# Design Optimization Workflow for a Dynamic Mass Envelope System using Complementary Digital and Physical Testing Methods

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**ABSTRACT:** Building envelopes significantly contribute to energetic gains and losses, relying on insulation and HVAC systems to maintain thermal comfort. The Thermally Active Ceramic Envelope (TACE) is being developed to capture, transform, re-distribute bioclimatic energy flows rather than act as a barrier. By redirecting rather than rejecting thermal energy, building envelopes act as on-demand variable mass systems which can achieve the same balancing effects as traditional thermal mass approaches, without such intensive material requirements. By managing entropy production at the envelope, it is reasonable to expect lower mechanical system energy expenditures to maintain thermal comfort.

This paper outlines two parallel methods of analysis, physical and digital, used to inform design decisions in the development of TACE systems. In the first method, digital simulation, multiple digital models were prepared to characterize the thermal performance of TACE tile modules. With a well-prepared simulation model, design iterations can be quickly tested for efficacy. The digital simulation model was developed using conservation of mass and energy equations and validated against CFD testing to assess possible performance of the TACE system. The second method of analysis is physical thermal characterization testing of TACE tile assemblies, using a modified hot-box test chamber to provide accurate thermal results. To leverage the benefits and minimize the shortcomings of each of the two methods, experimental results from this physical testing are used as a calibration tool for the digital simulation models.

Calibration inputs from the physical testing were used to adjust the digital simulation models to correlate all analysis results. With a calibrated digital simulation framework, TACE tile modules can be proposed and tested before investing time and materials into developing further prototypes. The end result is a design workflow to evaluate and assess thermal performance of TACE tile modules.

**KEYWORDS:** Active Façade, Thermal Transfer, CFD, Energy Modeling, High-Performance Façade

## INTRODUCTION

The trend in building product development is to present solutions that serve multiple roles. To be of significant value, for example, a new building product should contribute to energy efficiency, utilize abundant or recyclable materials and encourage local economic development through appropriate available technologies. Ceramic building materials fundamentally meets the requirement for material abundance, and because of its wide range of material properties can be intelligently designed and manufactured to meet the requirements related to energy efficiency. To more widely reintroduce architectural ceramics to the construction industry, traditional terracotta must be "reinvented" to support the thermal management of energy transfer across the building envelope.

When considering the transfer of energy across the building envelope, there are two broad categories of systems: active and adaptive. Mike Davies' characterization of the polyvalent wall in 1978 is an early provocation towards the development of these types of building envelopes. The contemporary work being developed at TU Delft in the Architectural Engineering + Technology Department, the Façade Research Group, and specifically the development of the integrated wall strategy by Professor Ulrich Knaack provides a guideline for the characterization of adaptive envelopes as a multivalent wall that engages the building envelope construction with bioclimatic forces, lowering reliance on energy intensive mechanical systems (Knaack, 2007)

A common passive approach to managing heat flows in building envelopes is through the utilization of high thermal mass materials such as concrete, stone, and brick. With these materials applied in walls and floor systems, sensible heat can be stored for later use or overall stabilization of temperatures in the building. One of the drawbacks of using these types of systems (e.g., terra cotta, clay brick, concrete, etc.) is the unregulated time lags of energy transfer and significant mass required to store the quantities of energy necessary to effect thermal comfort and overall energy balance. One solution to this problem that makes the qualities of thermal mass more effective in modern building operation is to activate these thermal mass materials through the integration of a controllable counter current heat exchanger device into the thermal mass building system. By controlling the transfer, storage and release of thermal energy across the building envelope, a thermal mass-based system can achieve the same balancing effects, without the unmanageable time lag while significantly reducing the overall mass of materials that would otherwise be required to make use of traditional, passive thermal mass strategies.

Thermo Active Building Systems (TABS) are considered to be active systems where a working fluid is used to heat or cool the thermal mass, typically an interior floor slab or mass based wall, through integrated piping (Olesen, 2012). One common application of this type of system is hydronic heating systems integrated into floorplates. TABS have typically, though not exclusively, relied on an active energy source (e.g., boiler, chiller, etc.) to charge the mass. An alternative to using an active energy source is to use locally available energy sources (e.g., ground or water temperature, ambient air temperature, solar insolation, etc.). While not a high quality of power, a system relying on locally available or even renewable energy resources uses significantly less input energy. Unlike systems that use energy intensive energy sources, this approach is not a brute force system. Available resources are often low grade or fluctuate and may not be able to be used based on weather, climate and building energy demand profiles; the system 'adapts' to the conditions to best use the resources available at the times where this is effective.

