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Lab Evaluation of Downward Capacity of Radiant Ceiling Panel Systems

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Disclaimer

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Executive Summary

Introduction

Ceiling-mounted hydronic radiant panels (referred to as “radiant ceiling panels” throughout this report) deliver heating and cooling through thermal radiation and natural convection, rather than forced convection like a traditional ducted space conditioning system. Hot or cold water from a boiler, chiller, water heater, or air-to-water heat pump flows through tubing attached to the ceiling, and exchanges heat with the occupants and furnishings present in the space below. Figure ES-1 illustrates the modes of heat transfer associated with a radiant ceiling panel.

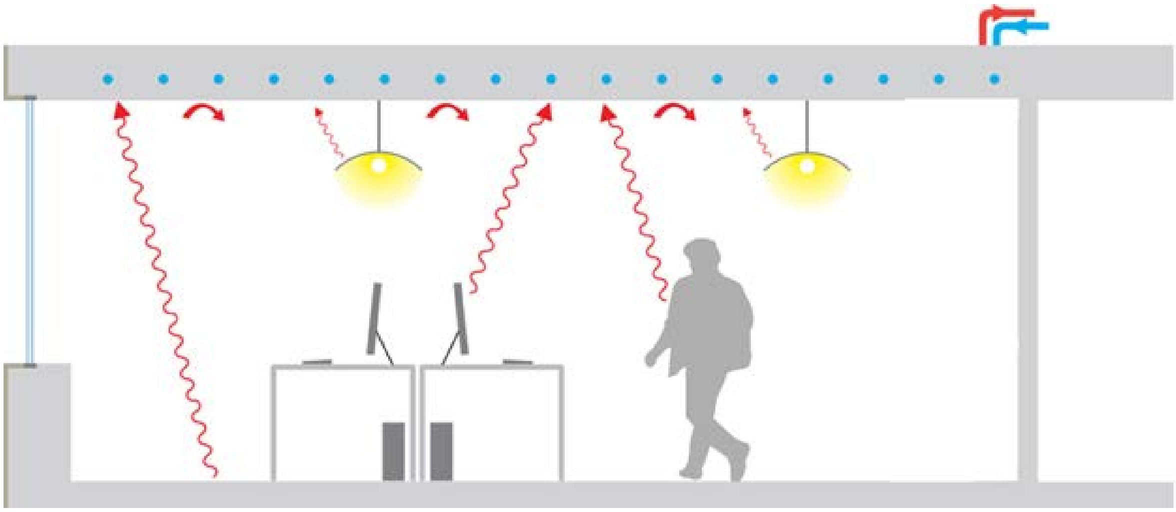

Figure ES-1. Representation of heat transfer effects with radiant ceiling panels in cooling mode

Figure from Caroline Karmann, Center for the Built Environment, UC Berkeley

Figure ES-2 shows a typical site-built radiant ceiling panel assembly, which consists of PEX (cross-linked polyethylene) tubing inserted into channels on both edges of a metal heat transfer plate and laid in the center of the joist bays in contact with the attic-side surface of the ceiling drywall. Attic insulation is installed above the assembly to minimize losses to the attic and ensure that the heating and cooling energy is delivered to the conditioned space.

Figure ES-2. Site-built radiant ceiling panels used in laboratory tests

Photo from Josh McNeil, Frontier Energy Inc.

This project investigated the cooling delivery effectiveness of radiant ceiling panels as a function of attic insulation level using multiple laboratory testing and analytical methodologies. Delivery effectiveness is the heating or cooling energy delivered to a conditioned space divided by the total heating or cooling energy added or removed by the space conditioning system. The lower the losses of the heating or cooling delivery method, the higher the delivery effectiveness. For ducted systems, delivery effectiveness is reduced by both air leakage and thermal losses (especially if the ducts are installed in attics), while the delivery effectiveness of a radiant system supplied by hot and cold water is only reduced by thermal losses, which can be mitigated by sufficient insulation above, or at the “back” of the panel. Being installed at or below the ceiling plane, sufficient back insulation should be provided by default in the form of the attic insulation above the radiant ceiling panels.

However, as with ducted systems, the accurate calculation of design loads including the expected losses in the delivery system is an important component of an effective system sizing process. Therefore, for accurate sizing of radiant ceiling panel systems, it is important for the designer and modeler to know the expected losses. Because radiant ceiling panel losses are primarily thermal losses to the attic, these losses must be understood in terms of attic insulation level.

Technical Approach

The specific research objectives for this project were to:

- Determine a minimum level of attic insulation that brings radiant ceiling panel thermal losses to roughly the same level as ducted systems that meet 2021 International Energy Conservation Code (IECC) prescriptive requirements (~12%

loss) and an insulation level that limits losses to those assumed for radiant ceiling panels in the 2021 IECC (~5% loss with components in attic and 0% loss if entirely in conditioned space).

- Evaluate whether laboratory findings and existing methods for modeling radiant ceiling panels in EnergyPlus® agree and attempt to identify the sources of any discrepancies.
- Attempt to identify other factors that negatively impact radiant ceiling panel performance and installation practices that could mitigate those impacts.
- Disseminate results to ensure installed delivery effectiveness aligns with industry expectations.

Site-built radiant ceiling panels were evaluated at Frontier Energy's Building Science Research Laboratory (BSRL) in a uniquely designed environmental test chamber with independently controllable indoor and attic spaces and a height-adjustable ceiling. Unfortunately, the assembly used for raising and lowering the attic was imperfectly sealed and insulated around the perimeter of the ceiling, resulting in potential energy losses that would not be as significant in actual residential radiant ceiling panel applications. The performance of these panels was evaluated in cooling at steady state with a range of insulation levels from R-19 to R-109. Test conditions were selected based on Frontier's decades of field experience with radiant ceiling systems. Key data points included the air temperature in the indoor and attic space, radiant ceiling panel total heat flow, surface temperatures of all indoor-facing surfaces, and heat flux through the indoor-facing ceiling surface.

These data were used to calculate the heat transfer rate between the radiant ceiling panels and the indoor space (the "downward" heat flux, including both radiative and convective components) using three methods:

1. The area-weighted average of the heat flux sensors.
2. The equations and methods provided in the ASHRAE Handbook (ASHRAE 2020).
3. A simplified calculation model developed by Birol Kilkis, which is frequently cited in radiant system research (Kilkis, Sager, and Uludag 1994).

Multiple methods of determining the downward heat flux were used due to the potential for application uncertainty in heat flux sensors.

Preliminary Testing and Modeling

Preliminary laboratory testing and 2D modeling with THERM was performed to analyze ceiling edge heat transfer effects on delivery effectiveness. Several lab tests were performed to help calibrate two THERM models, one that examined middle-of-panel heat transfer and one that examined edge effects. Even after significant fine-tuning, neither model matched the test results as closely as we would have liked, perhaps because the 3D nature of the heat transfer phenomena could not be captured accurately in a 2D model. However, the combination of the two models may give an adequate rough estimate of total edge losses. According to the models, somewhere between 0% and 19% of the heat delivered by the radiant ceiling panels was lost to the attic or through the walls of the test chamber. These results indicate significant edge effects that must be adjusted for when evaluating the panels' delivery effectiveness.

Laboratory Test Results

Because the two THERM models did not provide high confidence in the estimation of edge effects, the approach used in the lab testing to account for edge effects was to gradually increase the insulation levels from R-19 to R-109, at which point conductive losses and any possible air leakage through the insulation would be near zero. The expectation was that the measured delivery effectiveness would flatten out and the difference between a delivery effectiveness of 100% and the asymptote of the curve would be an estimate of edge effects. Edge effects could then be removed from the delivery effectiveness measurements to determine the theoretical value with an infinitely large radiant ceiling panel area.

The weighted average of the heat flux sensors showed a delivery effectiveness of 56% at R-19 and 87% at R-109, with only a 0.6% change from R-79 to R-109. The ASHRAE and Kilkis calculation methods showed a delivery effectiveness of 51% at R-19 and 83% at R-109, with only a 1.7% change from R-79 to R-109. These small changes from a 38% increase in R-value indicated that delivery effectiveness reached a stable value near R-109, and so the edge effects were taken to be the difference between the delivery effectiveness at R-109 and 100%. Once edge effects were removed, the delivery effectiveness could be compared to IECC requirements and assumptions. Radiant ceiling panels operating under the same conditions used in the lab test would achieve the comparable 2021 IECC target value of 88% for ducted systems with R-39 attic insulation, and the 2021 IECC assumed value of 95% for radiant ceiling panels with R-56 attic insulation. For applications with different operating conditions (attic temperature, cold water flow rate and temperature) the required insulation levels could be significantly different. Further testing could provide more details for comparison with IECC assumptions in annual energy models in various climates.

Comparisons to EnergyPlus

Eliminating edge effects also enabled comparing the laboratory tests to results from the Low Temperature Radiant System Model in EnergyPlus, which assumes an adiabatic edge for radiant ceiling panel systems. Various model inputs were adjusted to make boundary conditions consistent at steady state and as close to the laboratory conditions as possible, given the constraints of the modeling software. These difficulties are discussed in the report.

