# Systematic Review of Hygrothermal Computational Tools for New and Existing Buildings

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## ABSTRACT

The use of multiple design strategies seeking energy efficiency in buildings can offer a wide range of opportunities to improve energy and thermal performance. While thermal resistance is typically considered of high importance, to achieve energy efficiency and prolong the durability of buildings, hygrothermal conditions must also be taken into account. As new technology develops that is capable of measuring a given structure's real-time data, the research community is increasingly relying on software and tools for hygrothermal assessments of buildings. As the tools vary widely in both extent and functionality, defining a method to identify the effectiveness and accuracy of hygrothermal tools for various project scopes presents a technical challenge.

This paper presents a systematic review that organizes and summarizes a range of different software for hygrothermal assessment of new and existing buildings. This research review 11 hygrothermal models and tools based on three main characteristics: (1) interface and information transference, (2) hygrothermal assessment and scope, and (3) context and standards. This review seeks to offer a better understanding of technical tools for hygrothermal performance assessment to assist architects, engineers, and designers, promoting last-longing interventions, and improving assessments' accuracy for energy-use estimations.

## Introduction

The combined effect of heat and humidity, also known as hygrothermal movement, influences the energy performance of buildings and impacts the overall comfort of occupants (Tariku, Kumaran, & Fazio, 2011). The term "hygrothermal" refers to this movement of heat and moisture through a building (Delgado, Ramos, Barreira, & De Freitas, 2010). Moisture and thermal gradients arise from the difference in outdoor and indoor relative humidity and temperature conditions. Responses of buildings to such conditions depends heavily on their assemblies' design and exposure over time (Mukhopadhyaya, Kumaran, Tariku, & Van Reenen, 2006). Hygrothermal behavior in uninsulated buildings' assemblies is relatively simple to predict. However, in buildings that feature extra thermal insulation, air-seals, and/or vapor-retardant layers, hygrothermal performance becomes more complex and difficult to predict, which can increase the risk of envelope failure (Melton & Yost, 2014). Excessive moisture can cause problems such as dampness, condensation, mold, and rapid building envelope failure. In some cases, it can also reduce thermal performance, consume more energy than estimated, and create or exacerbate health problems among occupants (Mullen et al., 2016), making hygrothermal performance a highly significant topic in building physics and especially in efforts to achieve current standards in the design of high-performance buildings (Tariku, Kumaran, & Fazio, 2015).

The issue of moisture in buildings has attracted interest from the outset of the 2000s, but has gained even more attention in the past few years as modeling capabilities to predict hygrothermal performance have advanced across different disciplines (Delgado et al. 2010), including architectonic design and forensics (Desjarlais, Pierce, & Pallin, 2017). An important advantage of these hygrothermal models is the ability to rapidly assess the expected performance of constructive solutions, highlight problematic areas in the building envelope, and predict potential long-term problems likely to arise from deficient design and construction (Parker & Lozinsky, 2010), producing constructive pathologies and identifying potential damage to the building envelope. Moreover, widespread interest in assessing hygrothermal behavior in buildings has arisen (Mukhopadhyaya et al., 2006) as new trends in high performance and green buildings push envelope performance to its utmost, with ever-more project teams seeking out this type of modeling. These new practices are likely to change the ways engineers and others view existing construction systems and their hygrothermal behavior in buildings' envelopes (Glass, TenWolde, & Zelinka, 2013).

While extant literature explores many computer simulation programs for hygrothermal assessment, these tools usually diverge widely in terms of their scopes and sophistication level (Straube & Burnett, 2001). Assessment tools often take into consideration aspects such as boundary conditions (both indoors and outdoors), moisture transfer dimension, type of flow, materials, and construction quality – among other elements (Mumovic, Ridley, Oreszczyn, & Davies, 2006). Depending on the project, these factors can interact to produce unexpected complexities that are difficult to untangle (Melton & Yost, 2014), producing uncertainties in terms of accuracy. For that reason, understanding the advantages and limitations of the available models and tools is key to achieving proper insights of the implications of hygrothermal assessment in envelopes.

