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Energy Research and Development Division

FINAL PROJECT REPORT

THERMM: Integrated Heat and Moisture Calculation Tool for Building Envelopes

**Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transfer.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

THERMM: Integrated Heat and Moisture Calculation Tool for Building Envelopes is the final report for Contract Number: EPC-17-010 conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the [CEC's research website](http://www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

Moisture transfer and heat transfer are two critical and interrelated problems in building envelope design and optimization. Moisture can degrade the durability and thermal performance of the building envelope and can also introduce mold problems that endanger the health and safety of building occupants. Despite the interrelationship of heat and moisture transfer, moisture transfer is often evaluated separately from heat transfer, if at all. Integrating these two properties can help determine the optimal strategies for improving envelope design for new construction and retrofit applications.

This project enhances an existing heat transfer modeling software tool (THERM) and adds moisture and time-domain modeling capabilities. Integrating heat and moisture analysis capabilities to THERM will enable building professionals to design structures that will be durable and not be conducive to the formation of mold, which is a significant health hazard. THERM incorporated finite modeling and two-dimensional (2-D) steady-state heat transfer. The new modeling program engine incorporates a dynamic moisture transfer modeling capability into the existing model of heat transfer (THERMM). The new engine software is written in a modern programming language and has a new visualization tool. This new tool also offers a level of familiarity that thousands of building professionals are already accustomed to using, which should facilitate its rapid adoption and widespread use.

Keywords: Building envelope, windows, heat transfer, moisture transfer, dynamic, finite element method, THERMM.

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EXECUTIVE SUMMARY

Project Purpose

This project was jointly funded with the United States Department of Energy and builds on the existing THERM software that is widely used in the United States and around the world. This project combined thermal and moisture analysis of a building envelope into a single analysis tool. Previously, THERM was not capable of modeling moisture migration through the structure and the potential for condensation within buildings.

The new software tool, THERMM, integrates thermal and moisture modeling that will improve envelope design and analysis for new construction and retrofit applications. The integrated tool will offer a level of familiarity that thousands of building professionals are already accustomed to and ensure that strategies for energy efficiency do not lead to problems that could reduce technology adoption due to perceived and actual health and safety risks. THERMM has the potential to be broadly disseminated due to the existing THERM user base.

Project Approach

THERMM was developed as free, open-source software, and includes programming interface extensions for use by other programs, such as EnergyPlus, or by manufacturer websites or custom graphical user interfaces developed for specific purposes. The current simulation engine (ConRad) is augmented with a new numerical engine (HygroThermFEA).

The current method of analyzing walls employs simplified models that use idealized, one-dimensional construction that does not include thermal bridging. Typically, thermal bridging within a wall construction is not modeled correctly because these calculations use a predefined set of known wall assemblies. Therefore, they cannot easily be extended to new construction types. A two-dimensional numerical simulation is needed to enable more accurate calculations for new construction. However, this is neither easy nor accessible to building modeling practitioners due to the high cost of existing tools and their overall complexity. The THERMM can model any thermal bridging to allow building simulation practitioners to accurately model real building constructions.

Project Results

THERMM is an extension of the established heat transfer program THERM. It addresses issues such as water/vapor transfer as well as phenomena such as summer condensation and built-in construction moisture. It is capable of simulating all the relevant moisture transfer mechanisms that affect the water and vapor contents of building materials. Through the user-friendly interface, users can simulate two-dimensional heat and moisture transfer in building construction elements, accounting for thermal bridges and nonhomogeneous construction details. The enhanced visualization module enables users to display heat and moisture transfer effects throughout the construction period and over the time simulated.

THERMM includes an enhanced post-processor that lets users display time-dependent heat and moisture transfer results such as temperature, heat flux, humidity, and water content as a function of time.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Modeling software tools for thermal and moisture performance of buildings are widely sought and demanded by building professionals. The target market for the THERMM tool includes architects, engineers, builders, and consultants who participate in the design and implementation of building envelope components. This tool is user-friendly and free for users. It offers design envelope solutions for thermal and moisture management performance. THERMM should be adopted widely by the existing user base of THERM and WUFI¹ users (currently in the tens of thousands). THERMM software is available as an open-source platform posted on GitHub and can be used by building professionals in the United States and globally.

Many of the functionalities in THERMM also will be appreciated by the EnergyPlus development community since some of the features, such as dynamic modeling of thermal performance, can be incorporated directly into preparing wall thermal performance indicators, which are severely limited.

THERMM is applicable to new and existing buildings and residential and commercial construction. The API for the simulation engine is available, and the industry is expected to widely adopt the tool for developing materials and components of building envelopes and construction. It is expected that a number of companies will use the simulation engine API to provide online calculation tools for their user base.

THERMM will be distributed on GitHub under a free Berkeley Software Distribution (BSD) license: <https://windows.lbl.gov/therm-8-window-8>.

The source code for the calculation engine is available at: <https://github.com/LBNL-ETA/HygroThermFEM>.

Benefits to California

This project will benefit California investor-owned utility ratepayers by providing building professionals with a highly capable, user-friendly engineering software tool at no cost. California investor owned utilities ratepayers have enjoyed the benefits of the THERM program for years, as it is the benchmark software tool used in National Fenestration Rating Council rating and certification and will soon be used in the newly formed Window Attachments Energy Ratings Council for window attachments rating and certification. California was an early adopter and strong advocate for National Fenestration Rating Council ratings. Adding a moisture transfer modeling capability to THERM enables building professionals to design structures that will be durable and not conducive to mold formation, a significant health hazard. It is anticipated that THERMM, with its heat and moisture modeling capability, will lead to better energy and moisture ratings of building envelope assemblies, enabling more mainstream design of energy-efficient and moisture transfer resistant structures.

¹ WUFI® is a model that performs dynamic simulations of coupled heat and moisture transfer in 1-D.

California's residential and commercial building envelopes are responsible for approximately 0.37 quads of energy used (equivalent to approximately \$4 billion annually) and nationally, building envelopes are responsible for approximately 7.6 quads (approximately \$80 billion annually). Being able to design moisture control with a great deal of confidence when designing more energy-efficient building envelopes will improve building envelope energy efficiency and substantially prolong building life. Improving the building envelope energy performance by 5 percent is estimated to provide 0.02 quads of energy savings (approximately \$200 million annually) in California and 0.38 quads (approximately \$4 billion annually) nationally.

CHAPTER 1:

Introduction

To mitigate negative effects of accelerated global climate change, the United States Department of Energy (USDOE) and state and local governments nationwide have set zero-net energy (ZNE) building goals that are leading to more buildings being constructed with highly insulated and very tight envelopes. By failing to account for the moisture characteristics in the thermal envelope, designers and builders can introduce moisture-related problems that endanger the health and safety of building occupants, as well as the durability of the building itself. During the design of building envelopes, it is imperative to ensure excellent thermal performance without introducing moisture problems. This is true for a number of reasons. Damage from moisture is one of the leading causes of lawsuits in construction, and having tools for modeling moisture and thermal characteristics will help ensure that United States can meet its energy, comfort, health, and durability goals in buildings. Moisture research by itself is rarely supported by energy agencies because it does not save energy. Developing an integrated thermal and moisture tool will ensure that buildings are designed for energy efficiency while avoiding collateral moisture problems.

Analysis of moisture migration through building structures is primarily conducted by engineers using one-dimensional (1-D) simplified models, such as WUFI—a software tool for analyzing moisture migration through the building structure. These models ignore or make crude assumptions about thermal bridges and non-homogeneities in building construction. It is important to properly consider them in thermal/moisture analysis, considering that such elements are primary pathways and causes for condensation and moisture buildups.

The thermal analysis of building structures, including thermal bridges, is often done with the software program THERM. A Lawrence Berkeley National Laboratory (LBNL) team developed THERM in the early 1990s in response to the need for a user-friendly, two-dimensional (2-D) heat transfer tool for the analysis of windows and thermal bridges in building envelopes. THERM is a freely available computer program in wide use, with 20,000 unique users downloading the program annually, and more than 500,000 program launches. THERM is used by building component manufacturers, engineers, educators, students, architects, and others, but most prominently it is used as an official tool by the National Fenestration Rating Council (NFRC). It is also used by the Passive House Institute US (PHIUS) and by the Window Attachment Energy Rating Council (AERC).

THERM is used to calculate 2-D heat transfer in building components such as windows, walls, foundations, roofs, and doors, as well as appliances and other products where thermal bridges are of concern. THERM is based on the finite element numerical method (FEM) and incorporates sophisticated automated meshing and error estimation for rapid model generation that ensures accurate results. The new tool, THERMM, adds more functionalities using a new 2-D finite element engine (HygroThermFEM), expanded boundary conditions (BCs), material libraries, and a new visualization module. THERMM is now capable of modeling dynamic heat and moisture transfer, in addition to existing steady-state heat transfer, in building construction.

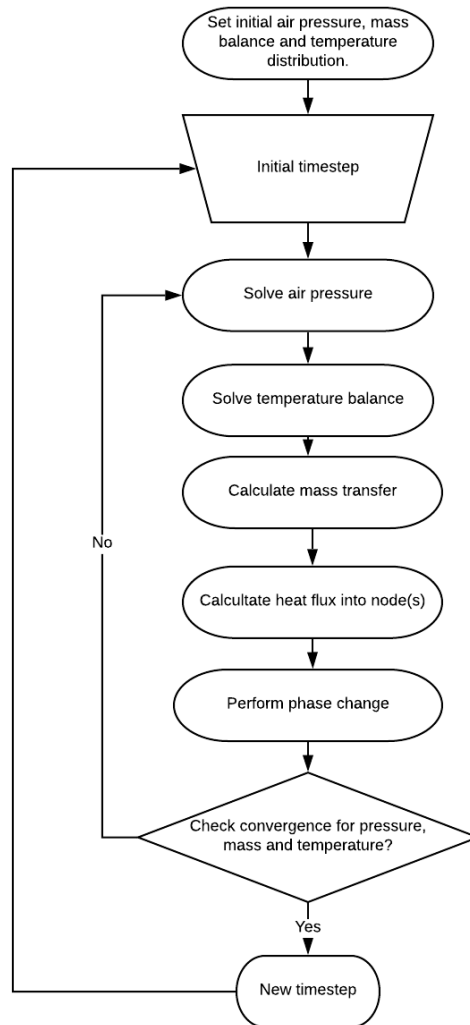
CHAPTER 2:

General Overview of Equations and Assumptions

This chapter provides a general overview of the mathematical model and assumptions in THERMM. A detailed description is provided in appendices to this report, from a theoretical background to a detailed mathematical and numerical model description. The result is a working finite element model able to calculate mass and temperature distribution within a given domain and within a given time.

The model described in this report is intended to calculate heat, air, and moisture transfer through the building component, along with calculation of temperature and moisture distribution. Because moisture and air distribution depend on temperature, and the temperature field depends on moisture content, these two cannot be observed and calculated separately. In addition, moisture can change its phase during the process. To perform calculations of such a complex physical model, the calculation must be segregated into logical units and calculations performed in several steps. This process is iterative until convergence is reached during each timestep (Figure 1).

Figure 1: Steps in Solving Coupled Heat, Air, and Moisture Transfer



Note: Convergence must be satisfied over all three fields (pressure, mass, and temperature) before proceeding to the next timestep.

Source: LBNL

The first model to be solved is Air Pressure Distribution, which is an important driver for water distribution and affects everything else in the domain. During the air pressure calculation, it is assumed that the mass of water and temperature of the domain are not changing. After calculating air pressure within the domain, the next step is to calculate Mass Distribution (Transfer). Again, in this step it is assumed that pressure and temperatures remain constant. The last step is to calculate Temperature Distribution, which will be considered under the constant mass and pressure field. The newly calculated temperature field will lead to information about the amount of heat flux and therefore will lead to calculation of Phase Change. Since recalculation of every model will lead to a different mass and temperature

distribution, this must all be calculated within iteration loops until convergence criteria have been achieved.

Coupled Heat, Air, and Moisture Transfer

Heat Transfer (Energy) Equations

The formula equations of heat and moisture transfer are described in great detail in the Appendices.

These equations are subject to three general types of boundary conditions: (1) convection boundary, (2) flux boundary, and (3) temperature/moisture boundary.

These systems of equations, subject to boundary conditions, are solved using the finite element numerical method (FEM), to this report and provided as an open-source code, HygroThermFEM.

CHAPTER 3:

Application Programming Interface

Introduction

In computer programming, an application programming interface (API) is a set of subroutine definitions, communication protocols, and tools for building software. An API presents a logical interface to a software component and hides the internal details required to implement that component. It offers a high-level abstraction for a module and promotes code reuse by allowing multiple applications to share the same functionality. Modern software development has become highly dependent on APIs, from low-level application frameworks to data format APIs and graphical user interface (GUI) frameworks. In fact, common software engineering terms such as modular development, code reuse, dynamic link library (DLL), software frameworks, distributed computing, and service-oriented architecture all imply the need for strong API design skills. Elegant and robust API design is a critical aspect of contemporary software development. Change is an inevitable factor in software development. New requirements, feature requests, and bug fixes cause software to evolve in ways that were never anticipated when it was first devised.

An API has to be expressed in a particular programming language. It is therefore important to understand the language-specific features that contribute to API design. Since the THERMM engine (HygroThermFEM) is written in C++, APIs will be designed through that language. A new version of the C++ specification has been approved by the International Organization for Standardization and the International Electrotechnical Commission (ISO/IEC). At the time of writing, C++ 11 was supported by most compilers, and the engine was written using that standard; however, new standards (C++ 14 and C++ 17) are on the way to be implemented by modern compilers, and it is most likely the HygroThermFEM API will evolve to adopt some of the new language features.

Using the HygroThermFEM

The engine was written in C++, mainly due to performance requirements of the finite element method. In addition, C++ compilers on different operating systems are well maintained and free to use, making the engine available on different operating systems. Because of this, direct communication with the engine will be possible only through the C++ interface. It is important to note that the HygroThermFEM API does not support reading and writing to a file(s) or a database, simply because that is not its purpose, and it would slow engine execution. Each user will need to decide which format of file(s) or database to use.

The CMake cross-platform build system was used to create and compile the project. CMake is designed to be used in conjunction with the native build environment, and therefore will make HygroThermFEM easy to compile and use on different platforms and different integrated development environments (IDE). Currently the engine has been developed and tested against several different compilers on Windows, OSX, and Ubuntu. This approach also will make it possible for the engine to be used easily by third-party tools by simply writing CMake code

that will automatically download and create a solution that easily connects and compiles a required version of the HygroThermFEM engine.

Download and Compilation

Currently, the program is hosted on Bitbucket, and it is configured through CMake. The plan is to be hosted on GitHub once all the licensing issues are resolved. While it is possible to download and set up the project manually, the easiest way is to use the CMake build system. It will take care of everything that is needed to create, compile, and use HygroThermFEM. This section provides guidance on how to set up the project that will use HygroThermFEM as the engine. It is assumed that the project that will use HygroThermFEM is configured with CMake as well.

All files described here should be in the root folder of the project. CMake files can be configured differently, and that can be done by changing paths in the files.

The first file is used to keep the connection and necessary version of the engine.

CMakeLists-HygroThermFEM.txt.in

```
include(ExternalProject)

ExternalProject_Add(HygroThermFEM
  GIT_REPOSITORY https://vidanovic@bitbucket.org/vidanovic/HygroThermFEM.git
  GIT_TAG "v_1.0.2"

  UPDATE_COMMAND ""
  PATCH_COMMAND ""

  SOURCE_DIR "${CMAKE_BINARY_DIR}/HygroThermFEM-src"
  BINARY_DIR "${CMAKE_BINARY_DIR}/HygroThermFEM-build"

  CONFIGURE_COMMAND ""
  BUILD_COMMAND ""
  TEST_COMMAND ""
  INSTALL_COMMAND ""
)
```

This small, compact file contains a repository path and tag version. In this way, users can easily find and update necessary data at any moment.