EnergyPlus predicted much lower delivery effectiveness, but this may have resulted from the flow rate of chilled water in the radiant ceiling panel model being lower than the test conditions. More noteworthy is the fact that the delivery effectiveness in the EnergyPlus model had not leveled off even with a simulated insulation level of R-109 and appeared to be a long way from reaching 100%. These modeling results seem to be implausible if the perimeter is adiabatic, and we are uncertain where the cooling energy in the model is being lost if not to the attic or through the edges of the panel.

Conclusions

After adjusting for edge effects, the test results indicated that R-56 attic insulation would be required to meet the 95% delivery effectiveness assumed by the 2021 IECC for radiant ceiling panel systems with components outside conditioned space, such as the plumbing from the chiller to the panel. If radiant ceiling panels are entirely within conditioned space, the 2021 IECC would assume a delivery effectiveness of 100%, which would require an attic insulation level greater than about R-79 based on the operating conditions tested in this study. R-39 insulation would be required to meet the target value of 88% for ducted systems assumed in the 2021 IECC.

EnergyPlus modeling of the test chamber and radiant ceiling panels identified some limitations and areas for improvement in the software. Although EnergyPlus predicted lower delivery effectiveness, even with very high attic insulation levels, the uncertainties surrounding the alignment of the model with test geometries and boundary conditions reduced our confidence in the results.

Recommendations

This project identified that there are issues with how EnergyPlus models radiant ceiling panel systems, and with delivery effectiveness assumptions used for radiant systems in IECC, but additional work is needed to fully flesh out the specific changes needed to EnergyPlus and IECC.

Recommendations for future study include the following:

- Additional laboratory testing in heating mode, and in cooling mode under a few more operating conditions (flow rate, inlet water temperature, attic temperature, and interior space temperature), with increased barriers to edge effects near the radiant ceiling panel mounting structure.
- Controlled testing using small lab houses or test huts with realistic attic behavior and natural convection that is impossible to replicate in a test chamber.
- Additional laboratory testing using radiant ceiling panels designed to be installed within the ceiling plane, typical of manufacturer prefabricated panels.
- A deeper dive into the methods used in EnergyPlus to model radiant systems to make specific recommendations to address the limitations and issues found in this project.

Additionally, IECC does not currently have installation requirements for radiant ceiling panels. It is clear that the IECC should have increased attic insulation requirements when radiant ceiling panels are installed, in order for the IECC delivery effectiveness assumptions to remain valid.

1 Introduction

1.1 Technology Overview

Delivery effectiveness is the heating or cooling energy delivered to a conditioned space divided by the total heating or cooling energy added or removed by the space conditioning system. The lower the losses of the heating or cooling delivery method, the higher the delivery effectiveness.

For ducted systems, delivery effectiveness is reduced by both air leakage and thermal losses (especially if the ducts are installed in attics), with air leakage typically being the larger of the two (Jump, Walker, and Modera 1996). Challenges with achieving low losses with duct systems, and the impacts of duct losses on heating and cooling system performance and sizing, have been widely documented (Downey and Proctor 2002; Proctor, Chitwood, and Wilcox 2011; Wilcox, Conant, and MacFarland 2024). Ductless systems, such as minisplit heat pumps, are typically considered to have ideal delivery effectiveness, as the delivery system is located entirely within conditioned space. Ducted systems can also achieve near-ideal delivery effectiveness by locating the ducts and air handling equipment entirely within conditioned space. As exposed ducts are generally considered unsightly in residential buildings, the ducts must be hidden in chases, dropped ceilings, and other interior voids, which reduce interior volume and increase design complexity. For these reasons, locating ducts in conditioned space can be costly, and production builders have struggled with implementing it (Hoeschele et al. 2015).

Ceiling mounted hydronic radiant panels are a topic of interest in new and retrofit residential construction (Bean, Olesen, and Kim 2010). Radiant ceiling panels deliver heating and cooling through thermal radiation and natural convection, rather than forced convection. Figure 1 shows a representation of these desired heat transfer phenomena in a room with a radiant ceiling. Not pictured but present are thermal losses from the radiant ceiling panel to the area above, and to the edge supports.

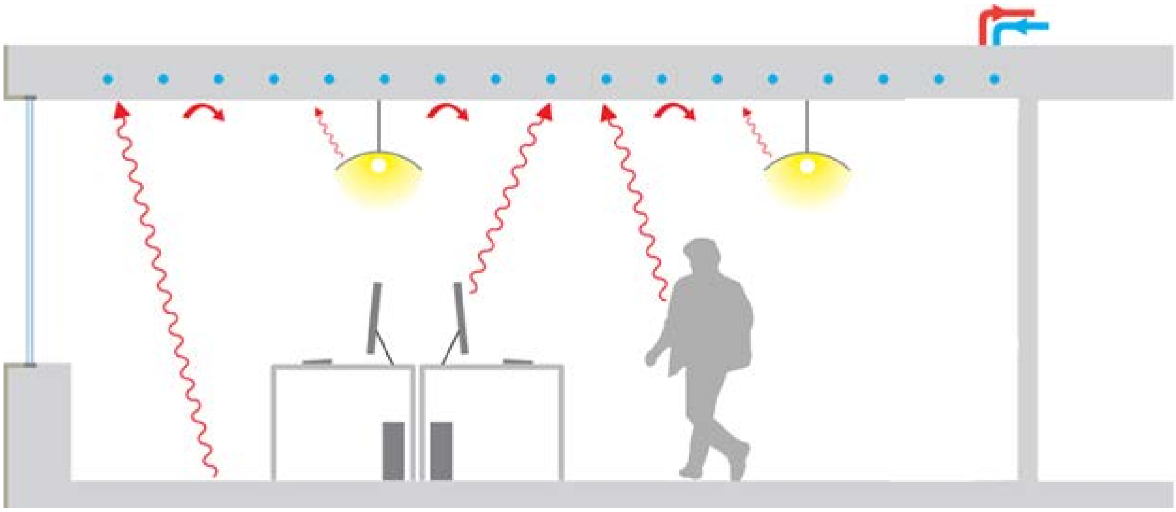

Figure 1. Representation of heat transfer effects with a radiant ceiling panel in cooling mode

Figure from Caroline Karmann, Center for the Built Environment at UC Berkeley

Radiant ceilings used for both heating and cooling use hydronic tubing embedded in the ceiling assembly. The water in the tubing is heated and cooled by a central plant (such as an air-to-water or water-to-water heat pump, chiller, or boiler). This heats or cools the ceiling surface, which in turn heats or cools the space. In cooling, the air in the space is cooled via natural convection while the objects in the space are cooled directly through radiation and indirectly through convection (Haile et al. 2018).

Being installed at or below the ceiling plane, radiant ceiling systems offer a potential advantage of increased delivery effectiveness without imposing as many architectural restrictions or significantly reducing the conditioned space. Unlike ducts, which have both thermal and air leakage losses, radiant ceilings use water or a water mixture, and thermal losses can be mitigated by sufficient insulation above, or at the back of the panel. For ceiling panels, sufficient back insulation should be provided by default in the form of attic insulation.

Figure 2 shows a typical site-built ceiling panel assembly, which consists of a metal heat transfer plate (also referred to as a fin) laid in the center of the joist bays in contact with the attic-side surface of the ceiling drywall.[1] In this installation, the plates are held in place using foamboard insulation. PEX tubing is inserted into channels on both edges of the plate. This heat transfer plate has several advantages, including the ability to install it without disturbing the existing ceiling and avoidance of direct contact with the ceiling joists.[2]

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[1] Frontier has previously evaluated radiant ceiling panels for PG&E (Haile, Springer, and Hoeschele, Project ET13PGE1065, 2016; Haile, Springer, and Hoeschele 2018), American Honda Motor Company (Haile, Dakin, and German 2023), and Sonoma Clean Power (Pallin and Haile 2022).

[2] Rehau markets this product as a radiant floor retrofit option, although there is no physical reason it would not function in a ceiling.

Figure 2. Site-built ceiling panels used in laboratory tests

Photo from Josh McNeil, Frontier Energy Inc.

1.2 Technical Challenges

Radiant ceiling panel capacity rating standards only consider the thermal capacity of the entire hydronic circuit, not just the usable thermal heat transfer between the panel and conditioned space, or “downward” heat transfer rate,[3] which is essential for accurate system sizing and modeling.

Radiant ceiling panels were evaluated at Frontier Energy’s Building Science Research Laboratory (BSRL) in 2021 to assess their performance in Sonoma County’s mild climate for Sonoma Clean Power’s Lead Locally program. Evaluations included two levels of attic insulation, R-19 and R-49. Significant losses were expected with R-19, but very high delivery effectiveness (~95%) was expected with R-49. Instead, delivery effectiveness with R-49 ranged from 66% to 77% in cooling and 61% to 66% in heating (Pallin and Haile 2022). This finding was concerning because it suggested that the delivery effectiveness of radiant ceiling panels below R-49 attic insulation was no better than typical in-attic ducted systems (NREL 2004).