To date, few attempts have been made to systematically review the available computational tools for hygrothermal analysis in the building sector. Worth noting among these is the repository of tools for hygrothermal assessment and models provided by Canada Mortgage and Housing Corporation (CRDBER, 2014), as well as the research of Delgado (2010) regarding hygrothermal numerical simulations. Both research projects identified over sixty models and computational tools; however, most of these remain unavailable for public use. The objective of this paper is to provide a systematic review that organizes and summarizes publicly available models and computational tools for hygrothermal assessment of building envelopes in the literature. The main goal is to provide an overview of the diversity of approaches currently used to evaluate hygrothermal performance in buildings, considering scope, boundary conditions, user interface, and delivery of validation outputs integrated with hygrothermal standards and/or existing policies.

## Method

A systematic review was performed to collect and analyze hygrothermal tools and models. This process included a four-step screening protocol:

**Phase 1 – Collect:** A keyword search was performed for publications and web articles included in these scientific collections: EBSCO, Web of Science, google scholar and ScienceDirect. For this search, a combination of keywords was used: "hygrothermal performance," "hygrothermal model," "hygrothermal simulation," and "hygrothermal tools."

**Phase 2 – Select:** The above search brought up 24 hygrothermal models and computational tools for the prediction and assessment of hygrothermal behavior. The process included a quick on-line availability check. While several models and tools have been developed, many remain restricted and unavailable for public use. This factor reduced the selection to 11 tools.

**Phase 3 – Analyze and categorize:** The 11 publicly available tools were studied and described. Evaluation based on three main conditions:

*Hygrothermal assessment:* capacity to provide an evaluation of measures for residential buildings by delivering accurate results. This includes the description of main capabilities of the tools, their model type and dimension scope.

*Interface and information transference:* capacity to deliver models taking into account user expertise, language platform and the license type.

*Context and standards:* in addition to hygrothermal assessment, capacity to provide outputs according to international standards, providing solutions and recommendations in terms of strategies and guidelines.

**Phase 4 – Report:** The 11 tools were outlined in terms of model capabilities, model assessment, expertise required, language or platform, type of license and international standards compliances or validations.

## Results

The entire set of hygrothermal models and tools are summarized in the following table. This table includes the developer, country of origin, the last update and whether or not it is possible to download for public use.

Table 1: Software and models for hygrothermal assessment found in the literature

| Model / software | Available to download | Developer | Country | Last update | Reference |
|---|---|---|---|---|---|
| 1D HAM 2.0 | ✓ | Chalmers University of Technology and Massachusetts Institute of Technology | Sweden and USA | 2000 | (Hagentoft & Blomberg, 2000) |
| AnTherm | ✓ | Kormicki | Germany | 2019 | (Kormocki Dienstleistungen, 2020) |
| CLIM 2000 | | Electricite de France | France | 1991 | (Gautier, Rongere, & Bonneau, 1991) |
| COMSOL | ✓ | Comsol | Sweden | 2020 | (Comsol Inc, 2020) |
| Delphin 6 | ✓ | Technical University of Dresden | Germany | 2019 | (Bauklimatik Dresden Software, 2020) |
| Domus 2.0 | | Pontifical Catholic University of Parana | Brazil | 2003 | (Mendes, Oliveira, & Santos, 2003) |