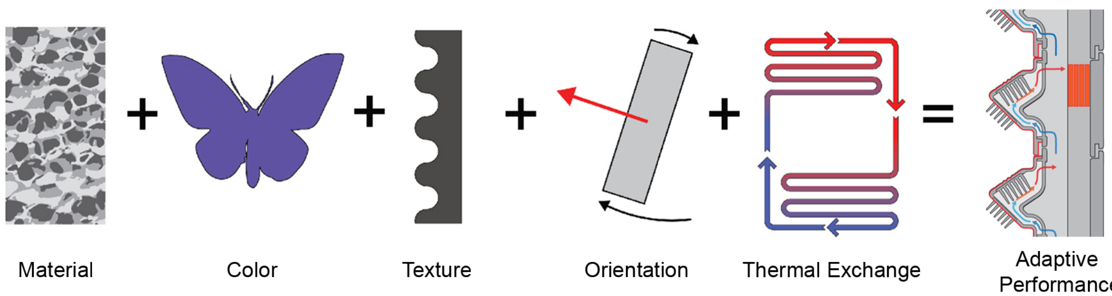


**Figure 1** - TACE module design performance variables

The Thermally Active Ceramic Envelope (TACE) described in this paper, is designed to use a multivalent strategy to absorb, release, and redirect heat to conserve energy by managing entropy production, is one instance within the larger field of Thermo Active Building Systems. TACE systems leverage morphology, color, texture, thermal mass and active energy vectoring, approaching the behavior of biotic systems (Fig.1). The system makes use of a working fluid within the façade assembly to assist in the heating and cooling of the interior of the building. It is active because it deliberately transfers energy, captured primarily from solar insolation, to achieve desired results. The differentiating quality, compared to traditional hydronic systems, is that the system adapts to the local conditions of energy resource and demand with minimal external energy inputs.

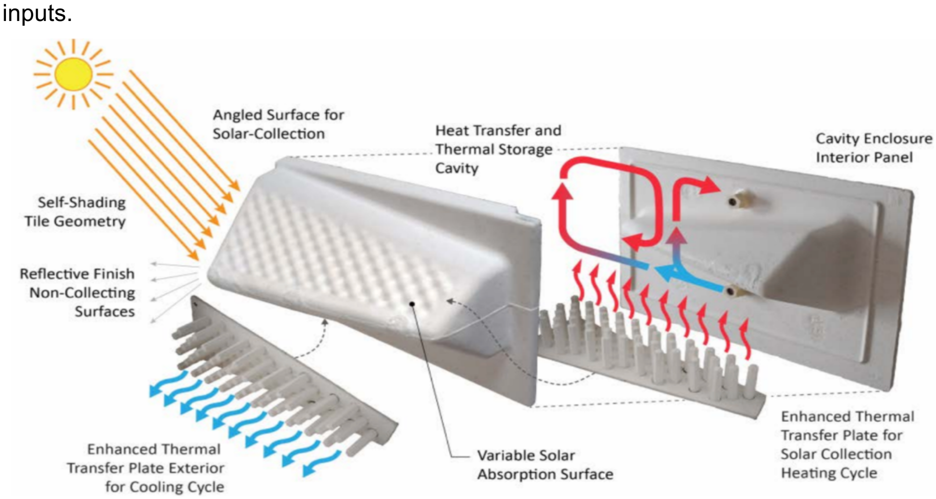


**Figure 2 -** TACE Minimum Viable Prototype Diagram. Image credit CASE/RPI

The TACE minimum viable prototype (MVP) (fig. 2), used as a platform for research in this paper, is developed to leverage specific design attributes that are hypothesized to affect the energy performance of the TACE system. In order to accurately evaluate the potential performance of the TACE system, a comprehensive energy model using industry standard metrics was developed. Without this model and testing data, it is difficult to 1) understand which design attributes are contributing to the performance of the TACE system, and 2) which future directions for refinement should the TACE be developing. This paper describes a workflow that leverages digital simulation and physical testing methodologies to isolate system components and evaluate effectiveness of various TACE design parameters. The concept of using both digital and physical simulation methods in parallel can be used as a tool to evaluate and characterize other dynamic building technology proposals.