This report documents a series of lab tests and modeling evaluations that examined the same site-built panels from the 2021 tests with higher insulation levels and the radiant ceiling panel installation shown in Figure 2. Resulting data were used to evaluate different methods for determining the downward heat transfer rate of ceiling panels and

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[3] There are no rating systems for radiant ceiling panels in the United States. Available standards are from Europe (EN14240) and Japan (ARCH: Cooling and Heating - Testing and Rating Standard (CHTRS) Ver. 1.1).

were compared to results from existing modeling tools and assumptions for radiant ceiling panels. Recommendations for installation practices to ensure high delivery effectiveness for radiant ceiling panels were also developed.

1.3 Project Objectives

The installed heat transfer characteristics of site-built radiant ceiling panels were examined to address uncertainties about heat loss and usable capacity. The specific research objectives included:

- Determine a minimum level of attic insulation that brings radiant ceiling thermal losses to roughly the same level as ducted systems that meet 2021 IECC prescriptive requirements (12% loss) and an insulation level that limits losses to design assumptions for radiant ceiling systems in the 2021 IECC (0% to 5% loss).[4]
- Evaluate whether laboratory findings and existing methods for modeling radiant ceiling systems in EnergyPlus® agree and attempt to identify the sources of any discrepancies.
- Identify other factors that negatively impact radiant ceiling performance and identify installation practices that could mitigate those impacts.
- Disseminate results to ensure installed performance aligns with industry expectations.

2 Technical Approach

2.1 Test Chamber

The tests were performed over approximately 20 days in Frontier Energy's BSRL. The BSRL is a 2,200 ft^2 test facility in Davis, California, constructed in 2003 for testing equipment, fabricating prototypes, and maintaining field monitoring systems. The laboratory has been used for the evaluation of heat recovery systems, evaporative cooling systems, ventilation cooling systems, shallow-bore geothermal systems, tankless water heaters, furnaces, and fan coils.

Within the facility, there are two large environmental chambers that can be used for testing residential and commercial HVAC technologies, water heating equipment, and building envelope components. A 15-ton variable capacity chiller and 155 MBH boiler provide hot and cold water to a multizone hydronic system, which conditions the small chamber. The larger chamber is most often used to simulate outdoor conditions and is served by a 10-ton commercial-scale packaged heating and cooling system. A National

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[4] In the 2021 IECC, delivery effectiveness is 0.88 for an untested ducted system. For radiant systems: 1.00 if entirely within conditioned space and 0.95 if components are located in unconditioned space.

Instruments CompactDAQ system and high-performance liquid cooled industrial computer with a redundant data backup system is used for data acquisition and control of the test chambers.

The small chamber, which included an independently controlled attic space and height-adjustable ceiling, was used for this project. Photos of the exterior and interior of the small chamber are shown in Figure 3 and Figure 4.

Figure 3. Environment chambers at the Davis Building Science Research Laboratory

Photo from Josh McNeil, Frontier Energy Inc.

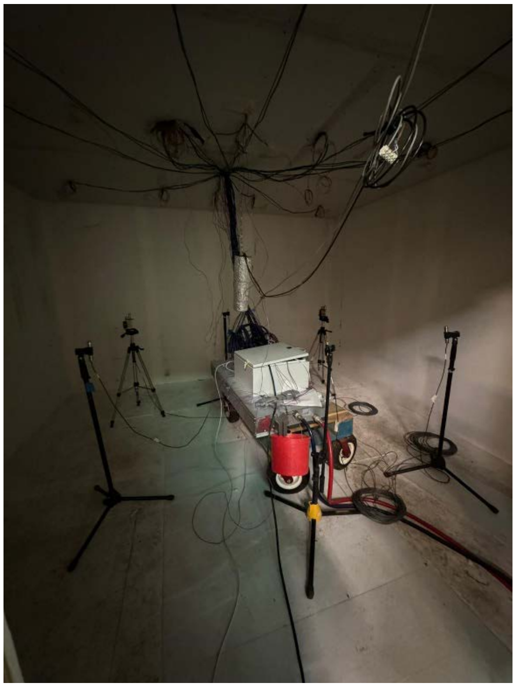

Figure 4. Interior of small environment chamber with instrumentation

Photo from Josh McNeil, Frontier Energy Inc.

Figure 5 illustrates how the site-built radiant ceiling panel system was installed in the chamber, along with expected heat transfer flow directions. The middle horizontal surface included the radiant ceiling panels under test. This horizontal surface could be lowered using remote controlled electric hoists, allowing adjustments to the level of insulation in the simulated attic, then returned to its original position while testing. Fiberglass batt insulation was layered above the ceiling to provide the desired R-value. The attic and indoor air temperatures were controlled using small hydronic fan coils facing away from the ceiling plane to minimize forced convection effects.

The heat flows shown in Figure 5 include the values of primary interest (heat flows up and down from the radiant ceiling panel to or from the interior space and attic), along with some undesirable heat flows that were minimized to the extent possible. These included heat losses from the test chamber to the indoor area of the laboratory, and losses to or from the edge of the radiant ceiling panels through the test apparatus and into the attic or interior spaces. The edges were not completely insulated (see Figure 6). Fully raised, a rubber gasket that runs the entire perimeter of the ceiling ensures an airtight seal while still allowing for the ceiling assembly to be raised and lowered to change the insulation level. However, edge losses were not negligible and were examined as part of this study.

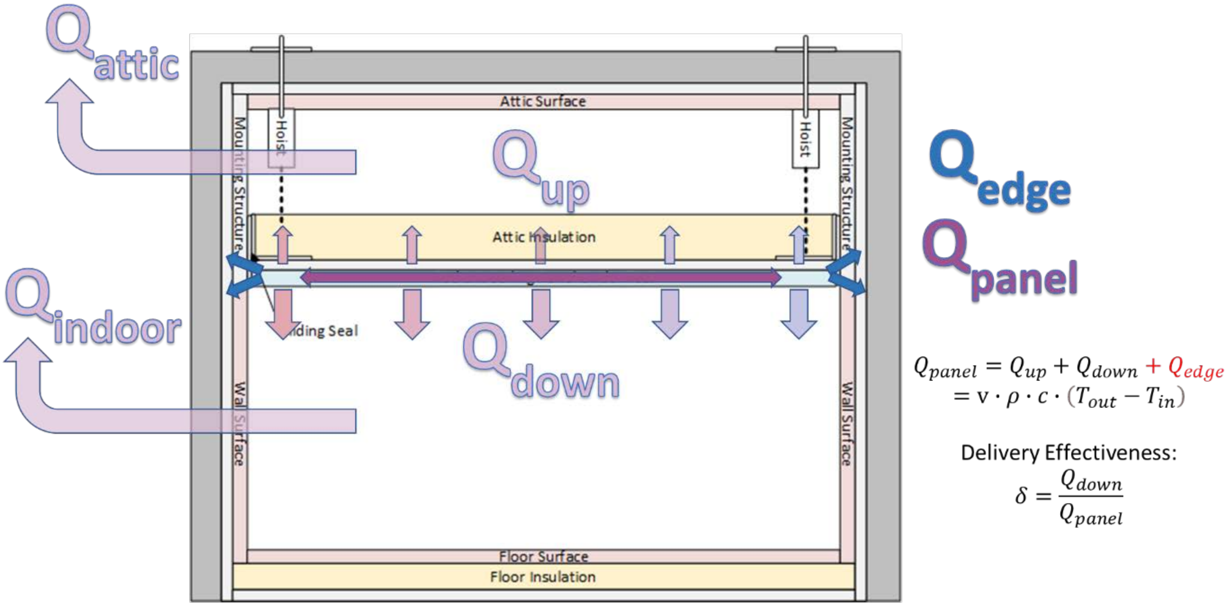

Figure 5. Diagram of environment chamber showing heat transfer from and to radiant ceiling panel system