| | | | | | |
|---|---|---|---|---|---|
| EMPTIED | | CMHC | Canada | 1999 | (Straube & Burnett, 2001) |
| ESP-r | ✓ | University of Strathclyde | United Kingdom | 2019 | (University of Strathclyde, 2020) |
| GLASTA | ✓ | Physibel | Belgium | 2009 | (Physibel, 2020) |
| HAM-Tools | | Chalmers University | Sweden | 2004 | (Kalagasidis, 2004) |
| HAMFitPlus | | Concordia University | Canada | 2011 | (Tariku et al., 2011) |
| HygIRC | | Institute for Research in Construction | Canada | 2003 | (Cornick, Maref, Abdulghani, & van Reenen, 2003) |
| IDA-ICE | ✓ | EQUA | Sweden | 2018 | (EQUA, 2020) |
| LATENITE V1, V1.2 | | Institute for Research in Construction | Canada | 1996 | (Geving, Karagiozis, & Salonvaara, 1997) |
| MATCH | | Thermal Insulation Laboratory | Denmark | 1990 | (Pedersen, 1991) |
| MOIST | ✓ | National Institute of Standards and Technology | US | 1997 | (NIST, 1997) |
| MOISTURE-EXPERT | | Oak Ridge National Laboratory | US | 2001 | (Karagiozis, 2001) |
| TCCC2D | | VTT Building Technology | Finland | 1984 | (Ojanen & Systems, 1994) |
| THERM | ✓ | Lawrence Berkley National Laboratory | US | 2020 | (LBNL, 2020) |
| TRATMO | | VTT Building Technology | Finland | 1984 | (Kohonen, 1984) |
| UMIDUS | | Pontifical Catholic University of Parana | Brazil | 1999 | (Mendes, Ridley, Lamberts, Philippi, & Budag, 1999) |
| WALLDRY | | CMHC | Canada | 1988 | (Schuyler, Swinton, & Lankin, 1989) |
| Wufi | ✓ | Fraunhofer Institute | Germany | 2019 | (Fraunhofer Institute, 2020) |
| TasAmbiens 2D | ✓ | EDSL | United Kingdom | 2019 | (EDSL, 2020) |

From the total 24 tools found, 11 of them were available for public use. These tools are analyzed and described as follow:

- **1D-HAM:** This tool solves problems of one-dimensional coupled heat, air, and moisture transport for a multi-layered wall. The program uses a finite difference technique and includes a time difference analysis. Moisture is transferred by diffusion and convection in the vapor phase. No liquid water transport occurs. Heat is transferred by conduction, convection, and latent heat.

- **AnTherm:** This program addresses the thermal behavior of building constructions with heat bridges and is used to analyze heat flow calculation among building components. It has a user-friendly interface for inputs and delivers quick and accurate assessments. It also calculates temperature distributions and heat flows in building structures, particularly thermal bridges. 2D and 3D modeling of thermal and hygrothermal performance. It includes calculations for harmonic and transient periods.
- **COMSOL:** This program includes a comprehensive set of features for investigating thermal designs and effects of heat loads. Users can model the temperature fields and heat fluxes in devices, components, and buildings. This software is capable to perform Multiphysics and  whole building simulations. It is highly suitable for researchers having a good understanding of building physics, mechanical engineering.
- **Delphin:** This one- or two-dimensional model shows transport of heat, air, moisture, pollutants, and salt in porous building materials, assemblies of such materials, and building envelopes in general. This software can generate one, two- and three-dimensional calculations simultaneously. Besides its capacity to calculate mold, it can also include the assessment of VOC transportation. Its library includes a large number of materials with anisotropic properties. New materials properties and functions can be added and or defined. It also detects drying problem and mold growths, calculates thermal bridges and is able to evaluate the hygrothermal performance inside the insulation and ventilated envelopes.
- **ESP-r:** Environmental Systems Performance Research is a modeling tool for building performance simulation equipped to model heat, air moisture, light, and electrical power flow at user-specified spatial and temporal resolutions. This tool has a range of different capacities to calculate thermal, visual and acoustic performance in complex buildings and systems. While this tool can provide holistic nature and range of features, users need specific and deep knowledge to complete tasks.
- **GLASTA:** This program uses the improved Glaser method for vapor transfer, condensation, and drying. It has three different calculation modes that can be used to check whether condensation occurs for a series of steady-state boundary conditions on both sides of a wall. It also provides assessments of multi-layered walls with indoor and outdoor climates and it is operational in five languages. This software requires only basic knowledge about heat and mass transfer.
- **IDA-ICE:** This tool generates a simulation of building energy consumption, indoor air quality, and thermal comfort, covering a large range of phenomena such as integrated airflow network and thermal models, CO2 and moisture calculation, and vertical temperature gradients. It uses a whole-building approach with a dynamic multi-zone simulation application to estimate the best model available. It has a modular structure that allows developing personalized extensions for simulations and it is able to use parametric optimizations. This software is for qualified engineers or designers with knowledge of building technologies and environmental control systems.
- **MOIST 3:** This is a user-friendly computer tool that predicts a one-dimensional transfer of heat and moisture in building envelopes. It is able to model simple and complex geometry such as walls, cathedral ceilings, or sloped roofs. This tool predicts the winter

moisture content in the exterior construction layer and whether a vapor retarded is needed. It provides assessments of relative humidity of surfaces in hot and humid climates and determines drying rates for materials.