The next file is necessary to create and compile the HygroThermFEM project:

CMakeLists-HygroThermFEM.txt

```
set(IncludeDir "${CMAKE_BINARY_DIR}/HygroThermFEM-src/include")
set(IncludeDir ${IncludeDir} "${CMAKE_BINARY_DIR}/HygroThermFEM-build")
set(IncludeDir ${IncludeDir} "${CMAKE_BINARY_DIR}/HygroThermFEM-src")

include_directories(${IncludeDir})

# Download and create HygroThermFEM library
configure_file(CMakeLists-HygroThermFEM.txt.in HygroThermFEM-
download/CMakeLists.txt)
execute_process(COMMAND ${CMAKE_COMMAND} -G "${CMAKE_GENERATOR}" .
  WORKING_DIRECTORY ${CMAKE_BINARY_DIR}/HygroThermFEM-download)
execute_process(COMMAND ${CMAKE_COMMAND} --build .
  WORKING_DIRECTORY ${CMAKE_BINARY_DIR}/HygroThermFEM-download)

add_subdirectory(${CMAKE_BINARY_DIR}/HygroThermFEM-src)
set(HygroThermFEM_LIB
"${CMAKE_SHARED_LIBRARY_PREFIX}HygroThermFEM${CMAKE_SHARED_LIBRARY_S
UFFIX}")
```

Note that the file includes a link toward "CMakeLists-HygroThermFEM.txt.in" that keeps basic information about the HygroThermFEM project. Instructions in this file tells CMake where to download and how to build the HygroThermFEM engine.

Finally, to create the HygroThermFEM library that connects to an external project, some additional lines are needed:

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.8)

set(target_name FEM_Reader)

project(${target_name})

# Additional project and compiler settings goes here

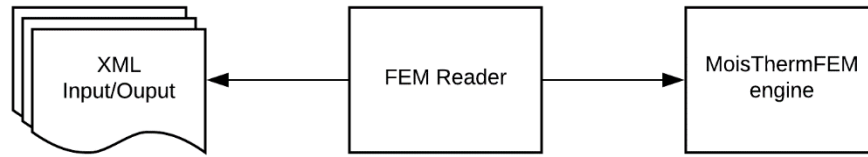
# Now include HygroThermFEM as library
include(CMakeLists-HygroThermFEM.txt)
target_link_libraries( ${target_name} HygroThermFEM )
add_dependencies( ${target_name} HygroThermFEM )

# More settings here
```

This will create an FEM Reader project that connects to the HygroThermFEM library (Figure 2) and uses its API to perform the necessary calculations and provide results. In this case, the FEM Reader is a simple program that reads XML input files and then converts them to

HygroThermFEM API that performs calculations and returns results that are then saved in an appropriate format.

Figure 2: FEM Reader Command Line Tool



Source: LBNL

To use the HygroThermFEM API, include the following line into the source code:

```
#include "HygroThermFEM2D.hxx"
```

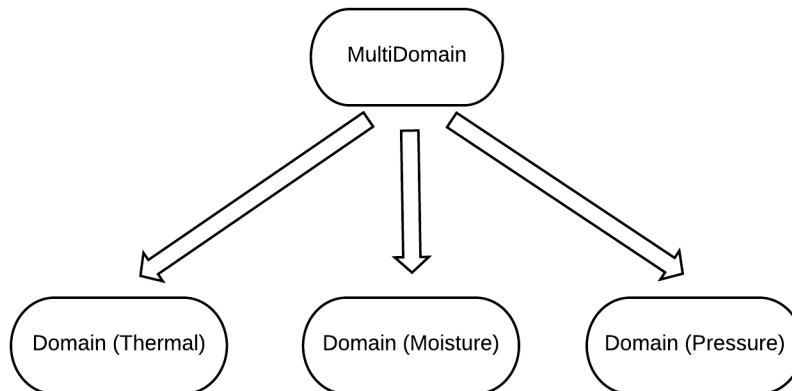
Once that is done, the program is ready to use the HygroThermFEM API.

Application Programming Interface Definition

General Notes

The HygroThermFEM engine is a finite element numerical solver for temperature and moisture transfer within a given domain in a two-dimensional space. However, the engine does not support finite element meshing, which must be done before HygroThermFEM is used. In other words, the engine input is a set of nodes and elements with defined materials and boundary conditions, and the output is a temperature and water content solution at given timesteps. The MoistThermFEM engine has several subdomains, as shown in Figure 3.

Figure 3: HygroThermFEM Engine Subdomains



Source: LBNL

While calculating a solution, the engine will iteratively find solutions for temperature, moisture, and pressure by using separate domains (or subdomains). It is important to note, however, that these subdomains will consist of identical geometry mesh and materials. The only difference is in the equations that are solved.

For that reason, the engine is designed to keep nodes and elements separate from any domain while making them accessible for necessity of calculation. Nodes are kept in a Singleton class called *NodePool*, and materials are kept in a Singleton class named *MaterialPool*. Those classes also prevent users from creating duplicates of node or material data.

Nodes

Nodes are simply defined by x and y coordinates and the initial condition of state variables. The interface supports node creation and node retrieval. Since the finite element method is solving for state variables in nodes, every node will contain each of the state variables (temperature, humidity, and pressure), which are defined as a separate C++ class.

State of Variables

State class is used to store and handle state variables. It is defined in each node, and it is needed as an input parameter for node creation.

```
State(  
double temperature = 0,  
double humidity = 0,  
double pressure = 101325,  
double liquidPercent = 1.0)
```

Input Parameters

```
temperature [optional]—initial temperature at the node (default = 0)  
humidity [optional]—initial humidity at the node (default = 0)  
pressure [optional]—initial pressure at the node (default = 101325)  
liquidPercent [optional]—percent of water content in liquid state at the node (default =  
1.0). This variable is important when node temperature is at freezing point.
```

Create Node

A node is created by using a simple interface:

```
Node2D & NodePool::Instance().createNode(  
size_t nodeIndex,  
double x,  
double y,  
State state)
```

Input Parameters

nodeIndex [required]—unique node identifier that will be used to form elements (no duplicates are allowed).
x [required]—x coordinate of the node.
y [required]—y coordinate of the node.
state [required]—Used to define initial temperature, water content and pressure.

Output Parameters

Node2D—reference to created node.

Get Node

Once node is created it can be retrieved:

```
auto & node = NodePool::Instance().getNode(size_t index)
```

Input Parameters

index [required]—index of node that is going to be retrieved. Exception will be thrown if index is out of range.

Output Parameters

Node2D &—reference to node.

Materials

Another important feature of the model is materials. All materials must be created before elements because an element interface requires material.

Material Creation

The interface for material creation is:

```
auto & material = MaterialPool::Instance().createMaterial(  
    const std::string & Name,  
    const double Density,  
    const double Porosity,  
    const double HeatCapacity,  
    const double ThermalConductivity,  
    const double DiffusionResistanceFactor,  
    const std::vector<std::pair<double, double>> & LiquidTransporatationCurve,  
    const std::vector<std::pair<double, double>> & SorptionCurve)
```

Input Parameters

Name [required]–Material name
Density [required]–Density of dry material
Porosity [required]–Porosity of the material
HeatCapacity [required]–Heat capacity of dry material
ThermalConductivity [required]–Thermal conductivity of dry material
DiffusionResistanceFactor [required]–Diffusion resistance factor of the material
LiquidTransportationCurve [required]–Liquid transfer curve of the material
SorptionCurve [required]–Sorption curve of the material

Output Parameters

Material & Newly created material.

Domains and Elements

When all nodes and materials are created, the program is ready to create a domain and elements. Domain creation is very simple and does not require any additional data:

MultiDomain domain;

After this, creation of elements is the next step.

Domain and MultiDomain

The engine's interface supports two different domain types:

- Domain
- MultiDomain

The difference is that a Domain is a class that is built to solve only one type of state variable, without influencing other state variables. If, for example, a user wants to simulate temperature distribution over time with a domain that is uniformly filled with water, that is possible through a domain. However, this approach is not correct because temperature change over time will influence water content, and vice versa. This is why users are encouraged to always use the MultiDomain class, because that class has a built-in iterative solver over temperature and moisture fields that will produce the most accurate results.

MultiDomain

The MultiDoman class supports creation of elements, boundary conditions, performing simulations, and producing results.

Elements

Several important rules must be followed when elements are created in the HygroThermFEM engine.

Orientation of nodes must be same for every element. If nodes in one element are entered clockwise, then all the other elements must follow the same rule.

Elements always have four nodes, even when triangular elements are present in the model. This, however, does not mean that triangular elements are not allowed. In case of triangular elements, the last node of the element should be entered twice.

Creation of elements

Creation of elements is done through a domain:

```
MultiDomain domain;  
domain.createElement(  
const Node2D & node1,  
const Node2D & node2,  
const Node2D & node3,  
const Node2D & node4,  
const Material & material);
```

Input Parameters

Node2D & node1, node2, node3, node4–Nodes from which element is composed. Order of nodes is important, and it should follow the same rule for every element will be created in same domain.
Material & material–material from which element will be composed.

Boundary Conditions

Several functions in the MultiDomain class support creation of boundary conditions. The following boundary condition are available:

- ConvectionBC
- TemperatureBC
- BlackBodyRadiationBC

Each boundary condition function will accept two nodes as parameters, along with the additional parameters necessary for that type of boundary condition.

ConvectionBC

Convection boundary condition contains data for thermal and moisture content at the boundary. It can be used as follows:

```
MultiDomain domain;  
domain.createConvectionBC(  
const Node2D & node1,  
const Node2D & node2,  
const double ConvectionFilmCoefficient,  
const double AirTemperature,  
const double AirHumidity);
```

Input Parameters

Node2D & node1, node2–Nodes from which boundary is made of.
double ConvectionFilmCoefficient–Convection film coefficient (used in both, thermal and moisture calculations).
double AirTemperature–Temperature of air (inside or outside)
double AirHumidity–Humidity of air (inside or outside)

TemperatureBC

The temperature boundary condition contains data for thermal simulation. It can be used as follows:

```
MultiDomain domain;  
domain.createTemperatureBC(  
    const Node2D & node1,  
    const Node2D & node2,  
    const double temperature);
```

Input Properties

```
Node2D & node1, node2–Nodes from which boundary is made of.  
double temperature–Constant temperature at boundary nodes.
```

BlackBodyRadiationBC

The Black Body boundary condition is used to define black body radiation. It can be used as follows:

```
MultiDomain domain;  
domain.createBlackBodyRadiationBC(  
    const Node2D & node1,  
    const Node2D & node2,  
    const double emissivity,  
    const double radiationTemperature);
```

Input Parameters

```
Node2D & node1, node2–Nodes from which boundary is made of.  
double emissivity–Surface emissivity  
double radiationTemperature–Radiation temperature
```

Simulation

Once all the data are provided, MultiDomain contains the interface that will perform simulation. Since the engine is set to calculate both thermal and moisture transfer, only transient simulation is possible through the MultiDomain.

```
Solution MultiDomain::transient(  
    std::vector<double> & temperature,  
    std::vector<double> & humidity,  
    const double DTime);
```

Input Parameters