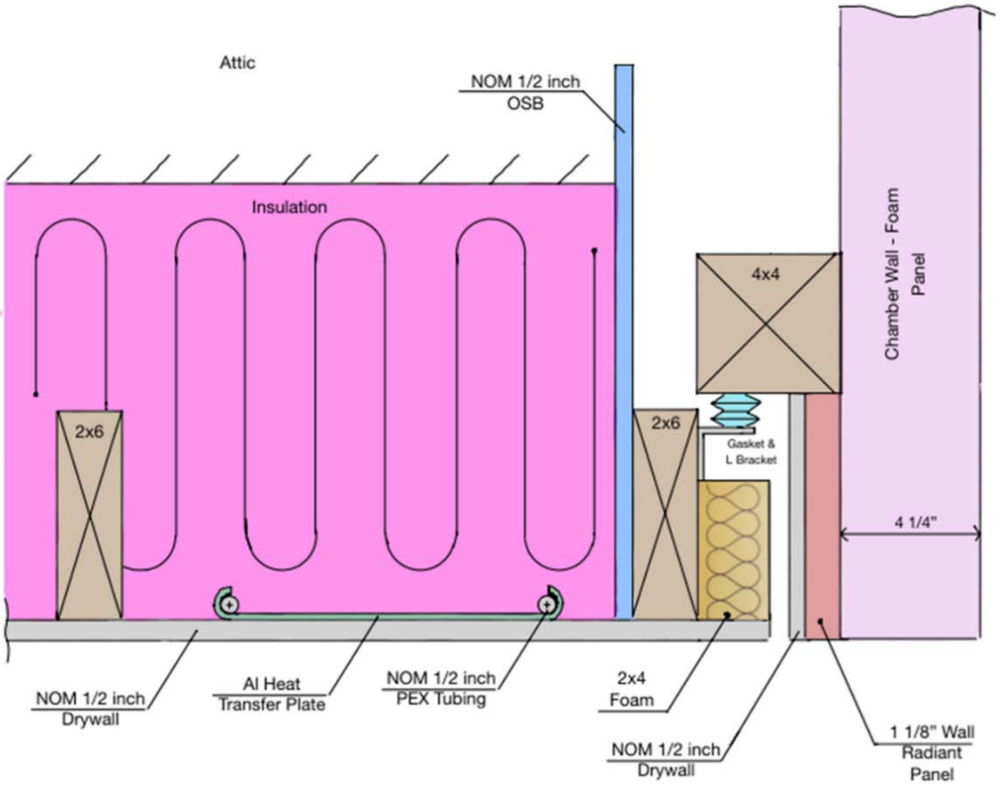

Figure 6. Detailed cross section of radiant ceiling edge including mounting structure

2.2 Test Methods

The goal of the radiant ceiling panel laboratory testing was to determine the delivery effectiveness, δ, defined as the ratio of the downward heat transfer rate, Q_{down}, over total energy released or absorbed by the hydronic system, Q_{tot}, under steady-state conditions (see Equation 1). The energy exchange between the attic and the radiant ceiling panel system, Q_{up}, is considered a loss (see Figure 5). The energy given to or taken from the ceiling edges, Q_{edge}, to the radiant ceiling panel system is also considered a loss.

Equation 1. Radiant Ceiling Panel Delivery Effectiveness

$$\delta = \frac{Q_{down}}{Q_{tot}} = \frac{Q_{down}}{Q_{down} + Q_{up} + Q_{edge}}$$

However, it is desirable to eliminate Q_{edge} because the edge losses in the environmental chamber are not representative of a real installation. Additionally, eliminating Q_{edge} from the analysis makes effectiveness values produced from lab testing representative of a radiant ceiling panel system of infinite area, or of a radiant ceiling in a room with no exterior walls. This is desirable for use in developing modeling assumptions that can be used with any size radiant ceiling panel surface.

To eliminate Q_{edge}, multiple tests were performed for a range of insulation levels. An asymptotic function curve was fitted to the test data to determine the highest possible ratio of downward heat transfer to total heat transfer. Comparing this curve to the same curve with an asymptote of 1 reveals the impact of edge effects and allows canceling them out from the analysis, assuming edge effects are relatively constant for a given set of boundary conditions and insulation levels.

The delivery effectiveness in cooling was evaluated by measuring the steady-state heat transfer rate between the panels and the space below for the following range of operating conditions:

- Attic insulation R-values of 19, 30, 49, 79, and 109.
- Panel entering water temperature of 55°F.
- Water flow rate of 1 gpm.
- Attic air temperature of 140°F.
- Indoor air temperature of 76°F.

These conditions were selected because they are what is typically seen in the field and allow more direct comparison of results from the prior research. Additional laboratory tests were conducted for model calibration and validation.

Data points collected included:

- Panel inlet and outlet water temperatures.
- Water flow rates.
- Surface temperatures of all interior surfaces of the indoor space at multiple points.
- Infrared (IR) temperature measurements covering several areas of the ceiling surface using six IR sensors on tripods.
- Ambient air temperatures and humidity in both the simulated attic and interior spaces.
- Heat flux at several locations on the interior panel surface and at the back of the panel.

The layout and placement of sensors, with the area of the ceiling temperatures within the view field of the IR sensors, are presented in Figure 7.

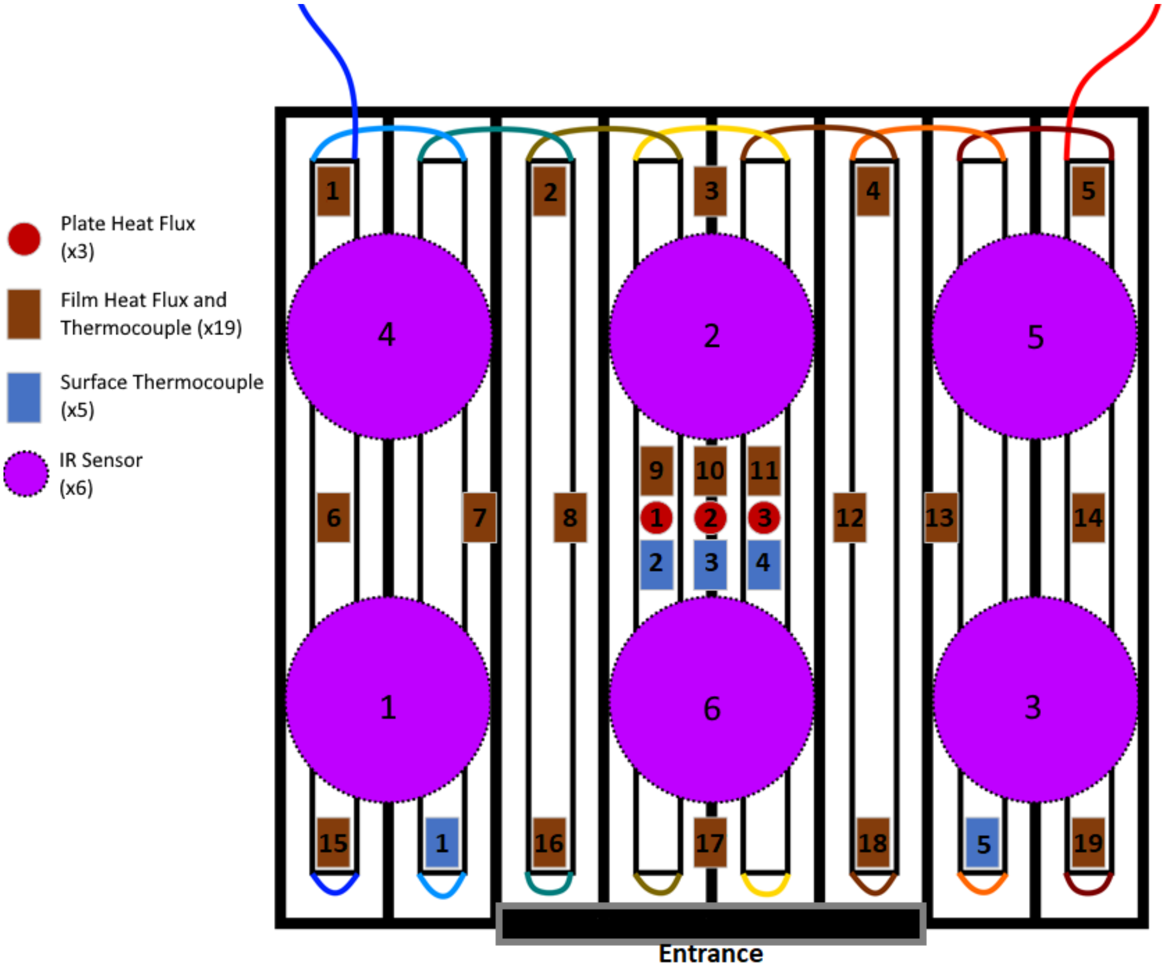

Figure 7. Layout of heat flux and temperature sensors relative to radiant ceiling panels

Heat flux transducers and thermocouples were strategically located on the ceiling surface to measure the heat flux under distinct sections of the ceiling (under the joists, sections with no heat transfer plate above them, sections with heat transfer plates above them, and sections with heat transfer plates and PEX tubing). These were used to produce an area weighted average heat flux rate for the entire ceiling.

Sensor data was logged at one-second intervals. Table 1 provides a list of instrumentation.

Table 1. Instrumentation Inside the Test Chamber

Measurement	Mfr. / Model	Type	Span	Accuracy
Air Temp.	Aspirated Vaisala HMP110	Pt1000 RTD	-4° to 176°F	±0.36°F (32° to 104°F) ±0.72°F (104° to 176°F)
Surface Temp. (IR)	Omega OS211-LT	Infrared Temp. Transmitter	-4° to 212°F	±1%
Surface Temp. (TC)	Omega SA1-T	Type T Thermocouple	-380° to 400°F	±0.9°F
Heat Flux (Film Sensors)	Hukseflux FHF05	Thermopile	-10000 to +10000 W/m²	±5%
Heat Flux (Plate Sensors)	Hukseflux HFP01	Thermopile	-2000 to +2000 W/m²	±3%
Water Temp.	Omega TQSS-116U-6	Immersed Type T Thermocouple	-380° to 400°F	±0.9°F
Water Flow	Omega FTB-4605	Turbine Flow Meter	0.15 to 13 gpm	±2%

The total heat transfer rate of the panels was calculated using the hydronic loop supply and return temperature and flow rate in Equation 2.