## 1. CALIBRATED SIMULATION FRAMEWORK

The primary research methods used for this paper are digital simulation and physical testing as a means of calibrating the digital simulation tools. The multi-modal simulation testing of TACE tile modules, leverages a combination of computational fluid dynamics (CFD) modeling, mass-energy balance modeling, and physical lab-scale testing to accurately characterize energy flows through the TACE system and evaluate the performance of the component as part of a building envelope assembly. A CFD environment was used for thermal transfer analysis in a steady state environment. Additional mass-energy balance modeling, using CFD results as calibration inputs, was completed in Modelica to understand the thermal behavior of the TACE tile modules in a dynamic (real-world) environment. Physical testing of TACE assemblies was conducted within a hotbox test chamber to more accurately characterize the thermal behavior of prototype TACE modules and compared to results from simulation testing. Physical quantitative test results from the hotbox test chamber were used to further refine and validate the digital simulations. The final results from this calibrated simulation framework can later be integrated with energy analysis tools to assess the potential energy savings of TACE assemblies compared to a baseline façade system (fig.3).

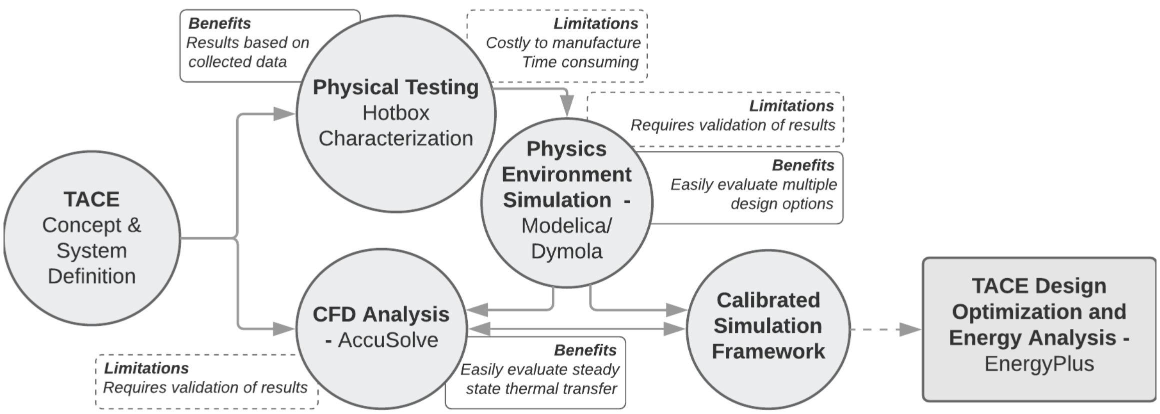


**Figure 3 -** TACE Simulation Framework

The current validated standard for modeling the performance of buildings in the United Sates is the EnergyPlus platform. It is widely used to model energy use in buildings, accurately characterizing internal and external loads. EnergyPlus is being used to develop an apples-to-apples comparison of TACE configurations in terms of Energy Use Intensity (EUI) a direct output of the model as well as relating and comparing TACE system performance to baseline building configurations. Because of the custom and dynamic nature of a TACE system, it is not able to be directly plugged into the EnergyPlus environment. However, due to the open-source nature of EnergyPlus, it can readily take inputs from other simulation environments. For EnergyPlus to accurately reflect the performance of the TACE system, the TACE components needed to be modeled in a more resolute environment that accounted for the dynamic performance. Modelica is an industry standard modeling language for building physics simulation environments and was therefore used to model the TACE module.

### 1.1 TACE MODULE DESIGN

The TACE system prototype being evaluated is ceramic tile module where the clay body used is alumina based for enhanced thermal transfer properties. The alumina formulation started with 97% industrial grade alumina ($Al^2O^3$), with minor constituents like $SiO^2$ and MgO from added materials. Recycled glass is added to increase silica content ($SiO^2$) up to 10%. The tile assembly is composed of three primary components all manufactured by Tegula Tile in Rensselaer NY for these experiments: 1) Outer tile face/primary solar absorber surface, 2) thermal transfer pin plate, 3) cavity enclosure interior panel (fig.2) The three primary components are bonded together to create a hollow cavity within the assembly that is filled with the working/heat transfer fluid (water was used in these tests). The experimental setup for both digital and physical testing was to isolate and compare two separate variables: 1) pin plate length, and 2) working fluid flow rate. The three pin plate lengths used for digital simulation are: 11.11mm (0.4375in), 29.34mm (1.155 in), and 44.45mm (1.75in). The three flow rates used for comparison were: Static/no flow, 1.25LPM(0.33GPM), and 2.5LPM(0.66GPM).