```
std::vector<double> & temperature–vector of node temperatures at current timestep  
std::vector<double> & humidity–vector of relative humidities at the nodes.  
const double DTime–timestep value
```

Output Parameters

Solution—solution for temperature, humidity, and pressure at new timestep.

Solution

Solution is a separate structure that contains simulation results. All results are stored in `std::vector`, and they represent results at nodes.

The structure Solution contains following results:

- temperature
- humidity
- waterContent
- liquidWaterContent
- vaporContent
- iceContent

CHAPTER 4:

Graphical User Interface Design

Introduction

To facilitate rapid adoption and ease of use, the GUI for the THERMM model was based on the familiar and widely used THERM model. THERM is 2-D heat transfer modeling tool, employing explicit solutions to steady-state conduction and radiation heat transfer. It also incorporates modeling of air flow in enclosed cavities using simplified correlations that were developed from experimental and detailed numerical work.

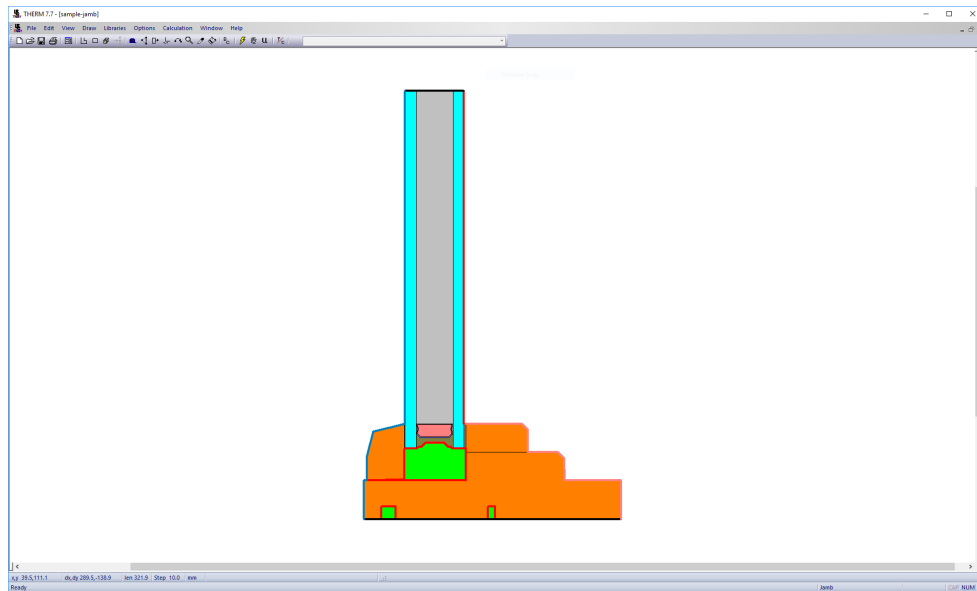
The GUI, which was originally developed primarily to model window frame cross sections, has several main parts:

1. General Properties
2. Program Options and Preferences
3. Drawing Aids
4. Libraries
5. Calculation Controls
6. Results and Display Options
7. Miscellaneous

Not all of the GUI's parts are affected by the development of THERMM. This chapter presents the portions of program that are affected, and the current versions of these parts are presented briefly below.

All the main parts of the THERM program are accessible from the main program screen, which is shown in Figure 4 and which retains most of its original look and feel. The areas that will undergo the most significant changes are Libraries (boundary conditions and material libraries) and Results and Display Options. Drawing Aids will largely remain the same.

Figure 4: Main THERM Screen



Source: LBNL

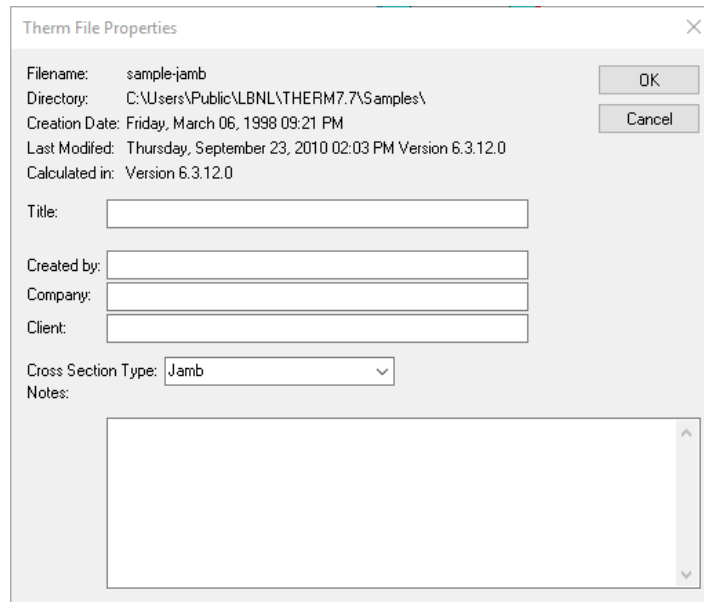
Graphical User Interface Redesign Areas

THERM File Properties

THERM File Properties (the general properties specific to a file, as opposed to an instance of the program) are accessed from File/Properties. This is used to enter project information, such as title, creator, etc., as well as the type of window frame cross section. Figure 5 shows the current design.

The file menu section also contains some general program functions, such as file management, printing, file import, file export, and list of recently opened files. Page setup and Print setup is also accessed from here. There is no current plan to change these areas. Figure 5 shows the current layout of the File Properties screen.

Figure 5: Current THERM File Properties Screen



Source: LBNL

The new “THERM File Properties” screen adds two areas to address calculation options and model orientation. Calculation options were added here since they belong to the instance of the file, as opposed to the instance of the user/program (e.g., when another user opens a saved file, these calculation options will be inherited from the file). These calculation options include both Heat transfer and Moisture calculation options, for both transient and steady state. Note that steady state includes two modes—true steady state and the “False Transient” approach, which uses transient simulation to calculate the steady state answer. Sometimes this approach provides a solution when true steady state fails to converge in a numerical solution.

Model orientation was added here to accommodate a new transient solution that would read input data from the weather data file (e.g., EnergyPlus typical weather year), which provides orientation-specific information. In addition, the gravity vector specification is moved from the “View” menu item to the “THERM File Properties” screen. Gravity vector will still be available from the “View” menu, but users will only be able to display it (read-only) from there and will be able to set gravity vector under “Therm File Properties.”

Additionally, all the Therm File-related properties were moved from the “Options/Preferences/Therm File Options” screen to “THERM File Properties.”

Figure 6 to Figure 8 show the proposed new design for the General Properties screen (three tabs).

Figure 6: Proposed New THERMM File Properties Screen – General Tab

The screenshot shows a dialog box titled "THERMM File Properties" with a close button (X) in the top right corner. The dialog has three tabs: "Them File Properties" (selected), "Calculation Options", and "Model Exposure". The "Them File Properties" tab contains the following information and input fields:

- Filename: Untitled-1
- Directory: G:\Shared drives\THERMM\Validation\ORNL 2D Example\Lib\
- Creation Date: Wednesday, February 24, 2021 11:25 PM (Version 8.0.9.0)
- Last Modified: Wednesday, February 24, 2021 11:25 PM (Version 8.0.9.0)
- Calculated in: Results need to be recalculated.
- Title:
- Created by:
- Company:
- Client:
- Notes:

At the bottom right of the dialog, there are three buttons: "OK", "Cancel", and "Apply".

Source: LBNL

The default values are listed in each screen design.

Figure 7: Proposed New THERM File Properties Screen – Calculation Options Tab

THERM File Properties

Them File Properties Calculation Options Model Exposure

Heat Transfer
 Moisture
 Transient

Initial Conditions
 Initial simulation conditions will be based on:
 Use values from text file (warm up section)
 Use first time step in text file
 User defined - Constant values everywhere
 Temperature C
 Relative Humidity %

Steady State
 No Time Variable
 False transient (using state BCs)

Initial Conditions
 Temperature C
 Relative Humidity %

Modeling Options
 Water Liquid Transportation
 Heat of Evaporation
 Capillary Conduction
 Vapor Diffusion Conduction
 Temperature and Moisture Dependency on Thermal Conductivity
 Latent Heat of Fusion

Simulation Engine
 ConRad
 HygroThermFEM

Simulation Engine Parameters
 Convergence Tolerance
 Relaxation Parameter
 Time Step sec
 Number of Time Steps

Mesh Control
 QuadTree Mesh Parameter
 Run Error Estimator
 Maximum % Error Energy Norm
 Maximum Iterations

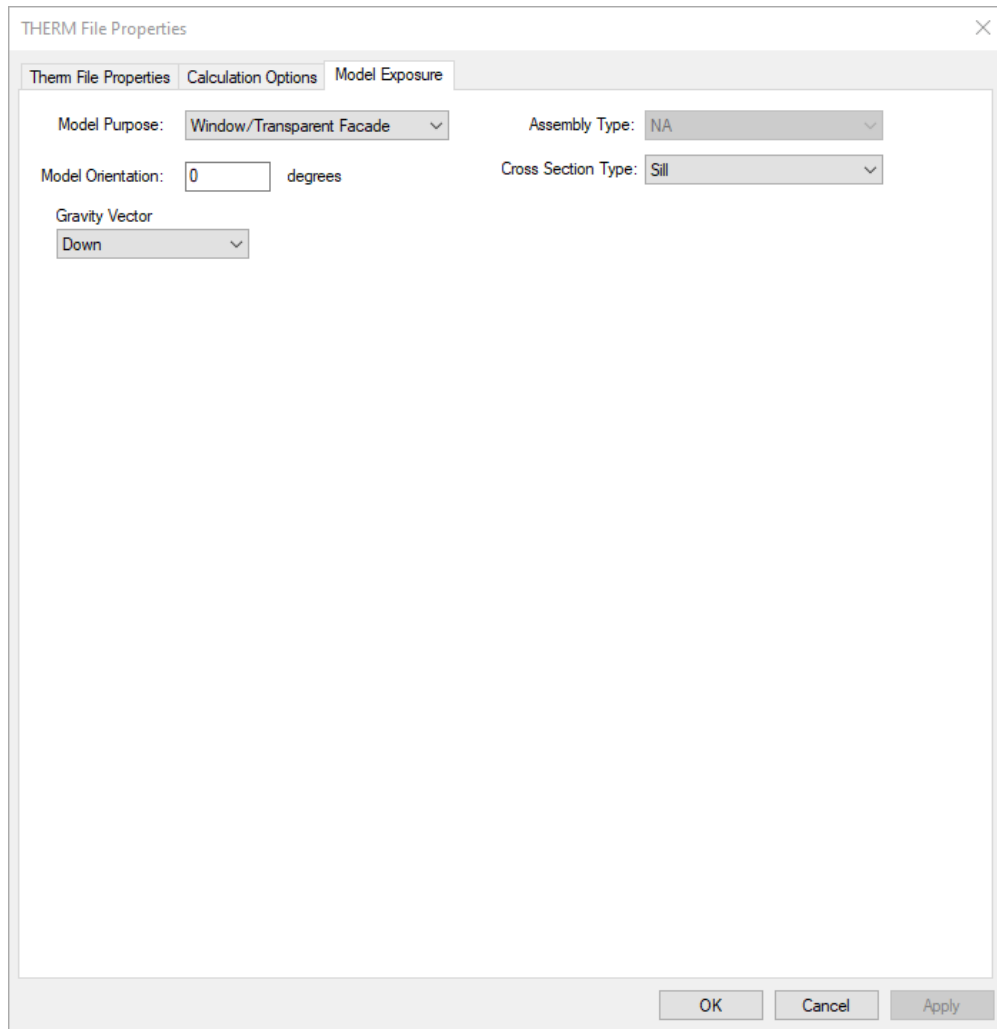
Miscellaneous Parameters
 Radiance Mode
 Use CR for Glazing Systems
 Check for Correct WINDOW BC on Glazing Systems

Modeling Options
 Automatically adjust relaxation parameter
 Adjustment step
 Maximum iterations
 View Factor Smoothing

OK Cancel Apply

Source: LBNL

Figure 8: Proposed New THERM File Properties Screen – Model Exposure Tab (Windows / Transparent Facades Option for “Model Purpose”)



Source: LBNL

Libraries

THERM has five different libraries:

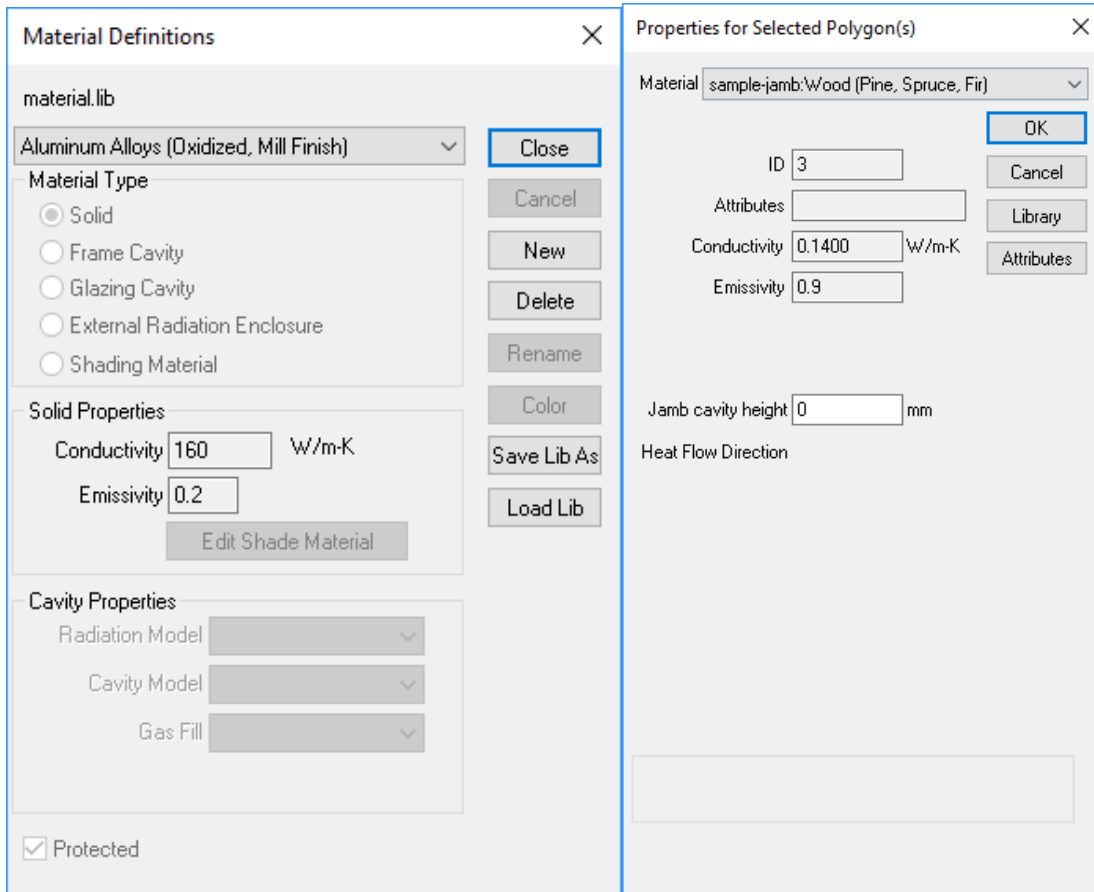
- Material
- Boundary Conditions
- Gas
- Glazing
- U-Factor Names

Material Library

The Material library has two aspects: (1) defining the new material, including displaying the detailed material properties, and (2) assigning a polygon to a material. Figure 9 shows a material definition screen on the left and material assignment screen on the right. The material assignment screen will appear when a user either double-clicks on a polygon or selects “Set Material” from the “Libraries” drop-down menu item.

The current display of the Material library does not offer a list view. The proposed design will include a list and detailed view, along with the expansion of the content to include moisture-related properties.

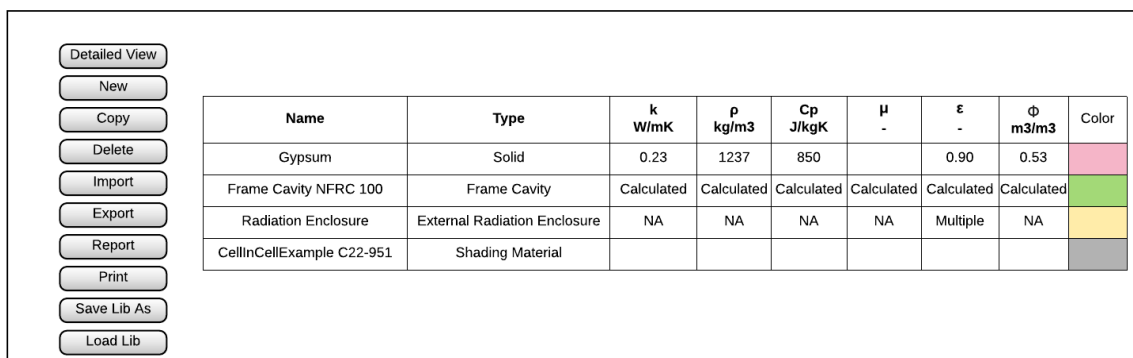
Figure 9: Current Material Definition and Material Assignment Screen



Source: LBNL

Figure 10 shows the proposed design for the list view of the Material library. The list view is an extension of the database list view with standard database controls (e.g., New, Copy, Paste). The proposed design for the detailed view of the Material library screen is shown in Figure 11.

Figure 10: New Material Definition List Screen



Source: LBNL

Figure 11: New Material Definition Detailed Screen

The screenshot shows a software window titled "Material Definitions" with a close button (X) in the top right corner. The window is divided into several sections:

- Material.lib:** A dropdown menu showing "Gypsum".
- Material Type:** Radio buttons for "Solid" (selected), "Frame Cavity", "Glazing Cavity", "External Radiation Enclosure", and "Shading Material".
- Solid Properties:** Input fields for:
 - Conductivity: 0.43 W/m-K
 - Emissivity: 0.9
 - Porosity: 0.53 m3/m3
 - Specific Heat Capacity: 850 J/kgK
 - Density: 1237 kg/m3
 An "Edit Shade Material" button is located below these fields.
- Cavity Properties:**
 - Radiation Model: Simplified (dropdown)
 - Convection Cavity Model: ISO 15099 (dropdown)
 - Moisture Cavity Model: (empty dropdown)
 - Gas Fill: Air (dropdown)
 - Emissivities: Side 1: 0.9, Side 2: 0.9
- Moisture Storage Function:** A text area containing a list of values: 0,0; 0,065,0,33; 0,113,1,01; 0,329,1,23; 0,582,1,76; 0,754,2,51; 0,96,4,99;0,974,6,5; 0,9883,12,7; 0,9939,22; 0,997,30,8; 0,9978,125; 1,183