Equation 2. Total Radiant Ceiling Panel Heat Transfer Rate

$$Q_{total} = \mathrm{V} \cdot 60 \cdot \rho \cdot c \cdot (T_{out} - T_{in})$$

where:

Q_{total} is the heat added to the water by the panels, Btu/hr

V is the volumetric flow rate through the panels, ${}^{gallons}/_{minute}$

ρ is the density of water at the mean temperature, ${}^{lbm}/_{gallon}$

c is the specific heat of water at the mean temperature (at sea level), ${}^{Btu}/_{lbm \cdot {}^{\circ}F}$

T_{out} is the temperature of the water exiting the panels, $^{\circ}F$

T_{in} is the temperature of the water entering the panels, $^{\circ}F$

The total heat flux from the room to the panels was determined using three different methods:

1. Using the area weighted average of the heat flux sensors.
2. Using other sensor data with the equations and methods provided in the ASHRAE Handbook (ASHRAE 2020).
3. Using other sensor data with the simplified calculation model developed by Birol Kilkis, which is frequently cited in radiant system research (Kilkis, Sager, and Uludag 1994).

Because of the potential for application uncertainty in heat flux sensors,[5] having more than one method of determining a quantity that is difficult to measure provided a means to check the results and provided a backup in the event that one of the measurement methods was determined to be inaccurate.

2.3 Test Procedure

2.3.1 Pre-Test

Prior to the tests, several action items were performed as preparatory steps. These steps included:

- Verify calibration of installed sensors.
- Perform a shakedown test.

2.3.2 Lab Evaluation

The general test procedure conducted during the testing included the following steps:

1. Adjust the level of insulation above the panels.
2. Set the attic space temperature and surface temperatures.
3. Set the entering water temperature.
4. Set the flow rate.
5. Wait for steady-state conditions, defined as minimal variation in ceiling supply temperature, ceiling flow rate, attic air temperature, indoor air temperature, and all heat fluxes and surface temperatures for at least one hour. Minimal variation was within 2°F for temperatures and 2%–3% for heat fluxes when averaged over 12-minute increments.
6. Repeat steps 1 through 5 for each insulation level.

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[5] Application error with heat flux sensors includes things that are difficult to quantify, including resistance and deflection error. See Chapter 6 of the user manual for some of the heat flux sensors used in this project: https://www.hukseflux.com/uploads/product-documents/HFP01_HFP03_manual_v2124_0.pdf.

Steps 2 through 4 were fully automated. The BSRL data logging and control system was programmed with target values for inlet water temperature, flow rate, and surface temperature.

2.3.3 Analysis and Modeling

Test data were used to evaluate the radiant ceiling model currently incorporated in EnergyPlus. The results from the EnergyPlus radiant ceiling panel model for the same conditions as the laboratory tests were compared to test data and results from the previously discussed alternative calculation methods. These comparisons may be informative to EnergyPlus developers in assessing the software's accuracy.

In the model, the test chamber was approximated by modifying an interior zone on the second floor of a commercial office building model provided as an example building (LgOffVAV.idf) within EnergyPlus (see Figure 8). The graphic on the left is a cross section viewed from the side, and on the right is a cross section through the test chamber viewed from above. The temperatures were controlled by a radiant ceiling panel above the test chamber interior, along with electric resistance heating in the interior and attic zones. The other zones were left uncontrolled.

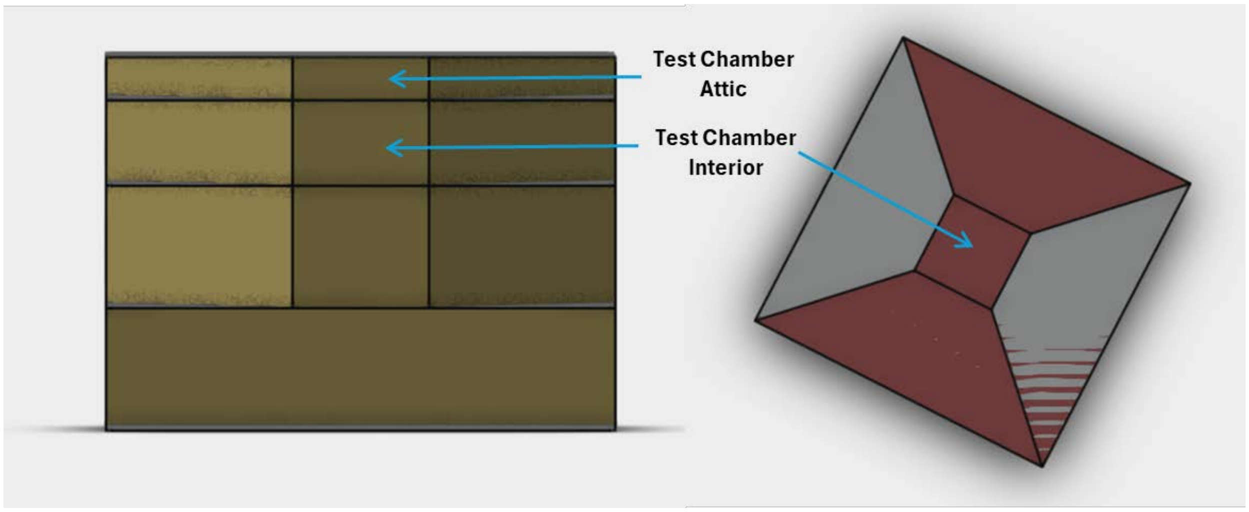

Figure 8. Geometry of EnergyPlus model

The radiant panel used the Low Temperature Radiant System Model in EnergyPlus, with constant inlet temperature and variable flow. This model was taken from an example file in EnergyPlus (RadLoTempHydrHeatCoolAutoCondFD.idf) but modified for installation at the ceiling instead of the floor. The autosize capability of EnergyPlus was used to determine flow rate. Actual test conditions, geometries, and material properties were used wherever possible in the model. However, the autosized flow rate did not allow a specific flow rate to be imposed without compromising the other restraints on the model, primarily zone temperatures. If the flow rate was held constant, the model would have changed the inlet and outlet water temperatures. A significant effort was made to match the chamber as closely as possible, but the test chamber is not a building, and it was extremely difficult to model it exactly using the available EnergyPlus options.

3 Results

3.1 Preliminary Testing and Edge Effect Analysis

Preliminary lab testing and modeling was performed to analyze edge effects using a calibrated two-dimensional THERM model. Because THERM is two-dimensional and edge effects are three-dimensional, there were limitations to the accuracy that could be achieved. In addition, the mounting and mechanical components around the edge of the panel (see Figure 6) were challenging to model accurately, because (1) the shapes were complex, (2) thermal contact between components was uncertain and some of the properties were unknown, and (3) natural convection around the edge assembly could not be easily quantified. A graphical view of the THERM model of the chamber edge effects is shown in Figure 9.

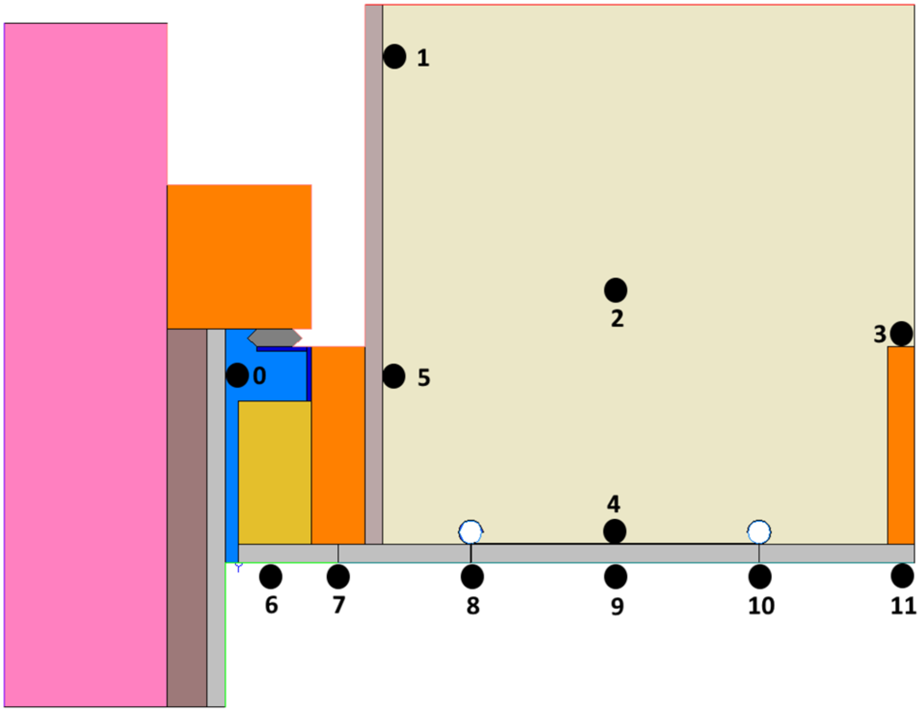

Figure 9. Graphic of 2D THERM model of edge effects

Several lab tests were performed to help calibrate this THERM model, using R-49 attic insulation and the radiant ceiling panel operating conditions described in Section 2. Twelve temperature sensors were installed in various locations around the edge of the radiant ceiling panel, as shown in Figure 9. One comparison of measured versus modeled temperatures with a known radiant ceiling panel flow rate and inlet temperature is shown in Table 2.