## 1.2 SIMULATION DESIGN

The simulation framework is designed to explore a wide range of tile and system designs. Calibrating the computational model that is the basis for the simulation framework is essential to developing results can be extrapolated to the building scale simulations. To validate the simulation framework, both a Computational Fluid Dynamics (CFD) model using Altair AcuSolve and quantitative physical testing was used to compare temperature profiles across the MVP TACE component filled with water which is used as the heat transfer medium.

Modelica is an open source modeling language that is used to solve complex physics-based problems. It is therefore useful in simulating complex building physics scenarios like mass and energy transfer at the building envelope. The TACE components are arranged within Modelica as a series of interacting physics objects. Modelica then outputs these interactions into a larger building simulation environment. The initial Modelica simulation was built based on assumed material properties of the TACE assemblies, without validating those assumptions. Variables such as effects of tile bonding or manufacturing inconsistencies were not able to be accounted for in the simulation. Results from physical were compared against Modelica results and the Modelica Model was adjusted to develop a fit curve that approximates these quantitative testing data.

Dymola is a Modelica modeling environment developed by CATIA Systems. Since Modelica is object oriented, specific performance components can be developed and link together as a connected network of blocks, each representing different transport phenomena. Dymola can also package and compile the model as a defined object called a Functional Mock-up Unit (FMU). The FMU is exported from Dymola as a code object that is compatible with an EnergyPlus IDF file for use in later simulations to characterize overall system performance.

## 1.3 MODELICA/DYMOLA CALIBRATION

The Modelica system model was configured to the same parameters and measurement points as the hotbox chamber set up (described below) to set up a direct comparison and calibration routine between the two test methods. The temperature of the working fluid in the storage tank was used as the baseline fluid inlet temperature for the Modelica model. A convection heat transfer coefficient was calibrated in the model on the hot side of the TACE exterior component to match the surface temperature as seen in the experiment. This convection heat transfer coefficient was assumed to be 100 W/ ($m^2$ K) due to the chambers of the hotbox being a small encapsulated space, resulting in a larger amount of air movement from the heating unit and the large temperature difference observed between the air in the exterior chamber and the TACE MVP module exterior component.

## 1.4 CFD MODEL CALIBRATION

The CFD model was developed to observe temperature rise based on a steady state system. A steady-state heat transfer problem was setup in AcuSolve where the alumina material of TACE was modeled with a water fluid cavity. This first phase of the calibration process compared the temperature increase between the TACE MVP Modelica system model and the outcomes of the CFD simulations conducted on the Altair AcuSolve software platform.

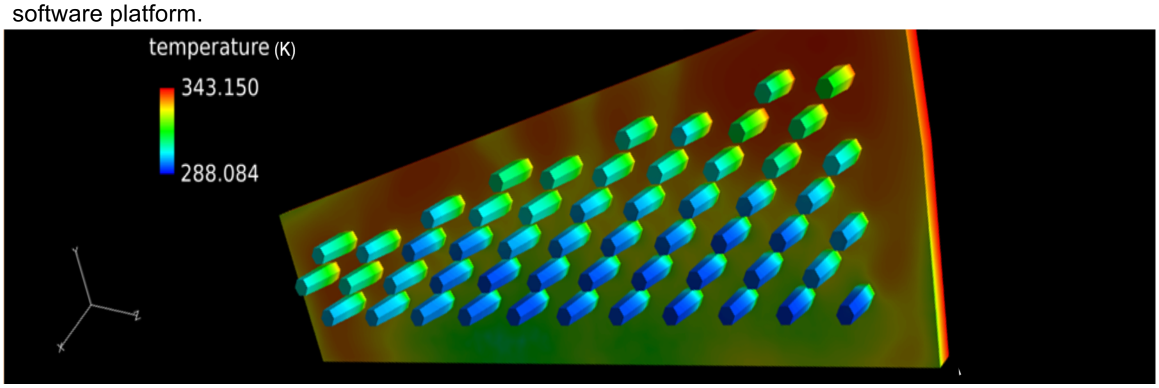


**Figure 4 -** CFD Analysis setup and results (Porterfield, 2017)

The steady state CFD model, as shown in figure 4, and a TACE MVP Modelica system model was produced with the same boundary conditions for direct comparison. A 70°C surface temperature was modeled on the top of the exterior TACE component. Simulations were run for a selection of flowrates: 0.625LPM(0.165GPM), 1.25LPM(0.33GPM), and 2.5LPM(0.66GPM) and the energy transfer component with specified pin lengths 11.11mm (0.4375in), 29.34mm (1.155 in), and 44.45mm (1.75in). Each configuration was run within the CFD model and Modelica system model for the duration required to achieve a steady state. The Modelica model was observed to be overestimating the temperature increase for each of the flowrates by about 2°C in comparison to the CFD model.