- Liquid Transport Coefficient, Redistribution, x=kg/m3 & y = m2/s:** Input field with value 0,0; 2,5,8E-11; 350,2E-5
- Liquid Transport Coefficient, Suction x=kg/m3 & y = m2/s:** Input field with value 0,0
- Sorption curves:** Input field with value 0,0
- Diffusing resistance factor:** Input field with value 0,0

On the right side of the window, there is a vertical toolbar with buttons: "List View", "Save", "Cancel", "New", "Copy", "Delete", "Rename", "Color", and a color selection box (currently showing pink).

At the bottom left, there is a checked checkbox labeled "Protected".

Source: LBNL

Material assignment to a selected polygon is accomplished through the new database list view selector, shown in Figure 12.

Figure 12: New Material Assignment List Screen

The screenshot shows a software window titled "New Material Assignment List Screen". At the top, there are buttons for "Select", "Cancel", "Detailed View", a search icon, and "Advanced". A "Polygon ID" field contains the value "3".

ID	Name	Type	k W/mK	ρ kg/m3	Cp J/kgK	μ -	ε -	Φ m3/m3	Attributes	Color
1	Gypsum	Solid	0.23	1237	850		0.90	0.53	NA	
2	Frame Cavity NFRC 100	Frame Cavity		--						
3	Radiation Enclosure	External Radiation Enclosure								
4	CellInCellExample C22-951	Shading Material								

Source: LBNL

The detailed view of the Material Assignment screen will depend on whether the record is for solid material or an air/gas cavity. Figure 13 shows the material assignment screen for the

example of solid material, while Figure 14 shows material assignment screen for the example of air/gas cavity material.

Figure 13: New Polygon Assignment Detailed Screen – Example of Solid Material

Material Assignment
✕

Material.lib
Gypsum ▼

Material Type

Solid
 Frame Cavity
 Glazing Cavity
 External Radiation Enclosure
 Shading Material

Solid Properties

Conductivity W/m-K
Emissivity
Porosity m3/m3
Specific Heat Capacity J/kgK
Density kg/m3

Internal Heat Generation W/m3

Protected

Moisture Storage Function

0,0;
0.065,0.33;
0.113,1.01;
0.329,1.23;
0.582,1.76;
0.754,2.51;
0.96,4.99;0.
974,6.5;
0.9883,12.7;
0.9939,22;
0.997,30.8;
0.9978,125;
1,183

Liquid Transport Coefficient, Redistribution, x=kg/m3 & y = m2/s

Liquid Transport Coefficient, Suction x=kg/m3 & y = m2/s

Sorption curves

Diffusing resistance factor

Select

Cancel

List View

Attributes

Source: LBNL

Figure 14: New Material Assignment Detailed Screen – Example of Air/Gas Cavity

Material Assignment
✕

Material.lib

Material Type

- Solid
- Air/Gas (Frame) Cavity
- Glazing Cavity
- External Radiation Enclosure
- Shading Material

Side 1

Temperature C

Emissivity

Side 2

Temperature C

Emissivity

ID

Horizontal Dimension mm

Vertical Dimension mm

keff W/m-K Def kg/m2-s

Nu Xu

Heat Flow Direction

Note: keff, Xeff, Temperature, emissivity may not be correct until a simulation has been done. The values shown are approximations.

Protected

Select

Cancel

List View

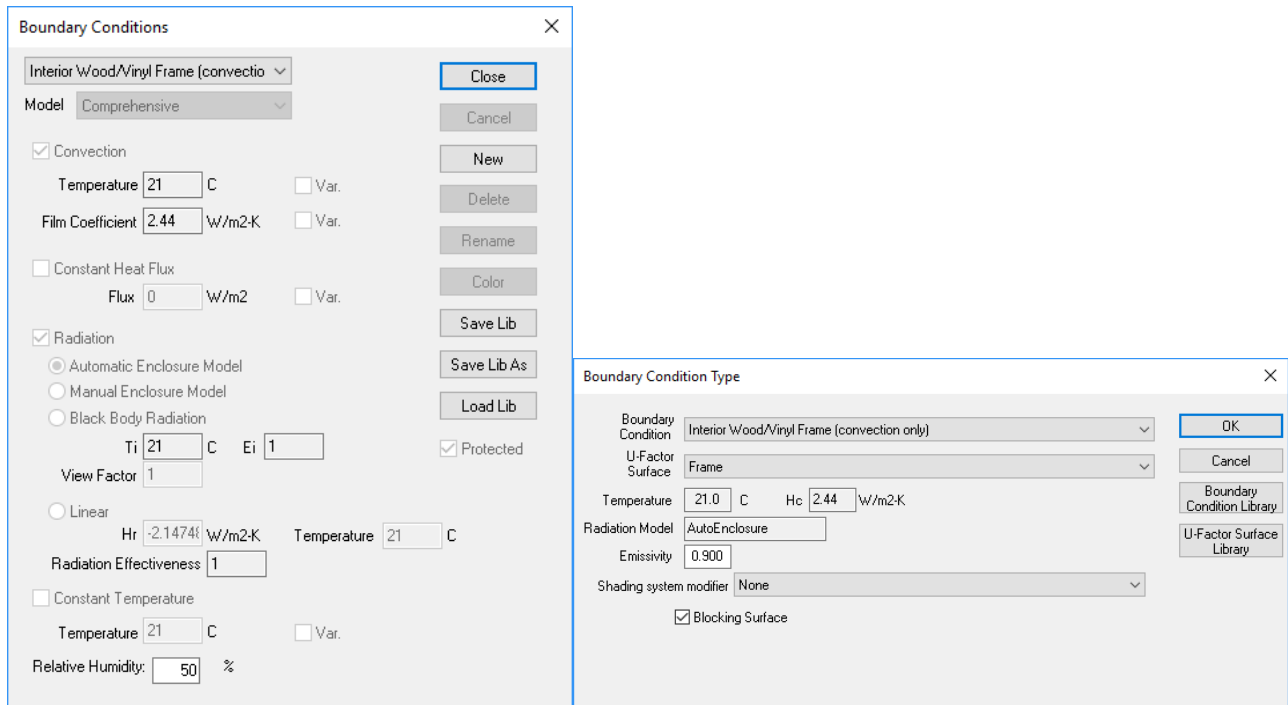
Attributes

Source: LBNL

Boundary Conditions Library

Similar duality exists for the Boundary Conditions library. There is (1) a definition of a boundary condition and (2) assignment of boundary conditions (BC) to a boundary segment(s). Figure 15 shows a current BC definition screen on the left and a BC assignment screen on the right.

Figure 15: Current Boundary Conditions Definitions and Assignment Screen



Source: LBNL

The current display of the BC library does not offer a list view, but the proposed new GUI design will incorporate a list view, as shown in subsequent sections.

Transient Boundary Conditions

Transient boundary conditions involve a time series of boundary conditions, which is best handled through the boundary condition file, rather than inputting them through dialog screens. On the other hand, steady-state BC requires a single set of input parameters, which also can be listed in a list view.

As with the Material library, there will be a list and detailed view. Figure 16 shows the list view, from which the detailed view can be selected.

Figure 16: New Transient Boundary Conditions Definitions - List View Screen

ID	Name	Type	Convection Model	Temperature C	Film Coefficient W/m2K	Heat Flux W/m2	Solar Radiation W/m2	Radiation Model	Film Coefficient W/m2K	Temperature	Humidity kg H2O/kg air	Color
1	Interior - Surface Film Based	Neumann	ASHRAE / NFRC Inside	21	File...	File...	File...	Enclosure	NA	NA	File...	Red
2	Exterior - Surface Film Based	Neumann	ASHRAE / NFRC Outside	-18	File...	File...	File...	Black Body	NA	File...	File...	Blue
3	Temperature BC	Dirichlet	NA	15	NA	NA	NA	NA	NA	NA	NA	Pink
4	Fixed Convection BC	Neumann	Fixed Coefficient	22	File...	File...	File...	Fixed Coefficient	File...	File...	File...	Green

Source: LBNL

The next several figures show examples of detailed views of transient BC definition screens. Figure 17 shows an example of a BC definition screen for the transient BC incorporating the

ASHRAE/NFRC Inside convection model and Enclosure Radiation model (Neumann BC type). Appendices show further examples of BC.

Figure 17: New Boundary Conditions Definitions Detailed View Screen – Example of ASHRAE/NFRC Inside BC

Source: LBNL

In these BC examples, several convection models are provided as hard-coded and more may be added later, based on needs and requests. There is no provision for a user to add a convection model, due to the inherent complexities of providing such an option.

The BC assignment to a selected boundary line segment in a model is accomplished through the new database list view selector, shown in Figure 18.

Figure 18: New BC Assignment List Screen

Select Cancel Detailed View search Advanced Polygon ID 3

ID	Name	Type	Convection Model	Temperature C	Film Coefficient W/m2K	Heat Flux W/m2	Solar Radiation W/m2	Solar Absorptance	Radiation Model	Emissivity	Film Coefficient W/m2K	Temperature	Humidity kg H2O/kg air	Color
1	Interior - Surface Film Based	Neumann	ASHRAE / NFRC Inside	File...	NA	File...	File...	0.50	Enclosure	0.90	NA	NA	File...	Red
2	Exterior - Surface Film Based	Neumann	ASHRAE / NFRC Outside	File...	NA	File...	File...	0.50	Black Body	0.90	NA	File...	File...	Blue
3	Temperature BC	Dirichlet	NA	File...	NA	NA	NA	0.80	NA	0.84	NA	NA	NA	Pink
4	Fixed Convection BC	Neumann	Fixed Coefficient	File...	File...	File...	File...	0.30	Fixed Coefficient	0.06	File...	File...	File...	Green

Source: LBNL

Figure 19 shows a detailed view of a BC Assignment screen for a transient model, including an example of ASHRAE/NFRC Inside BC.

Figure 19: New BC Assignment Detailed Screen for a Transient Model – Example Interior – Surface Film Based

Source: LBNL





Note: If the Radiance Mode is on, the Transient checkbox is grayed out in File Properties. If the user checks the Transient box and then tries to turn on the Radiance mode, a message pops up stating that it is not compatible with the Radiance mode.

Steady-State Boundary Conditions

For steady-state BC, reference property values are specified directly (rather than through a file) since steady-state BC requires a single set of input parameters.

Again, this will include a list view and detailed view. Figure 20 shows the list view, from which the detailed view can be selected.

Figure 20: Proposed Steady-State Boundary Conditions Definitions - List View Screen

ID	Name	Type	Convection Model	Temperature C	Film Coefficient W/m2K	Heat Flux W/m2	Solar Radiation W/m2	Radiation Model	Film Coefficient W/m2K	Temperature	Color
1	Interior - Surface Film Based	Neumann	ASHRAE / NFRC Inside	21	?	0	0	Enclosure	NA	NA	
2	Exterior - Surface Film Based	Neumann	ASHRAE / NFRC Outside	-18	?	0	0	Black Body	NA	-18	
3	Temperature BC	Dirichlet	NA	15	NA	NA	NA	NA	NA	NA	
4	Fixed Convection BC	Neumann	Fixed Coefficient	22	3.75	170	0	Fixed Coefficient	4.45	30	

Source: LBNL

Figure 21 shows the proposed boundary condition library detailed screen using an example of an ASHRAE/NFRC Interior, which will be a protected record.

Figure 21: New BC Definition Detailed Screen – Example ASHRAE/NFRC Inside

Boundary Conditions ✕

Boundary Condition: NFRC Interior Thermally Broken Frame Transient List View
Cancel

Neumann Boundary Condition Type

Convection

Convection Model: ASHRAE / NFRC Inside

Air Temperature: C

Film Coefficient: W/m2-K

Radiation

Radiation Model: Radiation (Thermal / Longwave)

Automatic Enclosure Model

Black Body Radiation

Fixed Radiation Coefficient

Emissivity: Radiation Surface Temp: C

Radiation Surface Emiss: View Factor:

Heat Flux

Heat Flux: W/m2-K

Solar

Solar Radiation: W/m2-K

Solar Absorptance:

Dirichlet Boundary Condition Type

Temperature C

Water Content

Protected

Source: LBNL

The BC assignment to a selected boundary line segment for the steady state model is accomplished through the new database list view selector, shown in Figure 23.

Figure 22: New BC Assignment List Screen – Steady-State

ID	Name	Type	Convection Model	Temperature C	Film Coefficient W/m2K	Heat Flux W/m2	Solar Radiation W/m2	Solar Absorptance	Radiation Model	Emissivity	Film Coefficient W/m2K	Temperature	Humidity kg H2O/kg air	Color
