continuous polynomials, and the resulting set of linear or nonlinear algebraic equations is solved using direct or iterative matrix-solving techniques.

3.2.9 *functionality, n*—of a hygrothermal model, the set of functions and features the model offers the user in terms of building envelope framework geometry, simulated processes, initial and boundary conditions, and analytical and operational capabilities.

3.2.10 *hygrothermal model, n*—a mathematical model that includes various thermal and moisture transport mechanisms with boundary system performance under applied conditions to represent a building envelope system or subsystem.

3.2.10.1 *Discussion*—May be either steady-state or transient approach and may be based on equations derived from basic principles of physics, established engineering functional

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329, http://www.ashrae.org.

[4] Available from Deutsches Institut für Normung e.V. (DIN), Am DIN-Platz, Burggrafenstrasse 6, 10787 Berlin, Germany, http://www.din.de.

[5] Available from Wissenschaftlich-Technische Arbeitsgemeinschaft für Bauwerkserhaltung und Denkmalpflege (WTA) e.V., Ingolstädter Str. 102, D-85276 Pfaffenhofen, Germany, http://www.wta-international.org.

relationships, statistical interpretations of empirical data, or a combination of all of these approaches.

3.2.11 *hygrothermal model code, n*—computer code used in hygrothermal modeling to represent a non-unique, simplified mathematical description of the physical framework, geometry, active processes, and initial and boundary conditions present in a building system.

3.2.12 *model selection, n*—process of choosing the appropriate computer model as an analysis tool capable of simulating those characteristics of the physical system required to fulfill the project's objective(s).

3.2.13 *Moisture Reference Year, MRY*—a year of hourly weather data that have been selected for use in hygrothermal analysis.

3.2.14 *numerical model, n*—model that uses numerical methods to solve the governing equations of the applicable problem.

3.2.15 *water penetration, n*—a process in which water gains access into a material or system by passing through the surface exposed to the water.

3.2.15.1 *Discussion*—For products with non-planar glazing surfaces (domes, vaults, pyramids, and so forth), the plane defining water penetration is the plane defined by the innermost edges of the unit frame.

3.3 *Symbols:*

q_v = mass flux rate of vapor flow (kg/m^2·s [lb/ft^{2}s])
X = vapor concentration (kg/m^3[lb/ft^3])
δ_p = water vapor permeability (kg/Pa·m·s [Perm-in])
h_e = specific latent heat of evaporation or condensation (J/kg [Btu/lb])
h_f = specific latent heat of fusion (freezing or melting) (J/kg [Btu/lb])
g_{air} = air mass flux (kg/m^{2}s [lb/ft^{2}s])
I_{il} = moisture content changing phase from ice to liquid (kg/m^{3}s [lb/ft^{3}s])
λ = thermal conductivity (W/mK [Btu/h·ft·°F])
m_{dry} = mass of dry material (kg [lb])
m_{wet} = mass of wet material (kg [lb])
P_{air} = air pressure (Pa [psi])
P_e = exterior air pressure (Pa [psi])
P_i = interior pressure (Pa [psi])
ρ_w = density of water (kg/m^3 [lb/ft^3])
ρ_s = dry density of material (kg/m^3 [lb/ft^3])
ρ_{air} = dry density of material (kg/m^3 [lb/ft^3])
c_w = specific heat capacity of liquid water (J/kgK [Btu/lb°F])
c_s = specific heat capacity of dry material (J/kgK [Btu/lb°F])
c_a = specific heat capacity of dry air (J/kgK [Btu/lb°F])
η = dynamic viscosity (s·Pa [lb·s/ft^2])
k_a = air permeability (m^2 [ft^2])
T = temperature (K [°F])
ϕ = relative humidity (-)
q_l = liquid transport flow (kg/m^{2}s [lb/ft^{2}s])
u = moisture content (kg/kg [lb/lb])
t = time (s)
x = x–coordinate
D_ϕ = liquid conduction coefficient (kg/ms [lb/ft•s])