Table 2. Edge Effect Calibration Results

Sensor Location	Final Model (°F)	Sensor Readings (°F)	Difference (∆°F)
0	106.5	91.4	15.1
1	137	116.2	20.8
2	95	94.6	0.4
3	89	92.5	-3.5
4	59	60.8	-1.8
5	105	105.6	-0.6
6	81	78.2	2.8
7	77	77.4	-0.4
8	65	70.3	-5.3
9	65	68.3	-3.3
10	67	71.9	-4.9
11	75	75.1	-0.1

Despite numerous attempts to fine-tune the model, the comparison indicates that the model does not match the test results very accurately. In some cases, the temperatures were off by 15°–20°F. However, many of the temperatures matched very well, and the model could be expected to give a reasonable estimate of total edge losses. The uncertainty in temperature readings was very small during the test, changing less than 0.1°F during steady-state conditions; the 0.9°F measurement accuracy from Table 1 was the larger concern. However, the difference compared to the THERM model was generally much greater than could be accounted for by measurement inaccuracy. Additional measurements using an IR camera may have been beneficial during the lab test to identify possible thermal shorts near the edge. Although our focus was on the interior of the edge assembly and only surface temperatures would have been measured, IR imaging would be helpful for similar tests in the future.

Figure 10 shows a thermal map of edge effects based on the THERM model, which indicates a significant distortion of the isothermal lines near the panel mounting assembly. According to this model, 58.4% of the heat removed by the radiant ceiling panel near the edge of the chamber came from the interior space. The other 41.6% was either lost to the attic or to the outside of the chamber. However, the temperature of the chamber walls in the model indicates that the ambient laboratory air (generally about 86°F) was actually cooling the chamber slightly near the edge of the radiant ceiling panel, and it is therefore unlikely that the chamber walls contributed significantly to the edge losses.

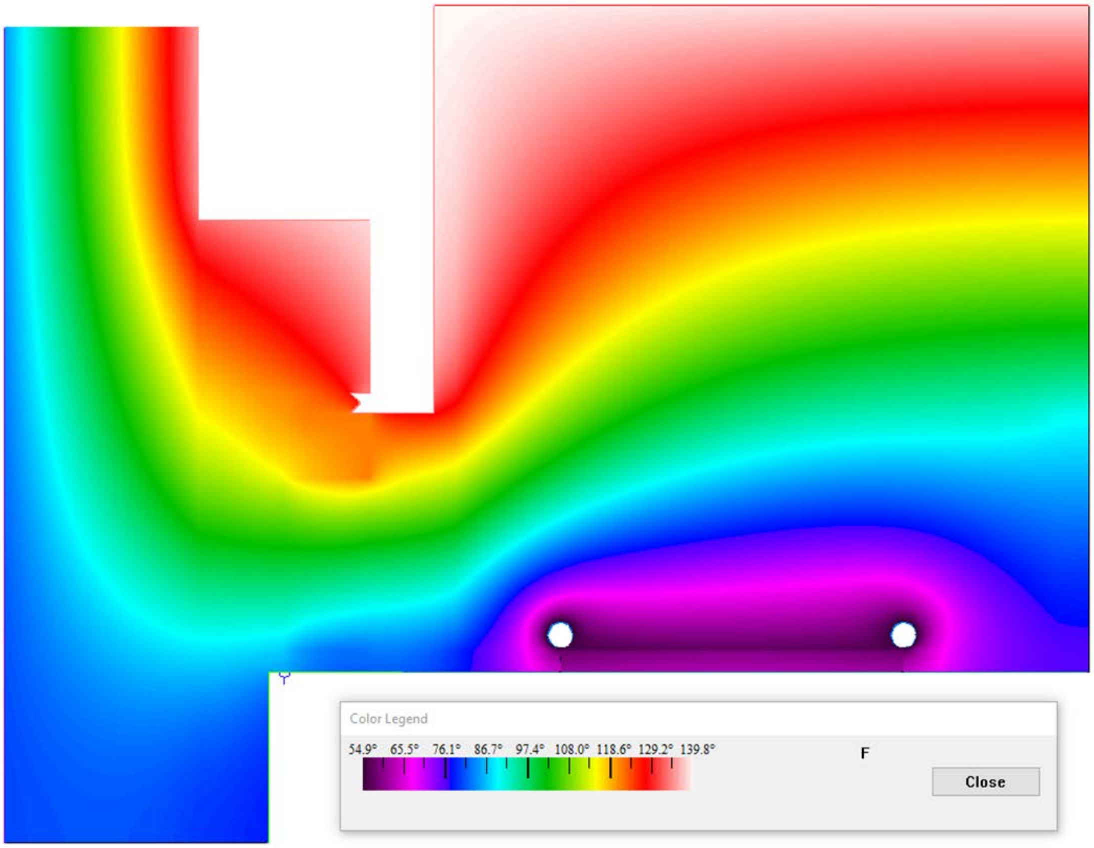

Figure 10. Thermal map of the radiant ceiling edge THERM model

A second THERM model was developed to examine heat transfer in the center of the panel, exclusive of edge effects. Figure 10 shows a graphic of the THERM model along with 12 new sensor locations. The calibration was slightly better for this model, but a few significant differences remained (see Table 3). In general, the model predicted cooler temperatures, especially at the ceiling surface.

This center-of-panel model estimated a delivery effectiveness of 77.1%. No edge losses were considered in this model, so comparing the results to the radiant ceiling panel edge model, about 18.7% of the radiant ceiling panel energy near the edge was lost to the attic or the outside of the chamber through edge effects (77.1%–58.4%). The remaining 22.9% of losses in the edge model would have been through the attic insulation (41.6%–18.7%). For the panel as a whole, the edge losses would be somewhere between 0% in the center and 18.7% near the edge. Uncertainty in the model accuracy based on the calibration process and limitations of 2D modeling suggests that these estimates are very approximate, but they indicate significant edge effects that should not be ignored.

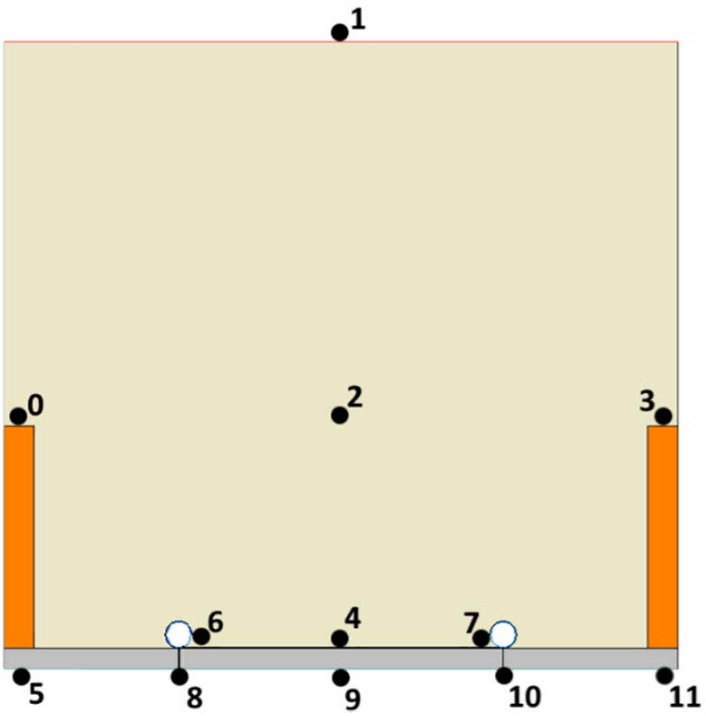

Figure 11. THERM model of radiant ceiling center joist bay

Table 3. Calibration Results for Radiant Ceiling Center THERM Model

Sensor Location	Final Model (°F)	Sensor Readings (°F)	Difference (Δ°F)
0	90	90	0
1	133	133.1	0.1
2	86	91.9	5.9
3	90	91.4	1.4
4	58	61.7	3.7
5	75	74.1	-0.9
6	57.5	57.5	0
7	57.5	58.7	1.2
8	62	70	8
9	61	70.2	9.2
10	62	74.1	12.1
11	75	74.9	-0.1

The laboratory test results are compared to both THERM models in Figure 12. The first three data points were based on direct measurements of the flow rate and temperature change of the water across the radiant ceiling panel, along with three different methods of quantifying the downward heat flux using sensor data. These estimates of delivery effectiveness were fairly consistent, averaging about 85%. The THERM model estimated a delivery effectiveness of about 77% in the center of the panel and 58% near the edge, both of which were significantly lower than the effectiveness indicated by the measurements with R-49 attic insulation.