1	Interior - Surface Film Based	Neumann	ASHRAE / NFRC Inside	21	Calculated	0	0	0.50	Enclosure	0.90	NA	NA	0.03	Red
2	Exterior - Surface Film Based	Neumann	ASHRAE / NFRC Outside	-18	Calculated	0	0	0.50	Black Body	0.90	NA	-18	0.03	Blue
3	Temperature BC	Dirichlet	NA	15	NA	NA	NA	0.80	NA	0.84	NA	NA	0.03	Pink
4	Fixed Convection BC	Neumann	Fixed Coefficient	22	3.75	170	0	0.30	Fixed Coefficient	0.06	4.45	30	0.03	Green

Source: LBNL

Figure 23 shows a detailed view of a BC Assignment screen for a steady-state model.

Figure 23: New BC Assignment Detailed Screen – Example Fixed Convective Coefficient

Set Boundary Condition ✕

Boundary Condition: Transient: Interior - Surface Film Based Transient

U-factor Surface: Frame

Filename:

Date Range (from file): Start Date: January 1, 2010; End Date: December 31, 2015; Date interval (timestep): 1 hour

Boundary Condition Details:

Neumann Boundary Condition Type

Convection

Convection Model: ASHRAE/NFRC Inside

Radiation

Radiation Model: AutoEnclosure

Emissivity:

Blocking Surface

Solar

Solar Absorptance:

Dirichlet Boundary Condition Type

Shading System Modifier: None

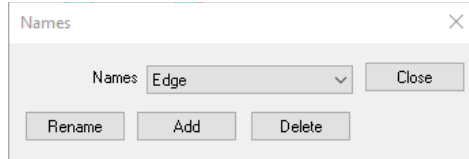
Protected

Source: LBNL

U-Factor Names Library

A U-Factor Names (also known as Tags) library is closely linked to the Boundary Conditions library, so U-factor Names have only definition screen, while assignment of names is done through the assignments of boundary conditions, as shown in the lower portion of Figure 15. No changes are proposed for the U-factor tags screen, shown in Figure 24.

Figure 24: Current U-Factor Names (Tags) Definitions Screen

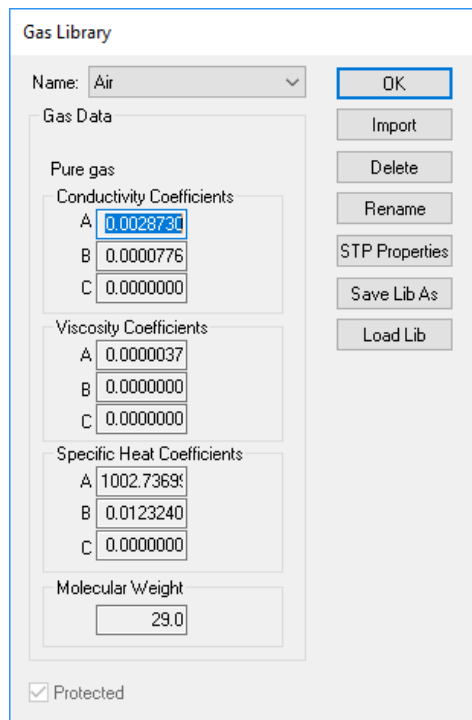


Source: LBNL

Gas Library

The Gas library (Figure 25) is closely linked to the Material library, so just as U-factor Names are assigned in the Boundary Conditions assignment screen, the different gases are assigned through the Material assignment screen.

Figure 25: Current Gases Definitions Screen



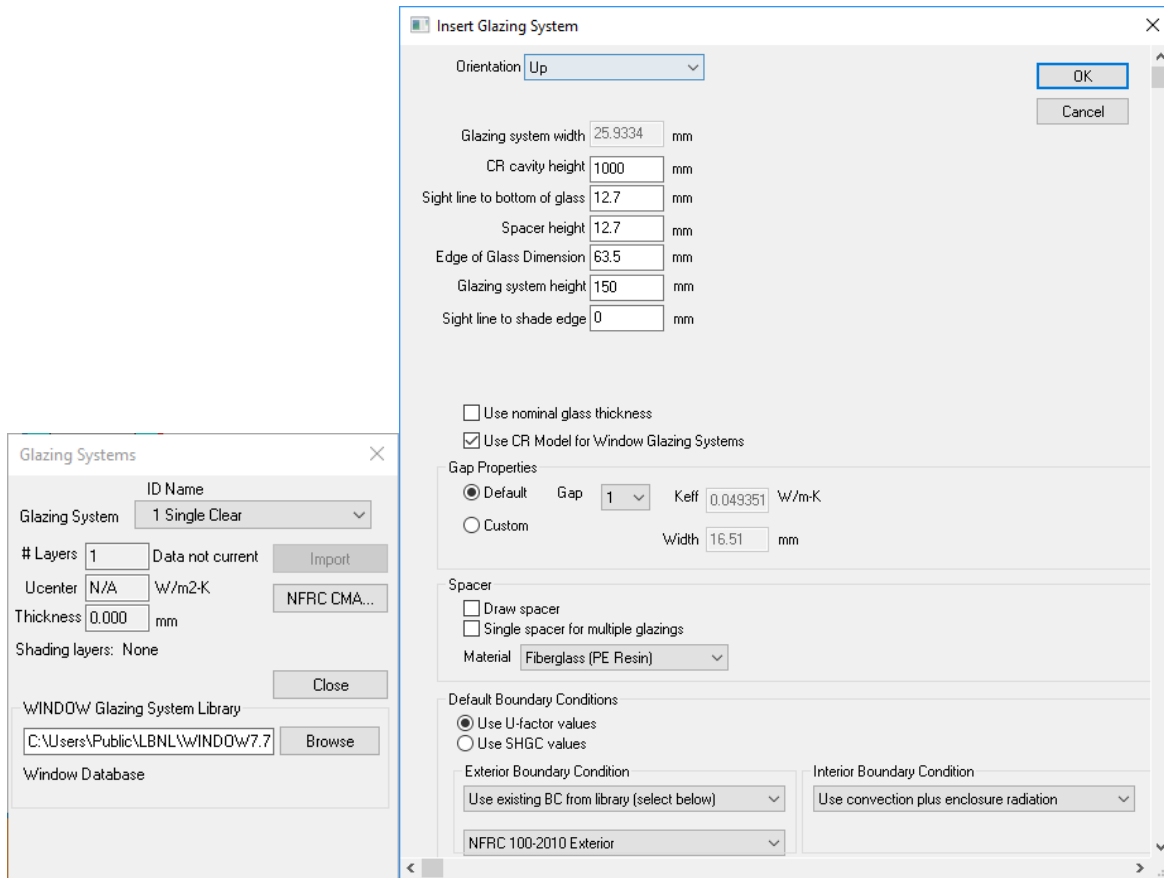
Source: LBNL

Glazing System Library

The Glazing system library is uniquely tied to window frames and edge of glazing modeling. It includes assignment screens only, since the glazing system was originally defined in the WINDOW software tool.

The Glazing system library will be largely unchanged, since windows analysis is inherently steady-state and does not have moisture issues. Figure 26 shows the current display screen for the glazing systems.

Figure 26: Current Glazing System Assignment Screens

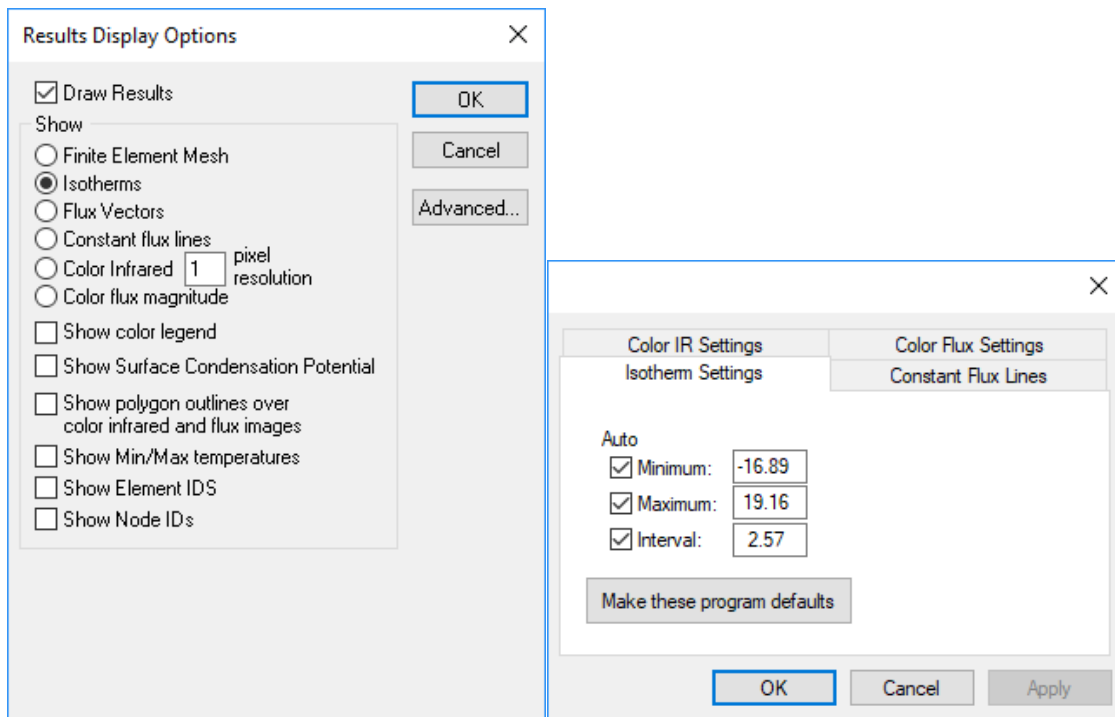


Source: LBNL

Results and Display Options

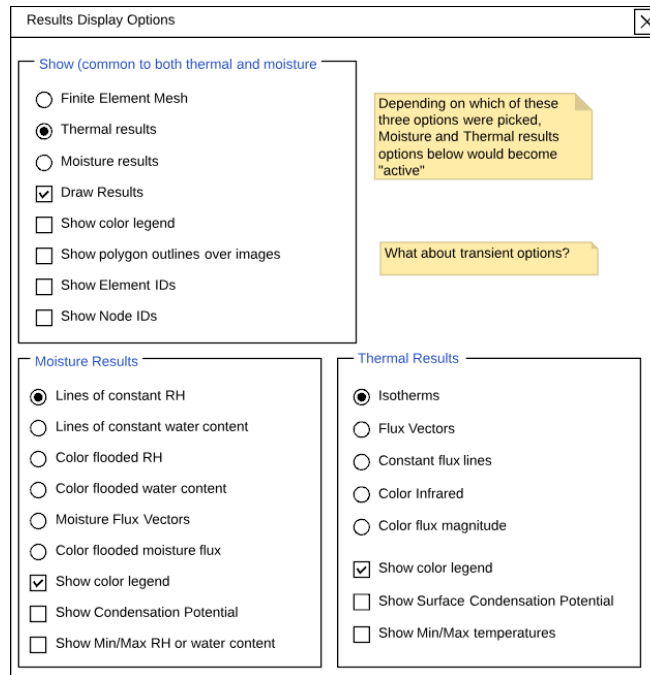
Results functionality and displays will also undergo substantial change due to the addition of moisture properties, and particularly due to the transient simulation which requires display of time series results, which is significantly more complex than a single set of results. Figure 27 shows the current results display controls. Figure 28 shows the proposed results display controls.

Figure 27: Current Result Display Screens



Source: LBNL

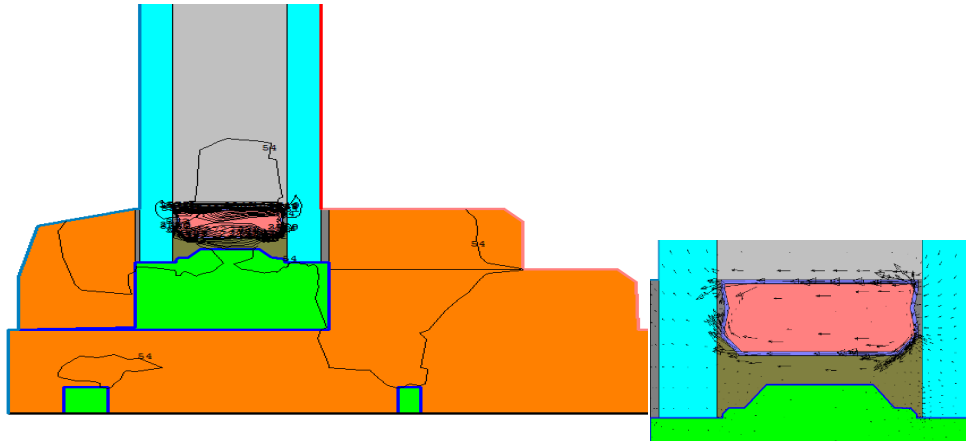
Figure 28: New Result Display Screens



Source: LBNL

Figure 30 shows results of constant values for heat.

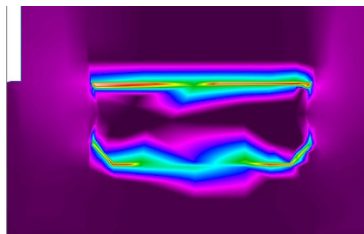
Figure 29: Current Results Display as Lines of Constant Values – Example Lines of Constant Heat



Source: LBNL

Figure 31 shows an example of constant heat flux results using color flooded plots.

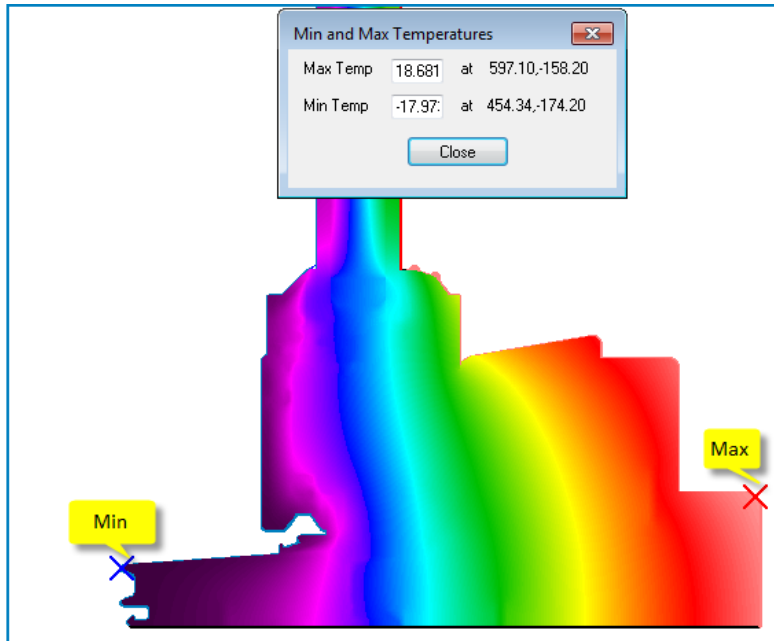
Figure 30: Current Results Display as a Color Flooded Plot – Example Lines of Constant Heat Flux



Source: LBNL

Figure 32 shows results of minimum and maximum temperatures using a color plot of constant temperatures.

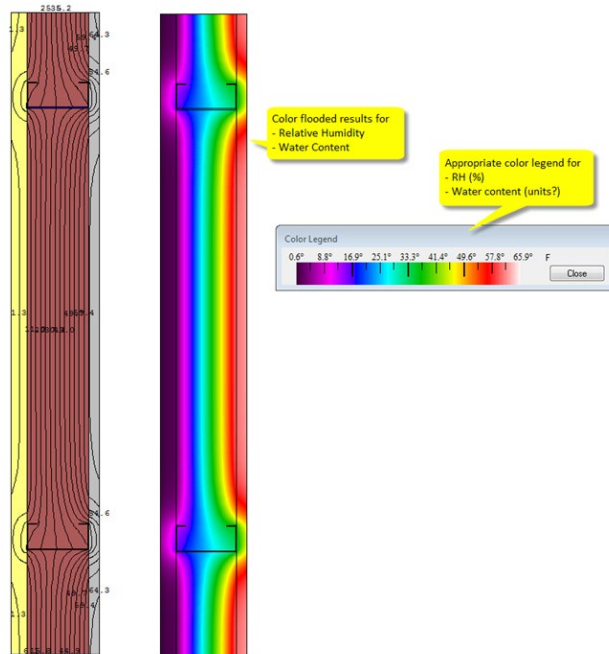
Figure 31: Current Results Display with a Color Flooded Plot of Constant Temperature Lines and Min/Max Temperatures



Source: LBNL

Figure 33 shows results for humidity and water content and constant temperature legends using color plots.

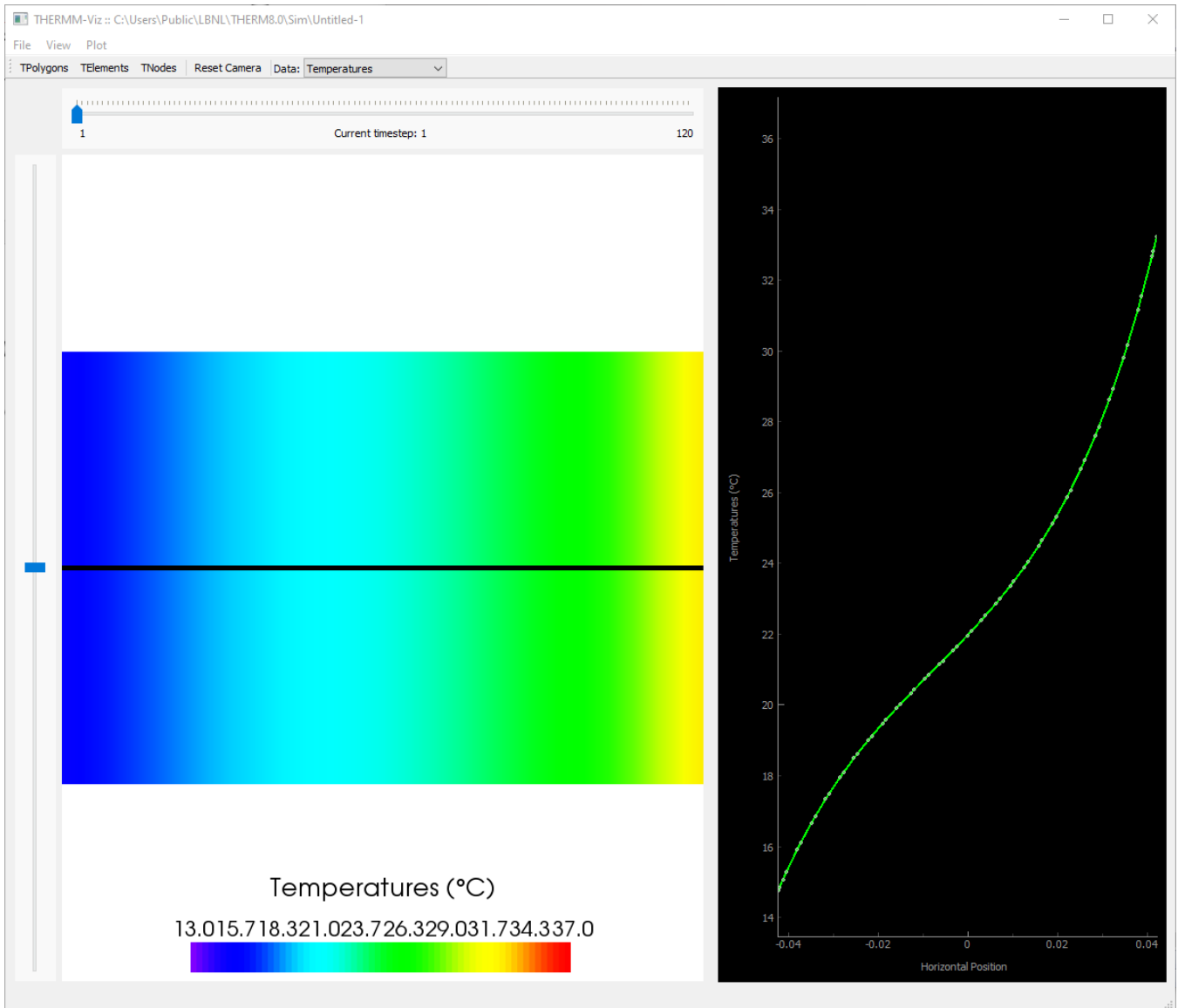
Figure 32: Current Results Display with Both Isotherms and a Color Flooded Plot of Constant Temperature Lines and Color Legend



Source: LBNL

Figure 34 shows a visualization of dynamic thermal results.

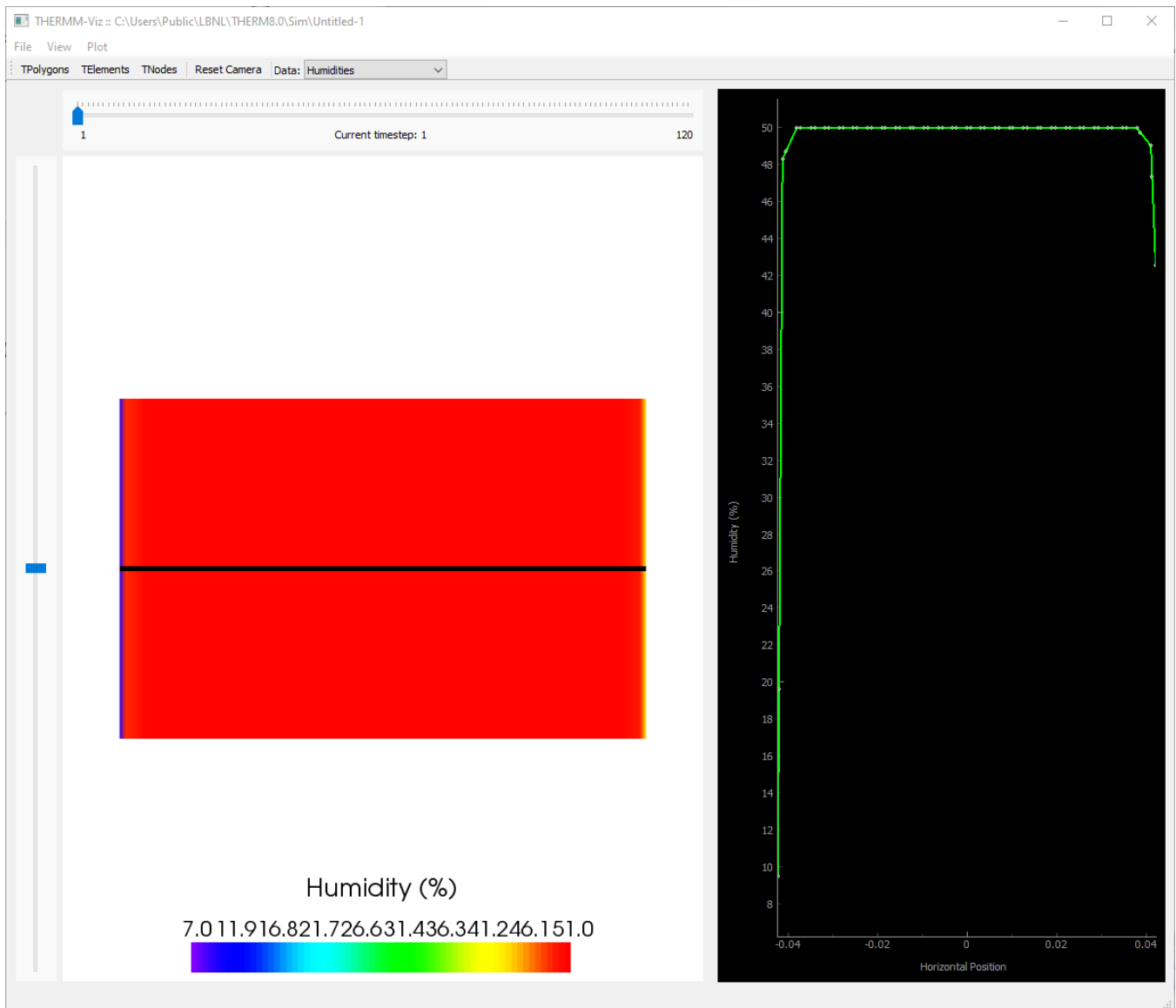
Figure 33: New Results Display with Temperature Distribution



Source: LBNL

Figure 35 shows humidity and water content (moisture modeling).

Figure 34: New Results Display with Humidity Distribution



Source: LBNL

Additional Examples of Boundary Condition Library Screens

Figure 36 shows a new boundary condition library detailed screen using examples of NFRC Exterior BC, which will be protected records.

Figure 35: New BC Definition Detailed Screen – Example NFRC Exterior

The screenshot shows a software window titled "Boundary Conditions" with a close button (X) in the top right corner. The main content area is divided into several sections:

- Boundary Condition:** A dropdown menu is set to "NFRC Exterior". To its right is an unchecked checkbox labeled "Transient".
- Neumann Boundary Condition Type:** This section is selected with a radio button. It contains a sub-section for "Convection" with a dropdown menu for "Convection Model" (options: ASHRAE / NFRC Inside, ASHRAE / NFRC Outside, Fixed Convection Coefficient, Yazdanian Klems, Kimura). Below this are input fields for "Air Temperature" (21 C) and "Film Coefficient" (26.00 W/m2-K).
- Radiation:** This section contains a "Radiation Model" with four radio button options: "Radiation (Thermal / Longwave)" (checked), "Automatic Enclosure Model", "Black Body Radiation", and "Fixed Radiation Coefficient". Below are input fields for "Emissivity" (greyed out), "Radiation Surface Temp" (-18 C), "Radiation Surface Emiss" (1.00), and "View Factor" (1.00).
- Heat Flux:** A sub-section with an input field for "Heat Flux" (0 W/m2-K).
- Solar:** A sub-section with input fields for "Solar Radiation" (0 W/m2-K) and "Solar Absorptance" (greyed out).
- Dirichlet Boundary Condition Type:** This section is unselected. It contains two unchecked checkboxes: "Temperature" and "Water Content", each followed by a greyed-out input field.
- Protected:** An unchecked checkbox at the bottom left.

On the right side of the window, there is a vertical column of buttons: "List View", "Save", "Cancel", "New", "Copy", "Delete", "Rename", "Color", and a blue color selection box.

Source: LBNL

Figure 37 is a proposed user view showing transient exterior boundary conditions for Transient ASHRAE/NFRC Outside BC.

Figure 36: New Boundary Conditions Definitions Detailed View Screen – Example of Transient ASHRAE NFRC Outside BC

The image shows a software dialog box titled "Boundary Conditions" with a close button (X) in the top right corner. At the top, there is a dropdown menu showing "Transient: Exterior - Surface Film Based" and a checked checkbox labeled "Transient". To the right of these are several buttons: "List View", "Cancel", "New", "Copy", "Delete", "Rename", and "Color". Below this, the "Neumann Boundary Condition Type" is selected with a radio button. Underneath, the "Convection" checkbox is checked, and a "Model" dropdown menu is open, showing a list of options: "ASHRAE / NFRC Outside" (highlighted in red), "ASHRAE / NFRC Inside", "Fixed Convection Coefficient", "Yazdarian Klems", and "Kimura". Below the convection options, the "Radiation (Thermal / Longwave)" checkbox is checked, with three radio button sub-options: "Automatic Enclosure Model", "Black Body Radiation" (selected), and "Fixed Radiation Coefficient". There are also unchecked checkboxes for "Heat Flux" and "Solar Radiation". At the bottom, the "Dirichlet Boundary Condition Type" is unselected, with unchecked checkboxes for "Temperature" and "Water Content". A "Protected" checkbox is located at the bottom left of the dialog.

Source: LBNL

Figure 38 shows a proposed user view showing the boundary conditions for temperature.

Figure 37: Proposed Boundary Conditions Definitions Detailed View Screen – Example of Steady-State NFRC Exterior BC

The screenshot shows a software window titled "Boundary Conditions" with a close button in the top right corner. The window is divided into several sections:

- Transient: Temperature Based**: A dropdown menu with a downward arrow and a checked checkbox labeled "Transient".
- Neumann Boundary Condition Type**: A radio button that is currently unselected. It includes a sub-section for "Convection" with a "Model" dropdown menu. The dropdown is open, showing options: "ASHRAE / NFRC Inside" (selected), "ASHRAE / NFRC Outside", "Fixed Convection Coefficient", "Yazdanian Klems", and "Kimura".
- Radiation (Thermal / Longwave)**: A radio button that is unselected. It includes sub-options: "Automatic Enclosure Model" (selected with a radio button), "Black Body Radiation" (unselected), and "Fixed Radiation Coefficient" (unselected).
- Heat Flux**: A radio button that is unselected.