- **THERM:** This drawing-based program allows users to calculate the thermal performance of specific assemblies based on composition and orientation. It is used primarily in conjunction with WINDOW, another LBNL software program, to calculate the U-values of glazing systems. It can also be used to determine various thermal properties, such as R-values and solar heat gain coefficients, of wall or roof assemblies. This tool offers a powerful drawing capability that makes it easy to model the geometry of cross-section and complex geometries. While software knowledge is required, it includes comprehensive documentation for learning.
- **Wufi:** This is a family of software products that includes the ***Wufi 6.4,*** a standard 1D tool that assesses moisture conditions in building envelopes. The most user-friendly and the easiest WUFI version in the market, it performs hygrothermal calculations including built-in moisture, driving rain, solar radiation, long-wave radiation, capillary transport, and summer condensation. Another member of the Wufi is the ***Wufi 2D,*** **an** upgraded version of WUFI pro, which incorporates 2D dimensions to assess complicated geometries such as corners, windows locations, and foundation connections. This tools also allows customize materials and add climate data files. The third and last Wufi tool is ***Wufi Plus*****.** The Plus version includes a 3D function that allows users to model whole buildings. This version also simulates the indoor environment and is capable of assessing both comfort and energy consumption in buildings. Extra modules enable analysis of thermal bridges and air exchange between conditioned zones and outdoors.
- **TasAmbiens2D:** This is a 2D tool that allows determining the effect of local air conditions on occupant comfort based on several comfort parameters, including radiant temperature, airflow, airflow temperature, humidity, metabolic rate, and clothing. It has a friendly interface that creates geometry by drawing a 2D slice through space. This program allows the creation of video with the interaction among the different comfort parameters and their behavior over time.

Table 2 shows hygrothermal assessments, interface and information transference and standards and validations for these 11 tools selected.

Table 2: Hygrothermal assessment features, Expertise, Interface, Standard extensions/validation.

| Software | Hygrothermal assessment | | | | | | | Expertise | | | Interface | | Standard extensions/validations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1D | 2D | 3D | H | M | A | O | lo | me | hi | Platform | License | |
| 1D HAM 2.0 | ✓ | | | ✓ | ✓ | ✓ | | | ✓ | | Windows | Required | No information |
| AnTherm | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | Windows | Required, free to try | EN ISO 10211; EN ISO 10077; EN ISO 13786 |
| COMSOL | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | Windows,<br>OS X,<br>Linux | Required, free to try | ISO 10077 |
| Delphin 6 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | Windows | Free for educational purposes, commercial license options | EN 150226:2007; EN 10211:2007 |
| ESP-R | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | Unix,<br>Windows | Free/Open source license | International validations, IEA Annex, BRE, EC PASSYS project |
| GLASTA | ✓ | | | ✓ | | ✓ | | ✓ | | | Windows | Required, free to try | EN 13788: DIN 4108 |
| IDA-ICE | | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | Windows | Required, free to try | ASHRAE 90.1-2010 |
| MOIST | ✓ | | | ✓ | | ✓ | | | ✓ | | Windows | Free/Open source license | ASHRAE WYEC (US cities). |
| THERM | | ✓ | | ✓ | | | | | ✓ | | Windows | Free/Open source license | ISO 15099 |
| Wufi 2D | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | Windows | Required, student license options | ASHRAE Standard 160-2009; ASHRAE Fundamentals; EN 15026; DIN 4108; WTA Code 6-1-01/D; WTA Code 6-2-01/D; BBR2011 |
| Wufi plus | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | |
| Wufi Pro | ✓ | | | ✓ | ✓ | ✓ | | | | ✓ | | | |
| TasAmbiens2D | | ✓ | | ✓ | | ✓ | | | ✓ | | Windows | Required, student license options | ASHRAE 140-1; EN-ISO 13791; EN-ISO 15255; EN- ISO 15265 |

1D: 1 dimension, 2D: 2 dimensions, 3D: 3 dimensions. H: Heat, M: Moisture, A: Air, O: Other parameters such as the estimation of pollutants transportation, and ventilation. Expertise level: lo= basic understanding of building physics, no steep learning curve; me= Good understanding of building physics; and hi= High level of knowledge in building physics and computational background.