4. Significance and Use

4.1 This guide is intended to provide the framework for characterizing the functions of the hygrothermal model and the level of sophistication used as inputs for each analysis. Hygrothermal modeling has become an important practice in support of the decision-making design processes involved in moisture management of building envelope systems. Increasingly, hygrothermal models are an integral part of building envelope performance assessment, retrofit, and restoration studies and provide insight in the screening of alternative design approaches affecting water management of the envelope system. Hygrothermal models are used in decision making during the design process of building envelope systems. They may also be used to assess performance of the envelopes of existing buildings, or to predict envelope performance in buildings undergoing retrofit, change in use, restoration or flood remediation. It is, therefore, important to have a methodology to document the model used in a hygrothermal investigation. This documentation provides needed characterization of the hygrothermal model to assess its credibility and suitability. This becomes even more important because of the increasing complexity of the building envelope systems for which new hygrothermal models are being developed. There are many different hygrothermal models available, each with specific capabilities, operational characteristics, and limitations. If modeling is considered for a project, it is important to determine if a hygrothermal model is appropriate for that project, or if a model exists that can perform the simulations required in the project.

4.2 Quality assurance in a hygrothermal analysis using modeling is achieved by using the most appropriate model with all important transport mechanisms, initial conditions, and boundary conditions. A well-executed quality assurance program in hygrothermal modeling requires systematic and complete documentation of the model and the inputs followed by consistent reporting of the results. This guide sets forth a format for reporting hygrothermal modeling results.

5. Hygrothermal Model Analysis Inputs

5.1 There are many hygrothermal models available to simulate, describe, or analyze different building envelope systems and the moisture migration characteristics that affect their performance. Therefore, it is important to understand the performance characteristics for which the model is intended to represent and recognize the evaluation of the model is only relevant for the performance characteristics it addresses. If the appropriate analytical and input techniques are applied to the model, then the results obtained should provide a valid solution to address the system deficiencies. Fig. 1 displays the various inputs and outputs needed for hygrothermal simulations. The effectiveness of the results is largely a function of the degree to which the model represents the system studied. Additionally, the inputs (climate data, orientation inclination, and material characteristics) are not addressed. Their influence on the calculation results is, however, very important (often more important than the capability of the hygrothermal model). This