- Solar Radiation**: A radio button that is unselected.
- Dirichlet Boundary Condition Type**: A radio button that is selected. It includes sub-options: "Temperature" (checked with a checkbox) and "Water Content" (unchecked).
- Protected**: A checkbox at the bottom left that is unchecked.

On the right side of the window, there is a vertical stack of buttons: "List View", "Cancel", "New", "Copy", "Delete", "Rename", and "Color". Below the "Color" button is a pink rectangular color selection area.

Source: LBNL

Figure 39 shows a proposed user view showing the boundary condition for a steady state NFRC exterior.

Figure 38: Proposed Boundary Conditions Definitions Detailed View Screen – Example of Steady-State NFRC Exterior BC

The screenshot shows a software window titled "Boundary Conditions" with a close button in the top right corner. The main content area is divided into several sections:

- Boundary Condition:** A dropdown menu is set to "NFRC Exterior" and a checkbox for "Transient" is unchecked.
- Neumann Boundary Condition Type:** This is the selected option, indicated by a radio button.
- Convection:** A dropdown menu for "Convection Model" is open, showing options: "ASHRAE / NFRC Inside", "ASHRAE / NFRC Outside", "Fixed Convection Coefficient", "Yazdanian Klems", and "Kimura". Below this, "Air Temperature" is set to 21 C and "Film Coefficient" is set to 26.00 W/m2-K.
- Radiation:** The "Radiation Model" section has "Radiation (Thermal / Longwave)" checked, with "Automatic Enclosure Model", "Black Body Radiation" (selected with a radio button), and "Fixed Radiation Coefficient" unselected. Below, "Emissivity" is a greyed-out field, "Radiation Surface Temp" is -18 C, "Radiation Surface Emiss" is 1.00, and "View Factor" is 1.00.
- Heat Flux:** A section with "Heat Flux" set to 0 W/m2-K.
- Solar:** A section with "Solar Radiation" set to 0 W/m2-K and "Solar Absorptance" as a greyed-out field.
- Dirichlet Boundary Condition Type:** This option is unselected. It includes checkboxes for "Temperature" and "Water Content", both with greyed-out input fields.
- Protected:** A checkbox at the bottom left is unchecked.

On the right side of the window, there is a vertical toolbar with buttons: "List View", "Save", "Cancel", "New", "Copy", "Delete", "Rename", and "Color". Below the "Color" button is a blue color swatch.

Source: LBNL

Boundary Condition Assignment Example

Figure 40 shows a proposed user view showing the boundary condition for transient model temperature.

Figure 39: Proposed BC Assignment Detailed Screen for Transient Model – Example Temperature BC

Set Boundary Condition

Boundary Condition: **Temperature BC** Transient

U-factor Surface: **Edge** Date Range (from file)
Start Date: January 1, 2010
End Date: December 31, 2015
Date interval (timestep): 1 hour

Filename: **Filename**

Neumann Boundary Condition Type

Convection

Convection Model: **ASHRAE/NFRC Inside**

Air Temperature:

Film Coefficient:

Radiation

Radiation Model: **AutoEnclosure**

Emissivity:

Radiation Surface Temp:

Radiation Surface Emiss:

View Factor:

Blocking Surface

Heat Flux

Heat Flux:

Solar

Solar Radiation:

Solar Absorptance:

Dirichlet Boundary Condition Type

Temperature:

Water Content:

Shading System Modifier: **None**

Protected

Source: LBNL

CHAPTER 5:

Results Validation and Verification

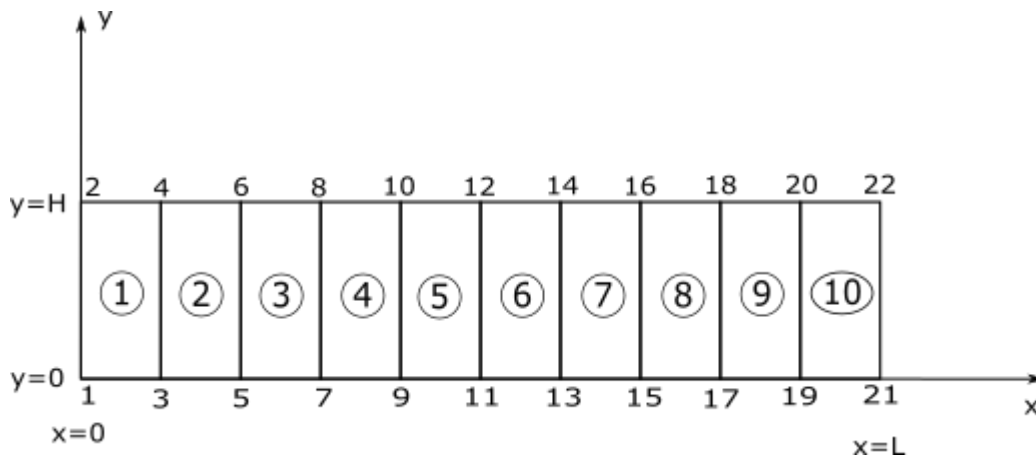
Introduction

This section details validation and verification exercises conducted to confirm the validity of THERMM's thermal and moisture transfer solutions. Analytical and numerical solutions are compared with the software tool. For analytical solutions, the calculation engine in THERMM, HygroThermFEM, was used as a stand-alone tool, while for numerical solution comparisons, both stand-alone and integrated software tools were employed.

Analytical Solution: Uniform Solid with 10 Elements

The finite element mesh used for all problems consisted of a 10-element mesh of length L meters in the x coordinate direction and height H meters in the y coordinate direction. The top and bottom surfaces of the finite element mesh are adiabatic, and boundary conditions are applied at $x = 0$ and $x = L$, as shown in Figure 41.

Figure 40: The Top and Bottom Surfaces of the Finite Element Mesh



Source: LBNL

Steady-State Cases

Temperature Boundary Condition

A slab of thickness L with surfaces at $x = 0$ and $x = L$ was kept at constant temperatures T_{s1} and T_{s2} , respectively.

Unit test name: Analytical_TemperatureBC_SteadyState

Solution (Incorpera-Dewitt; page 63): $\frac{T(x)-T_{s1}}{T_{s2}-T_{s1}} = \frac{x}{L}$

Parameters:

$$L = 1.0 \text{ [m]}$$

$$T_{s1} = 0.0[\text{°C}]$$

$$T_{s2} = 1.0[\text{°C}]$$

Results:

Table 1 shows the comparison of results for the steady-state thermal model using the analytical and THERMM solution.

Table 1: Comparison of Steady-State Thermal Results Using Analytical and THERMM Solutions

x-coordinate	temperature analytics	temperature HygroThermFEM	error
0	0	0	0
0.1	0.1	0.1	0
0.2	0.2	0.2	0
0.3	0.3	0.3	0
0.4	0.4	0.4	0
0.5	0.5	0.5	0
0.6	0.6	0.6	0
0.7	0.7	0.7	0
0.8	0.8	0.8	0
0.9	0.9	0.9	0
1	1	1	0

Source: LBNL

Humidity Boundary Condition

A slab of thickness L with surfaces at $x = 0$ and $x = L$ was kept at constant humidities φ_{s1} and φ_{s2} , respectively.

Unit test name: Analytical_HumidityBC_SteadyState

Solution (Incorpera-Dewitt; page 63): $\frac{\varphi(x) - \varphi_{s1}}{\varphi_{s2} - \varphi_{s1}} = \frac{x}{L}$

Parameters:

$$L = 1.0 \text{ [m]}$$

$$T_{s1} = 0.0[\text{°C}]$$

$$T_{s2} = 1.0[\text{°C}]$$

Results:

Table 2 shows the comparison of results for moisture model using analytical and THERMM solution.

Table 2: Comparison of Moisture Results Using Analytical and THERMM Solutions

<i>x</i> -coordinate	humidity analytics	humidity HygroThermFEM	error
0	0	0	0
0.1	0.1	0.1	0
0.2	0.2	0.2	0
0.3	0.3	0.3	0
0.4	0.4	0.4	0
0.5	0.5	0.5	0
0.6	0.6	0.6	0
0.7	0.7	0.7	0
0.8	0.8	0.8	0
0.9	0.9	0.9	0
1	1	1	0

Source: LBNL

Transient Cases

Constant Temperature Boundary Condition

A slab of length L with a uniform initial temperature T_0 and a surface at $x = L$ was kept at a constant temperature of T_{s2} and an adiabatic surface at $x = 0$.

Unit test name: Analytical_ConvectionBC_Transient

Solution (Carslaw-Jeager; page 97):

$$\frac{T(x, t)}{T_0} = \frac{4}{\pi} \cdot \sum_{n=0,1,2,\dots} \left[\frac{(-1)^n}{(2n+1)} \cdot e^{-F(2n+1)^2 \cdot \pi^2 \frac{t}{4L^2}} \cdot \cos\left((2n+1) \cdot \pi \cdot \frac{x}{2L}\right) \right]$$

$$F = \frac{k}{\rho \cdot C_p}$$

Where:

Parameters:

$$\rho = 2050 \left[\frac{kg}{m^3} \right]; C_p = 850 \left[\frac{J}{kg \cdot K} \right]; k = 1.8 \left[\frac{W}{m \cdot K} \right]$$

$$T_0 = 20[^\circ C]; T_{s2} = 0[^\circ C]; L = 0.1[m]$$

The simulation engine was set to a timestep of 36 seconds, with a number of timesteps set to 1,000.

Results:

Table 3 shows the comparison of results for the transient (time-dependent) thermal model using the analytical and THERMM solutions for a problem with constant temperature boundary conditions at the left model boundary ($x = 0$ m).

Table 3: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Constant Temperature Boundary Condition at $x = 0$ m

# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	10.171	10.2101	0.039104
200	4.064	4.104935	0.040935
300	1.623	1.64982	0.02682
400	0.649	0.663081	0.014081
500	0.259	0.2665	0.0075
600	0.104	0.107109	0.003109
700	0.041	0.043048	0.002048
800	0.017	0.017301	0.000301
900	0.007	0.006953	4.7E-05
1,000	0.003	0.002794	0.000206

Source: LBNL

Table 4 shows the comparison of results for the transient (time-dependent) thermal model using analytical and THERMM solutions for a problem with a constant temperature boundary condition at $x = 0.05$ m.

Table 4: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Constant Temperature Boundary Condition at $x = 0.05$ m

# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	7.195	7.224487	0.029487
200	2.874	2.902629	0.028629
300	1.148	1.166599	0.018599
400	0.459	0.468869	0.009869
500	0.183	0.188444	0.005444
600	0.073	0.075737	0.002737
700	0.029	0.030439	0.001439
800	0.012	0.012234	0.000234
900	0.005	0.004917	8.3E-05
1,000	0.002	0.001976	2.4E-05

Source: LBNL

Constant Convection Boundary Condition

A slab of length L with a uniform initial temperature T_0 has an adiabatic surface at $x = 0$ and is transferring heat by convection at $x = L$ to the ambient environment at temperature T_a .

Solution (Carslaw-Jaeger; page 122):

$$\frac{T(x, t)}{T_0} = \sum_{n=1,2,\dots} \left[\frac{2 \cdot L \cdot h_{conv} \cdot \cos\left(\frac{\beta_n x}{L}\right) \cdot e^{(-F \cdot \beta_n^2)}}{[L \cdot h_{conv}(L \cdot h_{conv} + 1) + \beta_n^2] \cdot \cos(\beta_n)} \right]$$

where β_n are the n roots of the transcendental equation:

$$\beta_n \cdot \tan(\beta_n) = L \cdot h_{conv}$$

Parameters:

$$\rho = 1 \left[\frac{kg}{m^3} \right]; C_p = 1 \left[\frac{J}{kg \cdot K} \right]; k = 1 \left[\frac{W}{m \cdot K} \right]$$

$$T_0 = 1 [^{\circ}C]; T_a = 0 [^{\circ}C]; h_c = 1 \left[\frac{W}{m^2 \cdot K} \right]; L = 1 [m]$$