## Discussion

This paper presents a preliminary review of 11 tools used for the hygrothermal assessment of building envelopes. Evaluation was based on three main parameters: hygrothermal assessment, interface, and information transference, and context and standards. In light of this review, hygrothermal and whole building simulation models and tools can be selected to assess the potential durability and efficiency of envelope assemblies. Modeling simulation can enable users to a) identify potential issues and failures an envelope may present, b) anticipate further problems in assemblies, and c) predict trouble spots in the building envelope. This review of tools based on performance, complexity, and ability to deliver information may offer a valuable resource for architects, engineers and designers to decide on a tool or a model according to their own personal preference, background knowledge, computational skills, and, most importantly, the objective of their hygrothermal assessment. Importantly, the purpose or goal of the assessment must first be identified. These can range from diagnosis to decision-making on assemblies to research projects.

This review identifies 2 tools ranked as a high-level of expertise that assess the three components of model type: heat, moisture and air; and delivers 1, 2, and 3 dimensional models. One is Wufi, created in the 1990s by the Fraunhofer institute in Germany. This tool can account for imperfections in building materials by identifying potential moisture sources in specific components. It includes a network of related software with specific applications such as Wufi Pro and Wufi 2D that feature single or multilayer assemblies, such as roofs, walls, and floors with a specific range of special conditions. Wufi also features related applications that allow the analysis of whole building assessment through Wufi Plus, a tool that enables the analysis of building components and behavior for a more comprehensive hygrothermal assessment. The inputs for Wufi 2D are considerably more complex, and the computational time is also significantly increased compared with the simpler Wufi Pro. Given the ease-of-use of Wufi Pro, it appears potentially desirable to keep the analysis one-dimensional. Wufi' s network has a large amount of documentation useful to support modeling, design strategies, calculation, and interpretations. These aspects are valuable to provide reliable results and assessment of hygrothermal modeling. While Wufi is one of the most used software for hygrothermal assessment, some limitations have to be accepted to understand the full potential of this tool. Some of them account for the limitations of the mathematical model that does not include all transport phenomena- for example, air flows in the component and uptake of groundwater. Other limitations are related to misinterpretations produce by slight inaccurate results.

The other tool identified is Delphin 6, a simulation tool that couples heat, moisture and matter transport in building materials and is used for a range of different applications such as thermal bridges and evaluation of hygrothermal problem areas, interior and exterior insulation systems, ventilated façade and roofs systems, evaluation of drying issues, among others. This software is able to deliver calculations in 1, 2 and 3 dimensions, and provides a wide range of output visualization assessments, providing flexible and versatile charts. Additionally, Delphin 6 has been validated under several standards such as HAMSTAD: transient heat, air and moisture transfer; EN 15026:2007: transient heat and moisture transport; EN 10211:2007: steady-state heat transport; and IBK Wetting and drying. This tool is able to integrate Python scripts for runtime coupling of detailed modeling.  Compared with Wufi, Delphin 6 has a smaller documentation repository which can limit the learning process, modeling approach, and analysis.

## Conclusions

The main goal of this paper was to provide an overview of the existing range of hygrothermal software in the market, including the main features and characteristics of these tools to inform researchers and stakeholders. Future research should focus on understanding experts' preferences in numerical modeling, input, and output. It is assumed that personal preference and technical practices may impact the manner in which such models are chosen.

To generalize, no perfect tool exists for hygrothermal assessment of building envelopes, especially when it comes to assessing physical phenomena driven by factors such as outdoor conditions and occupant behavior that can produce uncertainties. Although no common ground has as yet emerged among researchers regarding the optimal scope, numerical calculations, and methods to evaluate hygrothermal assessment, interest is growing in technology that supports our insight into implications of hygrothermal effects on building envelopes. The fact that results are calculated by the hygrothermal validated model, that does not make these tools infallible. It is important to point out that checking results and validation is an important part of the hygrothermal assessment.

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