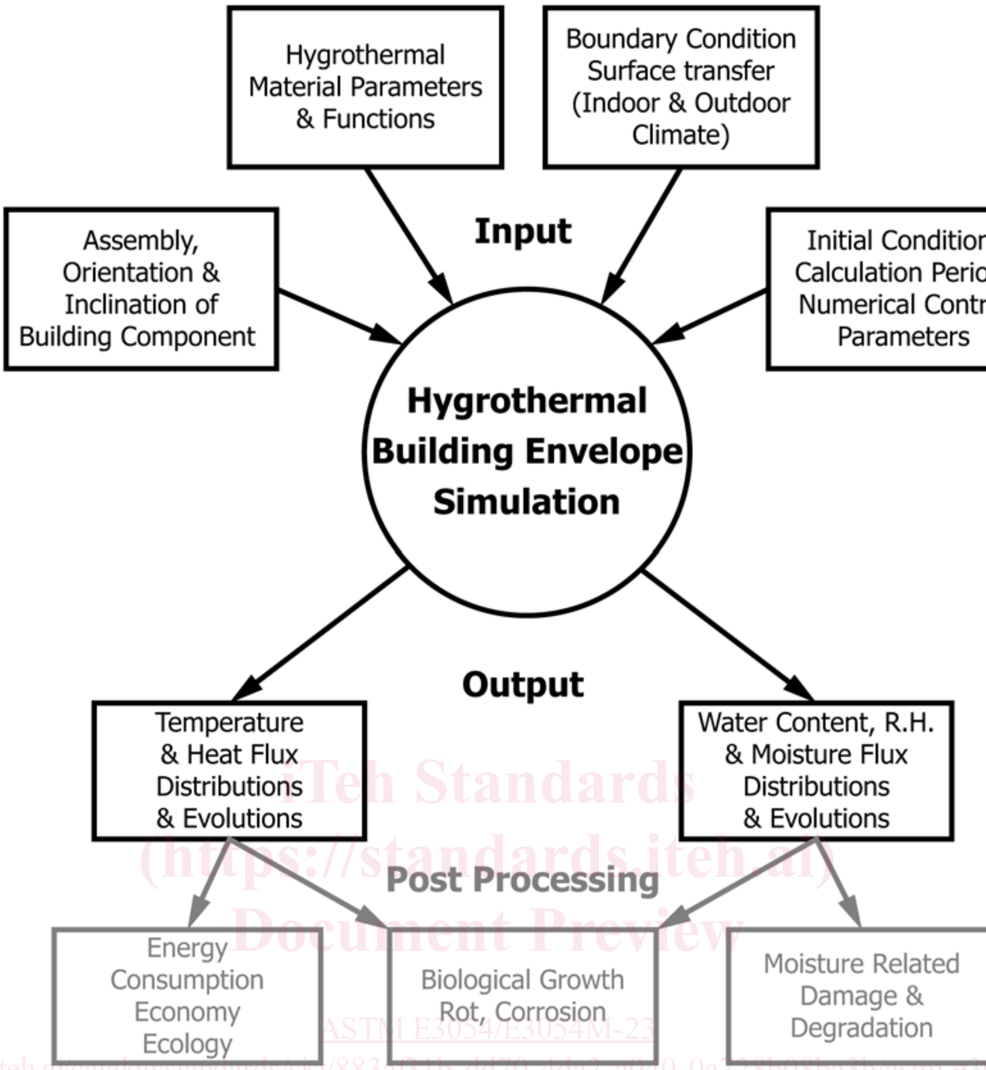

FIG. 1 Input and Output Chart for Hygrothermal Simulations

guide is complementary to the ASHRAE 160 Standard, DIN EN 15026, and WTA Guideline 6-2-01 that describes the design criteria for use in hygrothermal models.

5.2 A descriptive approach that can be used to classify hygrothermal models is discussed in the following. Fig. 2 describes graphically the descriptive approach proposed in this standard. Additional information related to the classification details are found in Karagiozis,[6] Trechsel (Chapter 1),[7] and Kuenzel.[8]

5.2.1 *Nature of Equations (D, S)*—Decision-making problems can be classified into two categories: deterministic or stochastic/probabilistic decision models. In deterministic models, point value results are expected; therefore, the outcome is deterministic. This depends largely on how influential the uncontrollable factors are in determining the outcome of a decision and how much information the decision-maker has in predicting these factors. When there could be a range of correct answers for a particular problem, then the analysis is stochastic. Models can therefore be:

5.2.1.1 *Deterministic (D)*—A single value solution to the equation set, or

5.2.1.2 *Probabilistic (S)*—Statistical variation of solution values to the equation set.

5.2.2 *Temporal Nature (ST, T)*—Two types of temporal models can exist. The first type defined as steady-state is when all transport processes achieve a state in which equilibrium occurs. The second type defined as transient state occurs when the transport processes are transitioning between two steady states. Hygrothermal transport in building applications is primarily a transient condition. Below the distinguishing features are presented in a 1-D diffusion transport framework.

5.2.2.1 *Steady-State (ST) (Time-Invariant Hygrothermal Models):*

[6] Karagiozis, A., "Chapter 6--Advanced Numerical Models for Hygrothermal Research," in *Moisture Analysis and Condensation Control in Building Envelopes,* MNL 40, H. R. Trechsel, Ed., ASTM International, West Conshohocken, PA, 2001

[7] *Moisture Control in Buildings*, MNL 18, H. R. Treschel, Ed., ASTM International, West Conshohocken, PA, 1994.

[8] Künzel, H. M., "Simultaneous Heat and Moisture Transport in Building Components--One and Two-Dimensional Calculation Using Simple Parameters," Dissertation, University of Stuttgart, 1994.