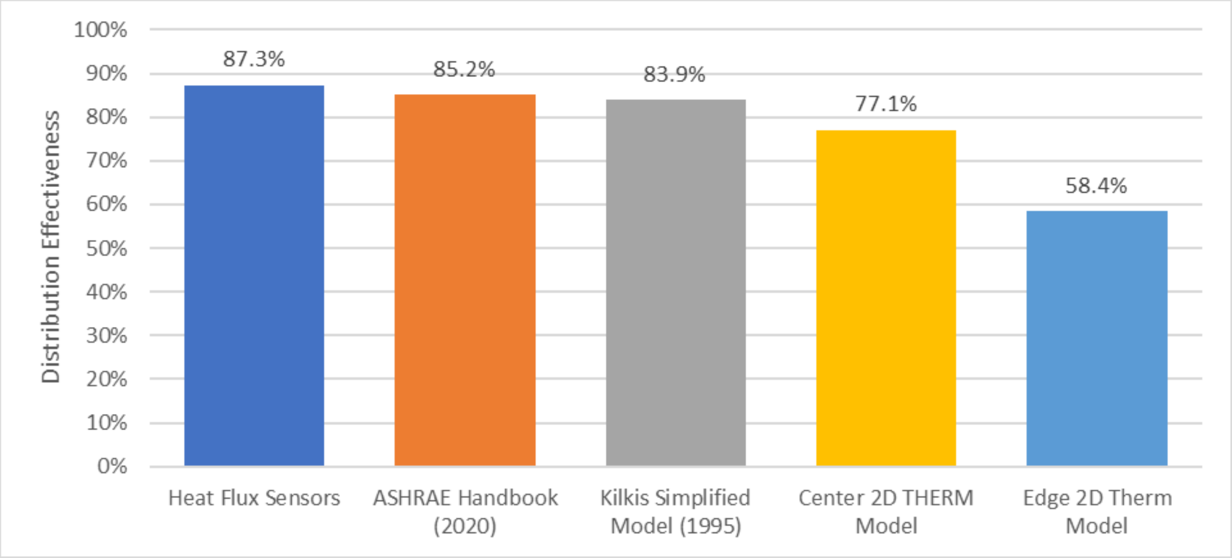

Figure 12. Comparison of delivery effectiveness from laboratory tests and THERM models of radiant ceiling center and edge

3.2 Laboratory Test Results

The main series of laboratory tests proceeded with the operating conditions and insulation levels described in Section 2. Because the THERM model did not provide adequate confidence in the estimation of edge effects, the approach used in the lab testing was to gradually increase the insulation levels up to R-109, which was the highest level that could be achieved within the limited attic space in the test chamber. The expectation was that the measured delivery effectiveness would either flatten out, or a curve fit could be applied to find the asymptote. The difference between 100% and this asymptote would be an estimate of edge effects, which could then be removed from the delivery effectiveness measurements to determine the theoretical value with an infinitely large radiant ceiling panel area.

The measured temperatures and heat fluxes for each insulation level are shown in Figure 13 through Figure 17. Despite occasional instabilities caused by lab ambient temperature fluctuations or occasional control issues, there were extended periods of time in each test from which steady-state values could be drawn. Legend labels are defined as follows:

- T_Indoor_F – The air temperature of the indoor section of the chamber, measured at the center of the space using an aspirated and shielded thermocouple.
- T_Attic_F – The air temperature of the attic section of the chamber, measured at the center of the space using an aspirated and shielded thermocouple.
- T_ShopAmbient_F – The air temperature of the shop inside which the chamber is installed, measured near the chamber (about a foot out from the surface of the chamber, a few feet above and to the left of the chamber door) using an aspirated and shielded thermocouple.
- T_CeilingSupply_F – The supply water temperature to the ceiling panel measured at the panel inlet below the attic insulation using an immersed thermocouple.
- HF_LeftBayCenter_Btuphrft2 – The heat flux at the center of the left-center joist bay. This is the plate heat flux sensor numbered 1 in Figure 7.
- HF_CenterJoist_Btuphrft2 – The heat flux at the center of the center joist. This is the plate heat flux sensor numbered 2 in Figure 7.
- HF_RightBayCenter_Btuphrft2 – The heat flux at the center of the right-center joist bay. This is the plate heat flux sensor numbered 3 in Figure 7.