To adjust for the trending 2°C increase in temperature from the Modelica model as observed by the CFD model, the pin convection heat transfer coefficient was reduced in scale by 30%, resulting in an overall efficiency of 70% in the Modelica model. The overall efficiency factor was also confirmed when observing that not all the pins transfer heat to the working fluid at the same rate, as shown in the CFD image in Figure 4 below. This reduction was developed from the steady state CFD simulation for the low (0.625LPM), medium (1.25LPM), and fast (2.5LPM) flowrates. However, the efficiency factor alone resulted in the Modelica model having a lower outlet water temperature than the CFD for lower flowrates and higher temperatures for fast flowrates. As shown in the figure 4 below, not all the pins transfer heat to the working fluid at the same rate. To account for this uneven thermal transfer rate observed at specific flowrates, a flowrate contingent function ($f$) described in Equation 1 below was applied that further refined the Modelica model by modulating the efficiency factor from 67% for 2.5LPM of flow up to 72% for 0.625LPM of flow based on aligning the Modelica results to the CFD more closely.

$\mathrm{f} = -2314.8 * \dot{v} + \mathrm{d}1.0509$ (where $\dot{v}$ is the volumetric flowrate in $m^3$/s.)

**Equation 1 –** Flowrate contingent function ($f$)

## 1.5 RESULTS AND DISCUSSION: CFD MODELING

After applying the efficiency factor and the flow dependent factor, the average temperature difference between the Modelica calibration model and CFD model did not exceed more than 0.41°C for each tested flowrate; a 4.04% disparity (table 2). The medium pin length TACE configuration was used in the subsequent physical testing had an average temperature divergence of 0.18°C; a 2.37% disparity (table 2). The CFD model did not take into account the ambient, transient or cumulative effects that might occur outside of the bounded steady state model.

| | Temperature Difference (˚C) Before CFD Calibration | | | Temperature Difference (˚C) After CFD Calibration | | |
|---|---|---|---|---|---|---|
| **Pin Length** | **0.625LPM (0.165GPM)** | **1.25LPM (0.33GPM)** | **2.5 LPM (0.66GPM)** | **0.625LPM (0.165GPM)** | **1.25LPM (0.33GPM)** | **2.5 LPM (0.66GPM)** |
| 11.11mm (0.4375in) | 13.06 | 9.57 | 7.17 | 9.83 | 7.46 | 5.37 |
| 29.34mm (1.155in) | 13.15 | 9.78 | 7.23 | 10.29 | 7.64 | 5.42 |
| 44.45mm (1.75in) | 13.19 | 9.79 | 7.14 | 10.3 | 7.64 | 5.42 |
| Average | 13.13 | 9.71 | 7.18 | 10.14 | 7.58 | 5.40 |
| CFD Results | 10.55 | 7.76 | 5.48 | 10.55 | 7.76 | 5.48 |
| Difference between Modelica and CFD(˚C) | -2.58 | -1.95 | -1.70 | **0.41** | **0.18** | **0.08** |
| Percentage change between Modelica and CFD | -19.67% | -20.11% | -23.68% | **4.04%** | **2.37%** | **1.42%** |

**Table 2 -** Modelica Model Results Before and After CFD Calibration

The TACE MVP module was initially designed to have offset working fluid. inlet and outlet ports, the logic being that the ports should be as far apart from one another as possible to maximize the potential for uniform heating of the working fluid. The inlet port was on the lower left side of the interior components when viewed from the inside; the outlet was placed on the upper right when viewed from the inside as shown in figure 5. However, the Modelica model and the CFD model were originally simulated with aligned inlet and outlet ports in the center of the module, bottom and top respectively, as shown in figure 5.

It was observed in CFD analysis that the model with the in-line central port configuration had a more even spread of heat transfer between the pins and fluid because of the inlet more evenly injected fluid flow into the pin region (fig. 5), while the offset inlet and outlet ports had a streamline fluid flow that would short-circuit the pin region thereby delivering less heat transfer from the pin components to the working fluid (fig. 5). The offset ports performed at a decrease of about 75% from the parallel ports.Therefore an additional 75% efficiency factor was added to the Modelica model when calibrating against the measure results to simulate the use of offset ports.