The simulation engine was set to a timestep of 36 seconds, with a number of timesteps set to 1,000.

Results:

Table 5 shows the comparison of results for the transient (time-dependent) thermal model using analytical and THERMM solutions for a problem with a convection boundary condition at the left model boundary ($x = 0$ m).

Table 5: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Convection Boundary Condition at $x = 0$ m

# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	0.99311	0.992644	0.000466
200	0.95064	0.950474	0.000166
300	0.8918	0.891909	0.000109
400	0.83095	0.831187	0.000237
500	0.77253	0.772803	0.000273
600	0.71768	0.717959	0.000279
700	0.66656	0.666831	0.000271
800	0.61903	0.619288	0.000258
900	0.57487	0.575118	0.000248
1,000	0.53386	0.534093	0.000233

Source: LBNL

Table 6 shows the comparison of results for the transient (time-dependent) thermal model using analytical and THERMM solutions for a problem with a convection boundary condition at the left model boundary ($x = 0.5$ m).

Table 6: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Convection Boundary Condition at $x = 0.5$ m

# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	0.950852	0.95051	0.000342
200	0.879624	0.87925	0.000374
300	0.815556	0.81526	0.000296
400	0.756958	0.75671	0.000248
500	0.702826	0.7026	0.000226
600	0.652646	0.65243	0.000216
700	0.606074	0.60587	0.000204
800	0.562834	0.56264	0.000194
900	0.522681	0.5225	0.000181
1,000	0.485393	0.48522	0.000173

Source: LBNL

Table 7 shows the comparison of results for the transient (time-dependent) thermal model using analytical and THERMM solutions for a problem with a convection boundary condition at the left model boundary ($x = 1.0$ m).

Table 7: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Convection Boundary Condition at $x = 1.0$ m

# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	0.724674	0.72358	0.001094
200	0.643861	0.64339	0.000471
300	0.589039	0.58885	0.000189
400	0.544232	0.54417	6.2E-05
500	0.504533	0.50452	1.3E-05
600	0.468266	0.46827	4E-06
700	0.434774	0.43478	6E-06
800	0.403731	0.40374	9E-06
900	0.374921	0.37493	9E-06
1,000	0.348172	0.34818	8E-06

Source: LBNL

Constant Flux Boundary Conditions

A slab of length L with a uniform initial temperature T_0 has an adiabatic surface at $x = 0$ and a uniform surface heat flux q_{flux} applied to $x = L$.

Solution:

$$T(x, t) = \frac{q_{flux} \cdot t}{\rho C_p L} + \frac{q_{flux} \cdot L}{k} \left\{ \frac{3x^2 - L^2}{6L^2} - \frac{2}{\pi} \sum_{n=0,1,2,\dots} \frac{(-1)^n}{n^2} e^{-F(n\pi^2)} \cdot \cos\left(\frac{n\pi x}{L}\right) \right\}$$

Parameters:

$$\rho = 1 \left[\frac{kg}{m^3} \right]; C_p = 1 \left[\frac{J}{kg \cdot K} \right]; k = 1 \left[\frac{W}{m \cdot K} \right]$$

$$T_0 = 0 [^{\circ}C]; q_{flux} = 1 \left[\frac{W}{m^2} \right]; L = 1 [m]$$

The simulation engine was set to a timestep of 0.001 seconds, with a number of timesteps set to 1,000.

Results:

Table 8 shows the comparison of results for the transient (time-dependent) thermal model using analytical and THERMM solutions for a problem with a flux boundary condition at the left model boundary ($x = 0$ m).

Table 8: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Flux Boundary Condition at $x = 0$ m

# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	0.168	0.008411	0.159589
200	0.122	0.061591	0.060409
300	0.166	0.143493	0.022507
400	0.246	0.23665	0.00935
500	0.338	0.334066	0.003934
600	0.435	0.433091	0.001909
700	0.534	0.532723	0.001277
800	0.634	0.632584	0.001416
900	0.733	0.732531	0.000469
1,000	0.833	0.832512	0.000488

Source: LBNL

Table 9 shows the comparison of results for the transient (time-dependent) thermal model using analytical and THERMM solutions for a problem with a convection boundary condition at the left model boundary ($x = 0.5$ m).

Table 9: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Flux Boundary Condition at $x = 0.5$ m

# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	0.061	0.058733	0.002267
200	0.158	0.157529	0.000471
300	0.258	0.2575	0.0005
400	0.358	0.3575	0.0005
500	0.458	0.4575	0.0005
600	0.558	0.5575	0.0005
700	0.658	0.6575	0.0005
800	0.758	0.7575	0.0005
900	0.858	0.8575	0.0005
1,000	0.958	0.9575	0.0005

Source: LBNL

Table 10 shows the comparison of results for the transient (time-dependent) thermal model using analytical and THERMM solutions for a problem with a convection boundary condition at the left model boundary ($x = 1.0$ m).

Table 10: Comparison of Transient Thermal Results Using Analytical and THERMM Solutions for a Problem with a Flux Boundary Condition at $x = 1.0$ m

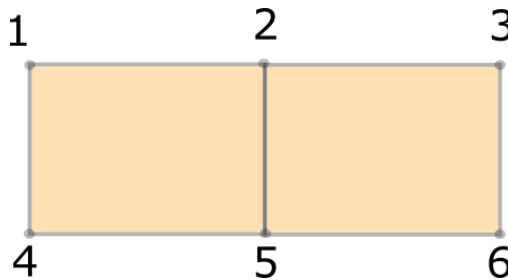
# of timesteps	Temperature Analytic	Temperature HygroThermFEM	Absolute Error
100	0.193	0.354122	0.161122
200	0.445	0.50335	0.05835
300	0.6	0.621505	0.021505
400	0.721	0.728349	0.007349
500	0.829	0.830933	0.001933
600	0.932	0.931908	9.2E-05
700	1.033	1.032276	0.000724
800	1.133	1.132415	0.000585
900	1.233	1.232468	0.000532
1000	1.333	1.332487	0.000513

Source: LBNL

Analytical Solution: A Uniform Solid with Two Elements

A homogenous material was analyzed using THERMM against an analytical solution. The material was subdivided into two identical elements with six nodes (Figure 42) and analyzed using the THERMM calculation engine HygroThermFem.

Figure 41: FEM Model used in the test



Source: LBNL

The model length is 0.2 m. Since this is a 1-D test, the height and depth have unit dimensions (e.g., 1 m).

Fixed film boundary conditions were applied to boundaries 1-4 and 3-6. Fixed ambient/air and domain temperatures were set for the simulation.

$$T_{ambient} = T_{domain} = 20[^\circ C]$$

The convective film coefficient on both sides was set to:

$$h_{c,left} = h_{c,right} = 2 \left[\frac{W}{m^2 K} \right]$$

The initial in domain humidity was set to zero, while the humidity on both sides was set to:

$$\varphi_{left} = \varphi_{right} = 0.4$$

The material used in the simulation is Cottaer Sandstone. The moisture simulation included water liquid transfer, capillary conduction, and vapor diffusion conduction. The timestep was set to one hour, and error tolerance was set to 10^{-5} .

Solution

In Domain Water Content

The solution from the HygroThermFEM after one timestep (one hour) is shown in Table 11.

Table 11: Water Content Prediction using THERMM

Node #	1	2	3
Water content [kg/m ³]	0.649337	0.001264	0.649337

Source: LBNL

Water content in the domain can be calculated as:

$$wc = \frac{wc_1 + wc_2}{2} \cdot l_1 + \frac{wc_2 + wc_3}{2} \cdot l_2 = \frac{0.649337 + 0.001264}{2} \cdot 0.1 \cdot 2 = 0.065060149 [kg]$$

Solution of the Equation for the Water Transfer through Boundaries

$$\dot{g}_{conv,ex} = \beta_{conv,ex} \cdot \left(\frac{e^{\left(\frac{77.345 + 0.0057 \cdot T_{surf,ex} - \frac{7235}{T_{surf,ex}}\right)}}}{461.4 \cdot T_{surf,ex}^{9.2}} \cdot \varphi - \frac{e^{\left(\frac{77.345 + 0.0057 \cdot T_{surf,ex} - \frac{7235}{T_{surf,ex}}\right)}}}{461.4 \cdot T_{air,ex}^{9.2}} \cdot \varphi_{ext} \right)$$

At the Start of the Timestep

The mass flow rate at zero time was calculated to be:

$$\dot{g}_{conv,ex} = 1.06703 \cdot 10^{-5} \left[\frac{kg}{m^2 s} \right]$$

Which then led to the following solution for the amount of water in the domain:

$$wc = 1.06703 \cdot 10^{-5} \left[\frac{kg}{m^2 s} \right] \cdot 3600 [s] \cdot 2 \cdot 1 [m^2] = 0.076825888 [kg]$$

This result is different from what HygroThermFEM calculated above (0.065060149 kg), and it reflects the lack of accounting of the decrease in water transfer as the material starts to absorb moisture.

At the End of the Timestep

The humidity solution at the boundary at the end of first timestep was:

$$\varphi = 0.0612582$$

Applying this humidity to the boundary condition equation gave:

$$\dot{g}_{conv,ex} = 9.03616 \cdot 10^{-6} \left[\frac{kg}{m^2 \cdot s} \right]$$

Which then led to the following solution for the amount of water in the domain:

$$w_c = 9.03616 \cdot 10^{-6} \left[\frac{kg}{m^2 \cdot s} \right] \cdot 3600 [s] \cdot 2 \cdot 1 [m^2] = 0.065060349 [kg]$$

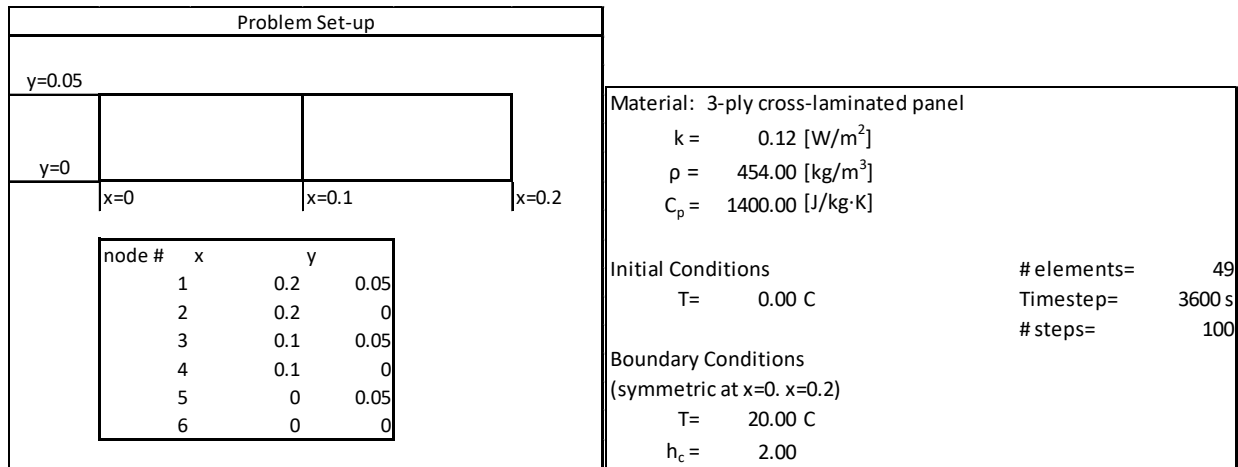
That result perfectly agreed with HygroThermFEM solution, confirming that the software tool properly takes into account a gradual decrease of water transfer through the boundary.

Numerical Solution: Uniform Solid with Two Elements

Cross-Laminated Panel

A cross-laminated panel with three plies was analyzed for heat transfer using temperature distribution as a comparison variable. One hundred timesteps were modeled. A comparison was made between THERMM, WUFI, and Comsol. WUFI is the other known moisture modeling program, and Comsol is a commercial, general purpose numerical modeling tool. The model geometry and input data are listed in Figure 43.

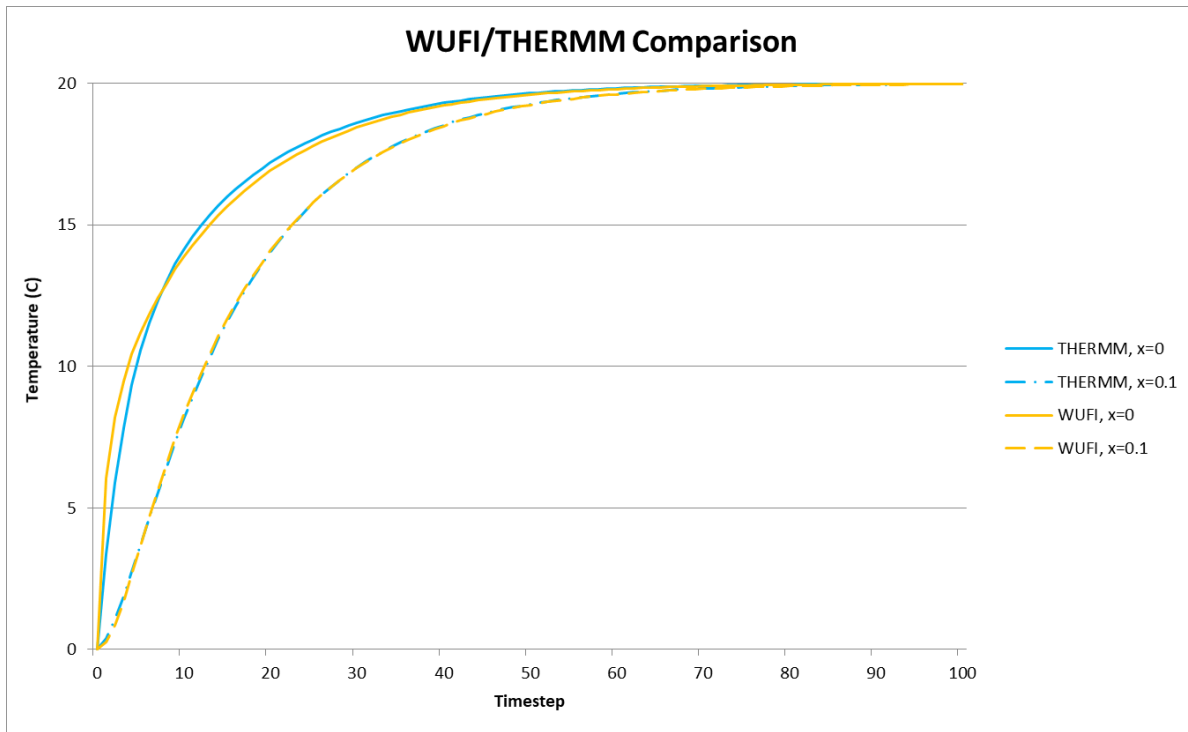
Figure 42: Model Geometry Definition and Input Data to the Model for a Cross-Laminated Panel



Source: LBNL

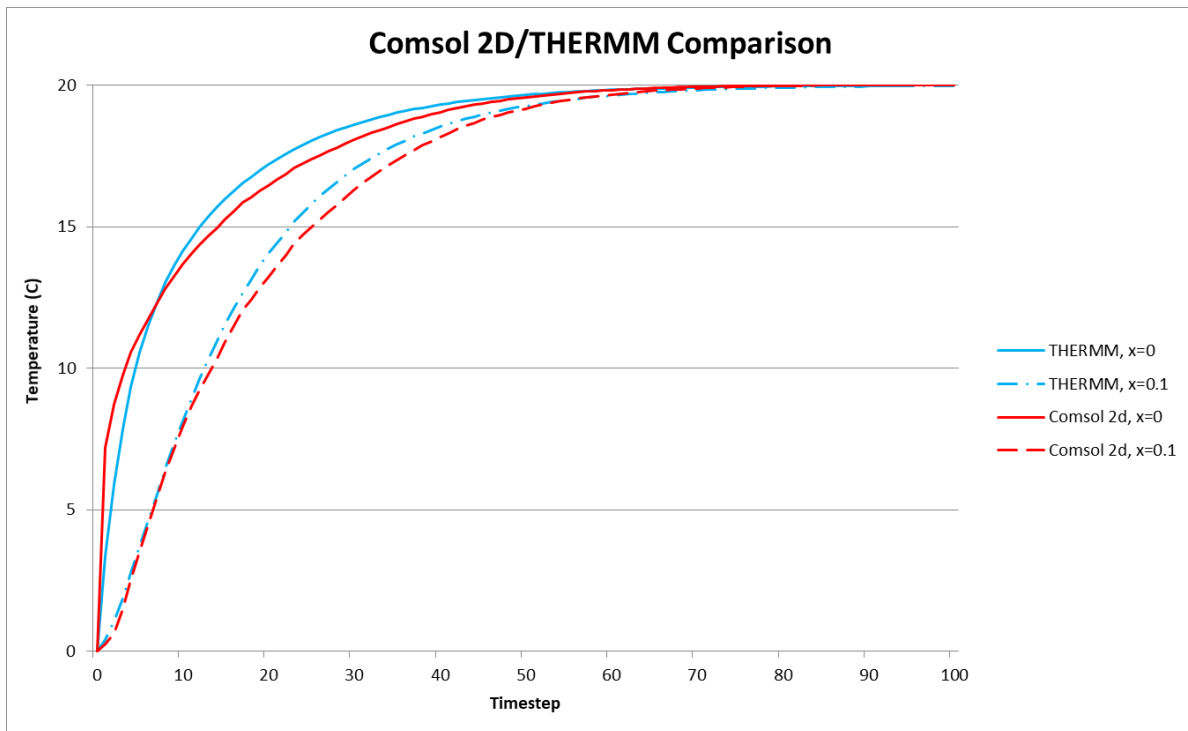
Results of modeling are shown in Figure 44 and Figure 45.