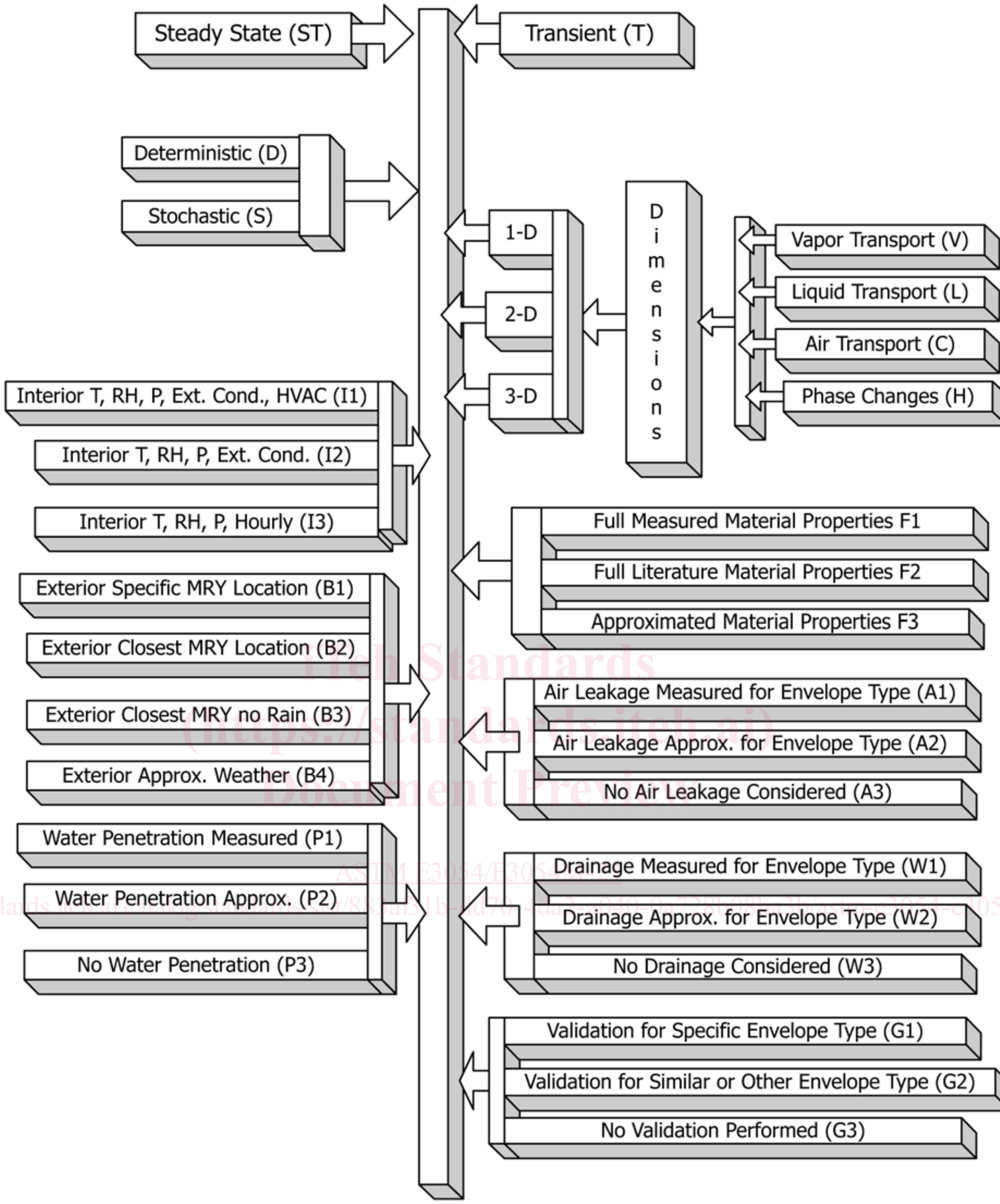

FIG. 2 Flow Chart for Hygrothermal Modelling Analysis

Energy Transport:

$$\left(c_s\rho_s + \cancelto{0}{c_w\rho_w}\right)\cdot\frac{\partial T}{\partial t} = -\frac{\partial q}{\partial x} + S \quad (1)$$

Moisture Transport:

$$\cancelto{0}{\rho_s\frac{\partial u}{\partial t}} = -\frac{\partial}{\partial x}\left(\underbrace{-\delta_P\frac{\partial P_v}{\partial x}}_{q_v} - \underbrace{D_\phi\frac{\partial \phi}{\partial x}}_{q_l} + \underbrace{g_{air}X}_{q_{air}}\right) + S_W \quad (2)$$