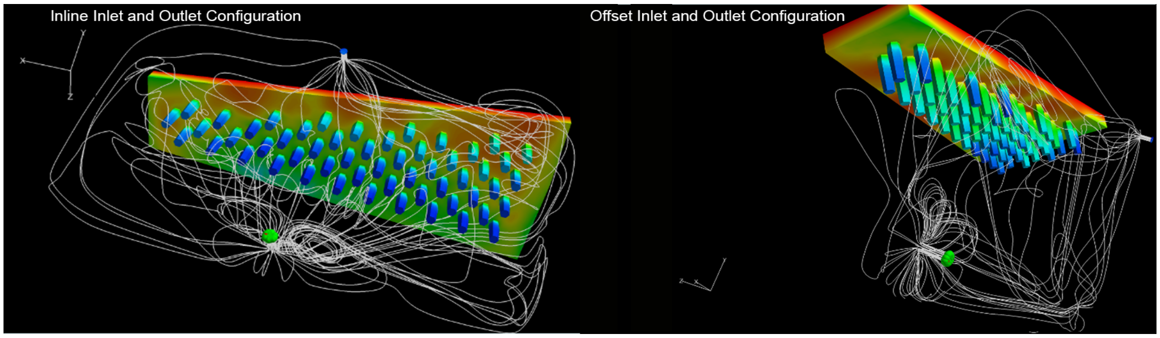


**Figure 5 -** Inline inlet and outlet streamline visualization from CFD (left). Inlet injects fluid more evenly into the pin region vs. offset inlet and outlet streamline visualization from CFD (right). Fluid flow from inlet to outlet can short circuit and avoid the pins entirely, reducing heat transfer (Zeng, 2017)

## 1.6 PHYSICAL TESTING SETUP

The physical testing was designed to thermally characterize the TACE MVP module and observe temperature profiles of the module assembly and working fluid over a period of time. Physical testing was completed using a modified hotbox test chamber, designed and constructed with guidance from ASTM C1363 Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus. The fundamental hotbox arrangement consists of two equally sized thermal chambers. These chambers are divided by an insulation panel which serves as a mounting frame for the TACE MVP. The outside of the TACE module is exposed to the interior of one of the insulated chambers noted as "Exterior." The inside of the of TACE module is exposed to the interior of the other chamber noted as "Interior". In this configuration, the only non-insulated connection between the two chambers is the TACE module itself. Because the TACE module is the only connection, thermal energy must pass through the module and the flow can be measured and characterized. For the module as a whole or for individual components. The chambers and TACE module are instrumented with an arrangement of thermocouples to record the thermal inputs and describe the thermal transfer from the exterior to the interior chambers and across the TACE MVP module.

The hotbox enclosure was designed and fabricated to contain one TACE MVP module within the insulated test panel frame (fig. 6). Chamber wall construction is comprised of 203.2mm(8in) thick expanded polystyrene foam insulation 32kg/m$^3$(2lb/ft$^3$). Panel joints used adhesive mastic to create a complete sealed surface and eliminate the need for mechanical fasteners to support a consistent insulation value and all interior seams were filled to limit air infiltration. A 950w enclosure heater with integrated fan was placed within the exterior chamber side of the hotbox enclosure which provided the thermal load on the exterior surface of the TACE MVP module. It was determined that the built-in thermostat for the enclosure heater had an inadequate level of precision and adjustability during initial trials. The heater was then improved to receive a PID controller and