Figure 43: Temperature Comparison Between WUFI and THERM for a Three-Ply Cross-Laminated Panel



Source: LBNL

Figure 44: Temperature Comparison Between Comsol and THERM for a Three-Ply Cross-Laminated Panel

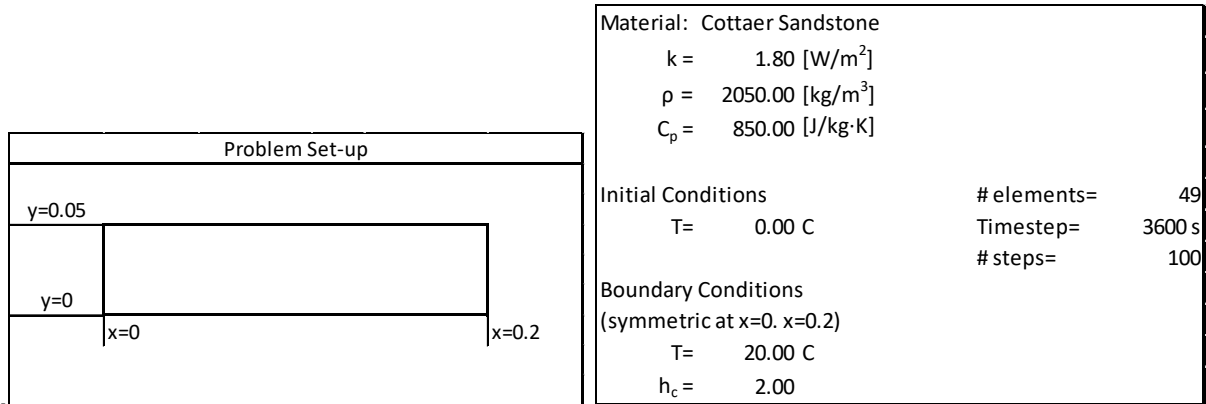


Source: LBNL

Cottaer Sandstone Slab

Cottaer sandstone slab was analyzed for heat transfer using temperature distribution as a comparison variable. One hundred timesteps were modeled, as with the previous case. A comparison was made between THERMM, WUFI, and Ansys. WUFI is the other known moisture modeling program, and Ansys is a commercial, general purpose numerical modeling tool. Input data are listed in Figure 46.

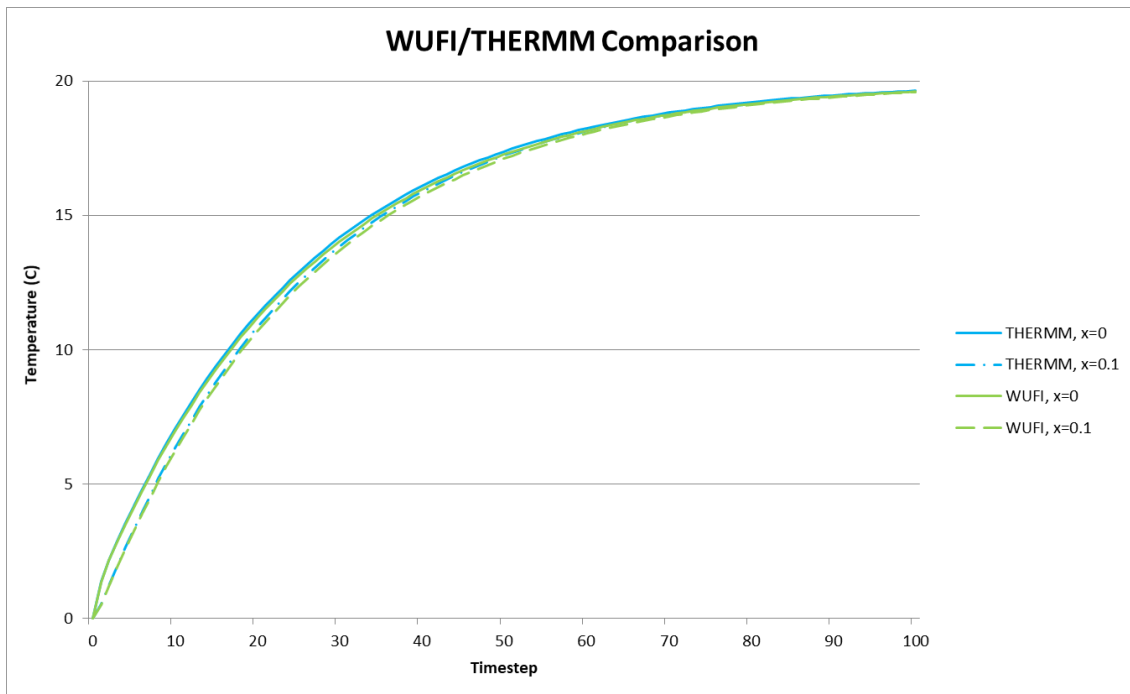
Figure 45: Model Geometry Definition and Input Data to the Model for a Cottaer Sandstone Slab



Source: LBNL

Results of a comparison between WUFI and THERM are shown in Figure 47.

Figure 46: Temperature Comparison Between WUFI and THERM for a Cottaer Sandstone Slab



Source: LBNL

CHAPTER 6:

Technology/Knowledge/Market Transfer

Activities

The target market for the THERMM software tool is architects, engineers, builders, and consultants involved in the design and implementation of building envelope components. This free tool will allow them to design envelope solutions that are both efficient from a thermal point of view and sound with regard to moisture management.

Free open-source software tools with a GUI and a strong scientific background have been shown to capture the market successfully in the past. For example, the WINDOW and THERM tools developed by LBNL are widely used across the United States and around the world.

A user-friendly, freely available software tool for modeling building thermal and moisture performance has been widely sought and demanded by building professionals. The currently available free software tool WUFI² is a 1-D modeling program with a significant user base. The limitation of this tool is that it can only be used to conduct 1-D modeling, therefore it is not applicable to modeling thermal bridges and inhomogeneous building constructions, which are often the causes for moisture problems. The 2-D version is available at cost from Fraunhofer IBP, but due to its high cost and difficult user interface it is not widely used. THERMM's easy availability will result in wide adoption by the existing THERM and WUFI user base, which currently numbers in the tens of thousands. The availability of this software as an open-source platform posted on GitHub will be appreciated by building professionals in the United States and globally.

Many of THERMM's functionalities also will be appreciated by the EnergyPlus development community, as some of the features, such as dynamic modeling of thermal performance, can be directly incorporated into preparing wall thermal indices, which are currently severely limited.

The availability of an API for the simulation engine will also result in wider adoption by industries developing materials and components for building envelopes and construction in general. The software tool will be applicable to both new and existing buildings and residential and commercial construction. It is expected that a number of companies will use the simulation engine API to provide online calculation tools for their user base.

THERMM will be distributed on GitHub under a BSD type of license, which is already utilized for other USDOE software tools, such as EnergyPlus.

² Available at <https://web.ornl.gov/sci/buildings/tools/wufi/>.

CHAPTER 7:

Conclusions and Recommendations

The result of this project is THERMM, a highly capable software tool that analyzes thermal and moisture performance of 2-D building components and assemblies in a user-friendly GUI environment. It builds on the foundation of the widely used software tool THERM, which was primarily used for steady-state heat transfer analysis in windows, doors, skylights, and other transparent facades. Expanding its modeling capabilities enables its existing user base to adopt new functionality for modeling hygrothermal performance of building envelopes.

The new modeling engine HygroThermFEM, developed through this project, is posted as an open source, freely accessible code on GitHub. It is expected that this approach will not only involve the broader software development community in enhancing the calculation engine's capabilities, but also help facilitate the repair of any bugs that may be encountered. Furthermore, the API has been developed for easy and consistent implementation of the calculation engine in third-party software tools that are designed to analyze thermal and moisture performance of building components and assemblies. Examples of such tools include EnergyPlus, HoneyBee, and others.

Future development should include further enhancements to the newly developed engine, bug fixes, an improved visualization module, and additional GUI improvements. Software tools like EnergyPlus can benefit from the dynamic analysis of thermal bridges. An additional program can be developed that converts THERMM analysis results into EnergyPlus-compatible layer-by-layer opaque envelope construction.

CHAPTER 8:

Benefits to Ratepayers

This project will benefit California's, as well as the rest of the nation's, utility ratepayers by providing building professionals with a highly capable, but user-friendly engineering software tool at no cost. California ratepayers have been enjoying the benefits of the THERM program for a long time, as it is the benchmark software tool that is used in National Fenestration Rating Council (NFRC) rating and certification and will be soon used in the newly formed Window Attachments Energy Ratings Council (AERC) for window attachments rating and certification. California was an early adopter and strong advocate for NFRC ratings. Adding moisture transfer modeling capability to THERM will enable building professionals to design structures that will be durable and not conducive to mold formation, which is a significant health hazard. It can be expected that the THERMM software tool developed by this project, which combines heat and moisture modeling capability, will lead to a better energy and moisture rating of building envelope assemblies, enabling more mainstream design of energy-efficient and moisture transfer resistant structures.

California's residential and commercial building envelopes are responsible for approximately 0.37 quads of energy used (equivalent to approximately \$4 billion annually); nationally building envelopes are responsible for approximately 7.6 quads (approximately \$80 billion annually). Being able to design more energy-efficient building envelopes with the ability to design moisture control with great confidence will improve building envelope energy efficiency and will substantially prolong building life. It is estimated that 5 percent improvement in building envelope energy performance can be attributed to more confident building envelope design, resulting in 0.02 quads (approximately \$200 million annually) in energy savings in California and 0.38 quads (approximately \$4 billion annually) nationally.

This study did not estimate the health benefits based on reduced mold in buildings, due to a lack of relevant data; however, it is expected that healthier buildings will provide additional tangible and intangible benefits to building occupants. Homeowners and building owners alike are more concerned with health and safety issues than they are with energy concerns, and it is likely that this tool will be adopted as a way of reducing health risks due to moisture-related mold problems in buildings.

This project focused on the residential and commercial sectors, and improved moisture design of building envelopes is expected to benefit both sectors. It is likely the tool will be used in design of new construction and retrofit applications.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
AERC	Window Attachment Energy Rating Council
Comsol	A commercial, general purpose numerical modeling tool
API	Application programming interface
BC	Boundary condition
BMP	Bitmap image file
BSD	Berkeley Software Distribution
CAD	Computer-aided design
CEC	California Energy Commission
CMake	Cross-platform build system
DLL	Dynamic link library
USDOE	United States Department of Energy
DXF	Drawing exchange format
EPIC	Electric Program Investment Charge
FEM	Finite element method or finite element numerical method
GUI	Graphical user interface
IDE	Integrated development environments
IEC	International Electrotechnical Commission
IOU	Investor-owned utility
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
HygroThermFEM	A finite element numerical solver for temperature and moisture transfer within a given domain in a two-dimensional space
NFRC	National Fenestration Rating Council
PHIUS	Passive House Institute U.S.
WUFI®	A software tool for analyzing moisture migration through the building structure
ZNE	Zero net energy

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