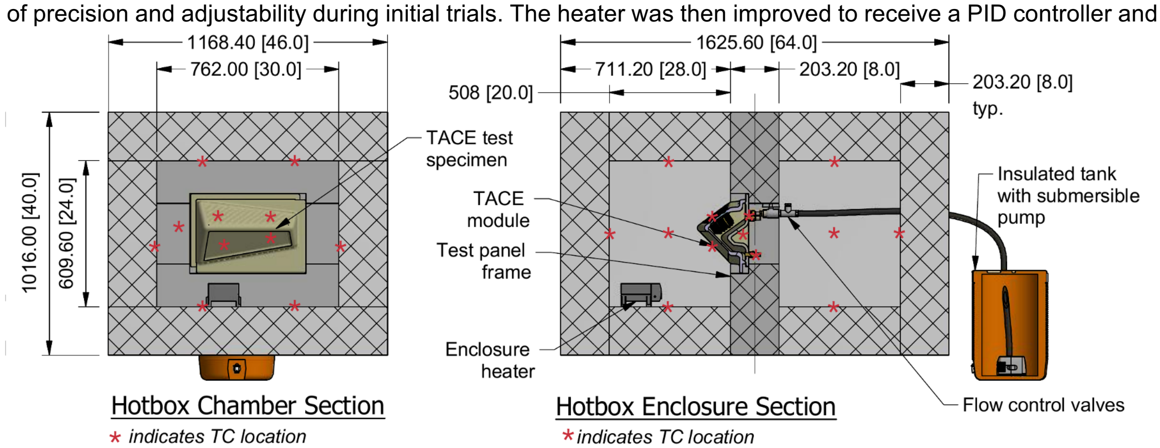


**Figure 6 -** Test chamber assembly

T-type thermocouple that provided for an accurate control of the temperature and therefore energy that was applied into the system. The thermocouple used to modulate the heater energy was placed adjacent and above the TACE MVP module on the test panel surface.

The thermal conditions in the hotbox enclosure were observed and recorded with a 16 channel DAQ system equipped with a 16-channel extension unit for a total of 32 thermocouple channels. The DAQ system was manufactured by Measurement Computing, models (USB-2416-4AO and AI-EXP32). Data was recorded using the Measurement Computing DAQAMI data acquisition software. The data sampled rate was set for 1 measurement per second per thermocouple using T-type thermocouples. For the calibration experiment, there were 28 total thermocouples distributed throughout the experimental setup: (8) distributed across the interior surfaces of the "interior" and "exterior" chambers, (1) ambient condition, (1) submersed in water tank, (4) distributed across interior and exterior faces of the TACE tile, (1) at each water inlet and outlet port.

The active thermal of the TACE MVP design includes a thermal mass transfer plumbing loop, and instrumentation. The TACE MVPs used for testing has ports on the interior component of the TACE module for inlet and outlet of the working fluid and additional ports which serve as instrumentation ports for thermocouples. The inlet and outlet ports were fitted with ball valves to modulate the flowrates and are used for servicing experimental set up. The working fluid is circulated at flow rates (identified above) through the insulated piping into the insulated storage tank. The total volume of working fluid in the system is 9.46 liters (2.5gal) of water. The working fluid volume of the TACE MVP module was 4.74 liters (1.25 gal).

Three testing rounds were conducted to develop the comparison with the simulation framework. Throughout each test run, relative starting temperature, set-point temperature, ramp time, soak time, and fluid volume were maintained as consistent. The only variable used to create the ramp profiles was the flowrate of the working fluid. The tested flow rates of the experimental setup were identical to the simulation framework: static/no-flow, 0.625LPM(0.165GPM) low flow, and 2.5LPM(0.66GPM) high flow. The control valves were adjusted in order to achieve the designated testing flowrate.

At the start of the experiment, both hot (exterior) and cold (interior) chambers were at a steady state near equilibrium ambient temperature with no discernable flow. The pre-defined ramp temperature and soak temperature profile began with convective airflow coming from the enclosure heater. The set temperature for the hot side of the chamber was set at 60°C (140° F); the ramp time was 38 minutes; the soak time was 80 minutes. Once the ramp time was achieved, the heater was turned off. The thermocouples continued to take readings until both sides of the chamber reached a new steady state, based on how much energy was put into the test chamber.

## 1.7 RESULTS AND DISCUSSION: PHYSICAL MODEL

The data collected from physical experiments was compiled and directly compared to data generated in parallel Modelica simulations. Instrumentation points of particular interest are working fluid inlet and outlet temperatures as well as tile face (interior and exterior) surface temperatures. The data that was logged from the hotbox enclosure when the TACE MVP was fitted with the energy transfer component with medium pin length 29.34mm (1.15in) with the 0.625LPM (0.GPM) flowrate was compared to the Modelica Calibration model that was modified with the calibration data from the CFD and steady state model.

The temperatures of the outward facing surfaces of the Modelica systems model of the exterior and interior components was compared to the measured data logged from the hotbox chamber experiment. These temperature ranges appear to match in quantity and ramp profile as shown in Figure 7.

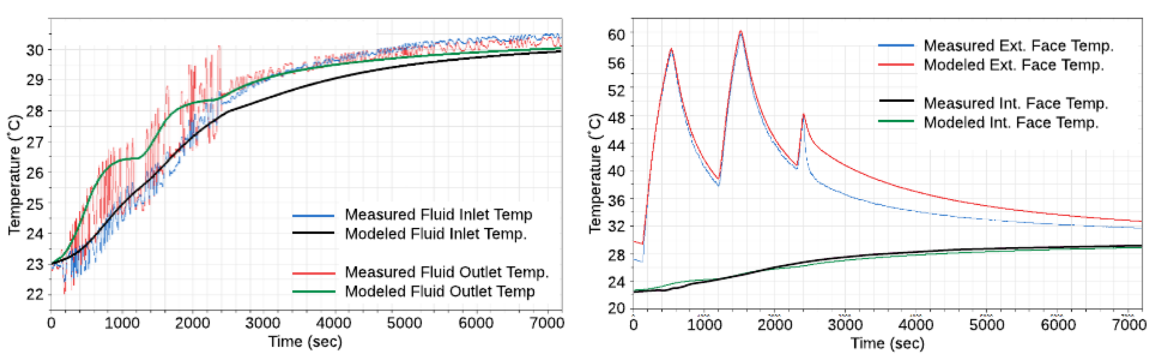


**Figure 7 -** Comparison of fluid inlet temperatures (Left) and comparison of tile face temperatures (right)

The working fluid outlet temperature of Modelica Module Model showed more movement due to the high temperature peaks in the surface on the exterior component temperature than the hotbox chamber experiment. As expected, the higher peaks of the outlet port working fluid temperature for the model corresponds to the temperature peaks on the surface of the exterior component. While a significant amount of noise was recorded in the working fluid temperature as show in Figure 7, the peaks in temperature can be noted, though not to the quantity or clarity of the Modelica Module Model results. Modifications (e.g., adding more mass to the model, changing surface areas, etc.) to the Modelica Module Model were implemented in an attempt to better align with the lower peaks of the experiment results. No modification developed a better fit curve to than the one shown in Figure 7.

**CONCLUSION**

While the focus of this paper is on developing the calibrated simulation framework and not co-simulation with EnergyPlus, the TACE system has been compiled and co-simulated with EnergyPlus to generate comparative EUI results for various TACE system configurations. Initial analysis runs demonstrate a significant reduction in EUI when compared to existing traditional envelope systems, and smaller reductions in EUI when compared to a typical ASHRAE curtain wall system (fig. 8). While these initial results do not show significant performance improvements compared to an ASHRAE curtain wall, it should be noted that this was an initial calibration test and not considered an optimized TACE system design.

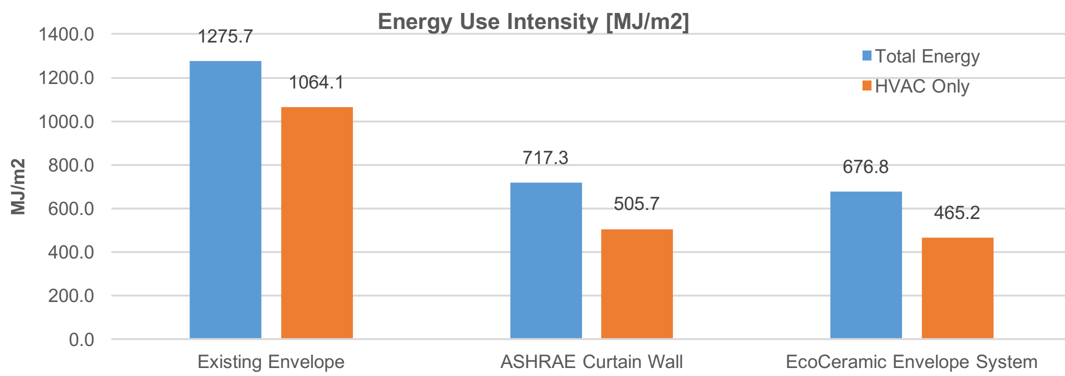


**Figure 8 -** Energy Use Intensity (EUI) for building envelope system types

Future development of the TACE system should include efforts to improve the accuracy of fit curves between the experimental ramp profile and simulated data. Additional comparisons are being evaluated that examine more discreet and isolated variables of the TACE. However, the combination of CFD analysis, physical testing and simulation in Modelica demonstrated here do successfully make up a calibrated simulation framework that can be used as a design tool to characterize TACE system efficacy and its impact on overall building energy consumption. Future TACE development will focus on a parametric model that accounts for changes in design and orientation and subsequent performance output and effect on EUI attributed to the TACE system. This methodology of testing and calibration has demonstrated its effectiveness at evaluating the performance of the TACE system and can be applied to development of other dynamic envelope systems.

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