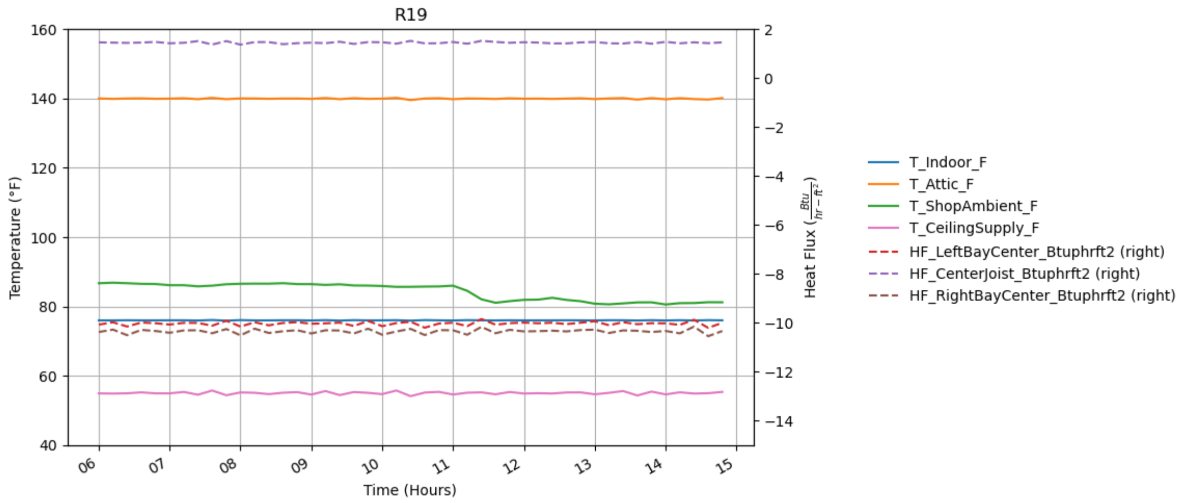

Figure 13. Heat flux and temperature readings for the R-19 test

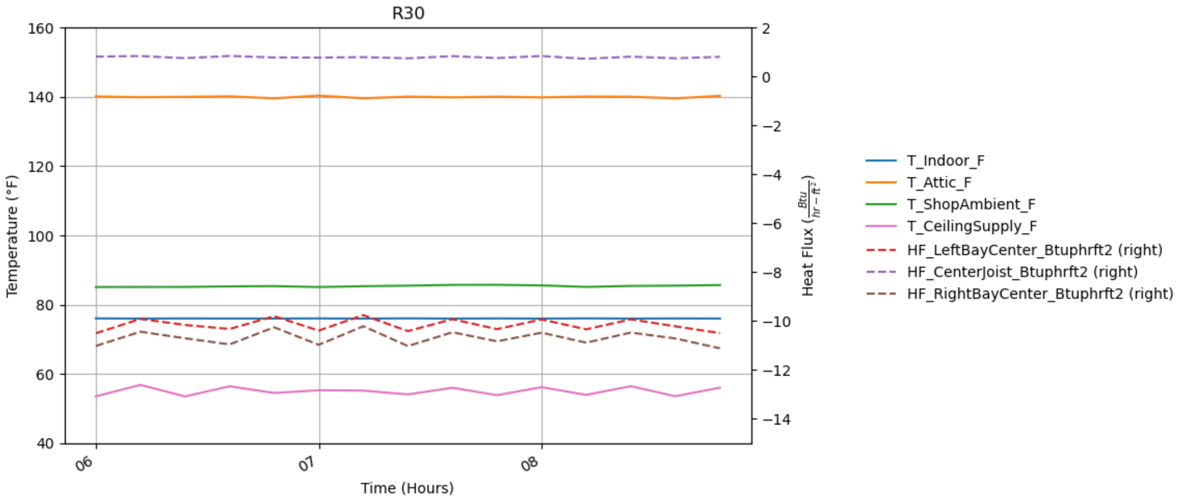

Figure 14. Heat flux and temperature readings for the R-30 test

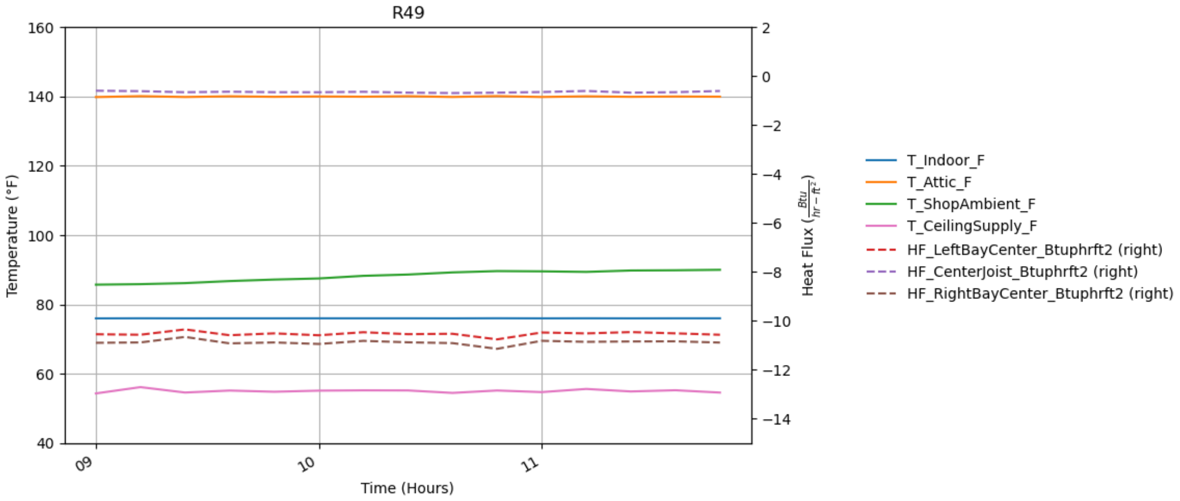

Figure 15. Heat flux and temperature readings for the R-49 test

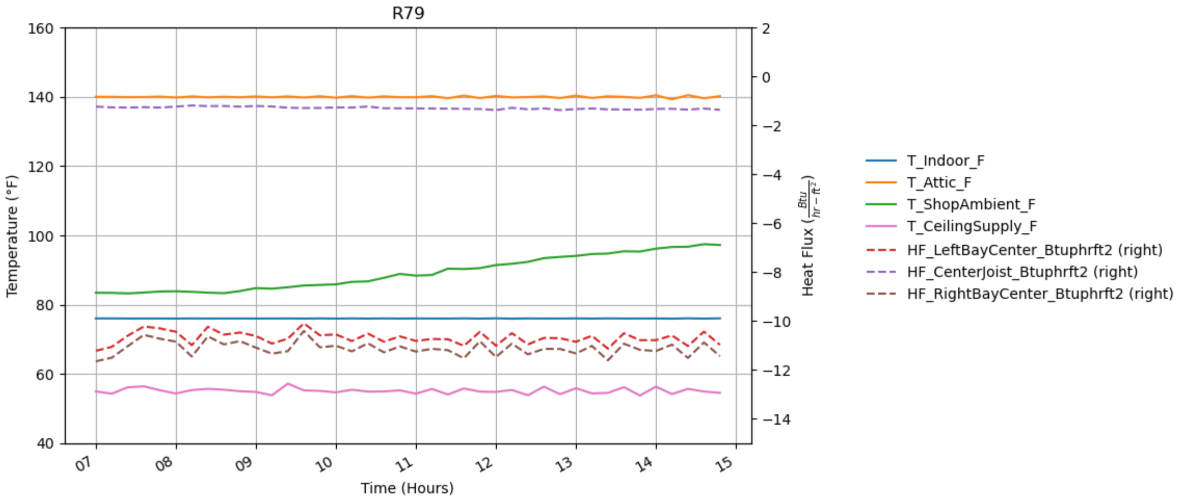

Figure 16. Heat flux and temperature readings for the R-79 test

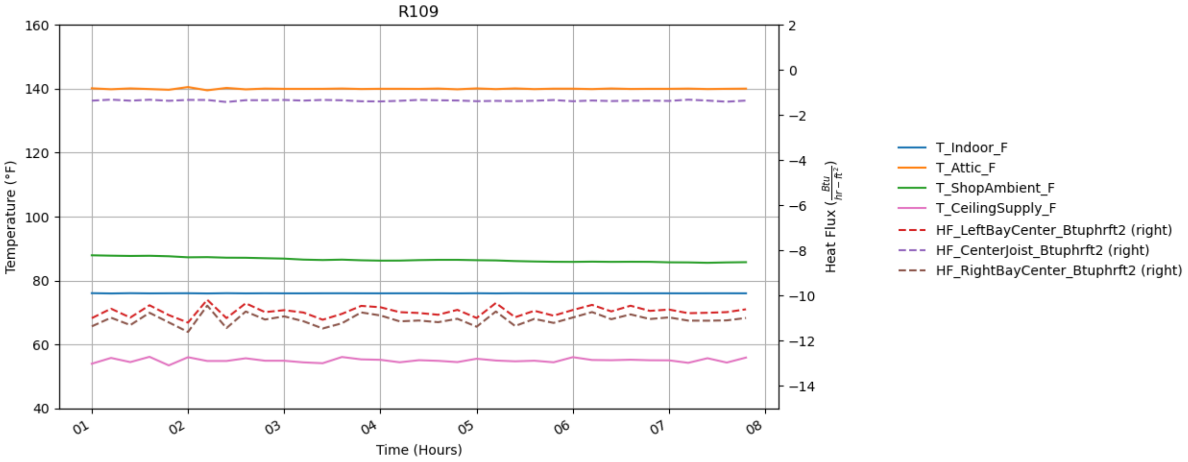

Figure 17. Heat flux and temperature readings for the R-109 test

Using the equations described in the technical approach, delivery effectiveness was calculated at each insulation level, as shown in the top graph of Figure 18. Very little change occurred between R-79 and R-109, indicating that the edge effects caused the delivery effectiveness to remain below 100%. Depending on the approach used to determine downward heat flow (Kilkis and ASHRAE curves practically overlap), the edge losses appear to be in the range of 13%–17%. Downward total heat flux is shown in the middle graph of Figure 18.

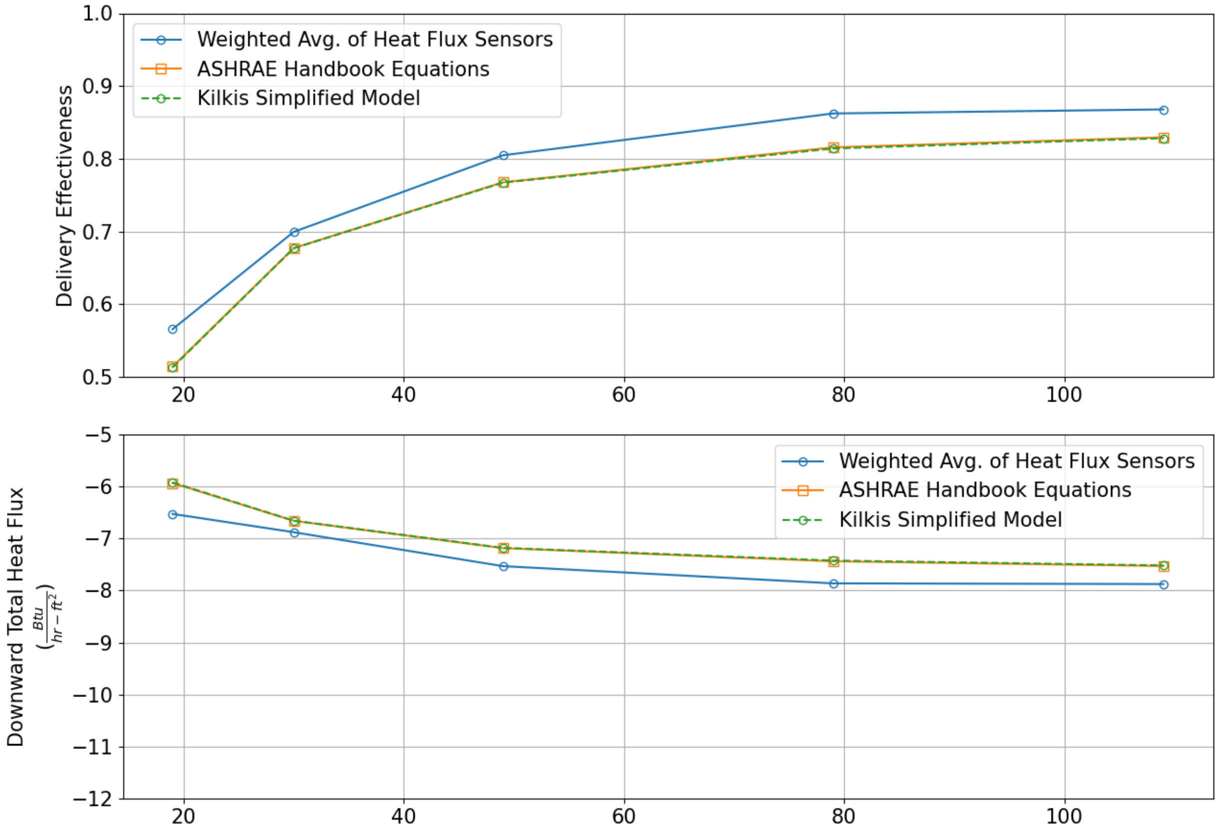

Figure 18. Delivery effectiveness and average heat flux across insulation levels

Delivery effectiveness adjusted for edge effects is shown in the bottom graph of Figure 19 for each insulation level. The data indicate that delivery effectiveness reached a stable value at R-109, so we assumed the adjusted value would reach 100% at that point. Once edge effects were removed, all three methods for calculating downward heat flux provided fairly consistent results. The target value of 88% (meeting the 2021 IECC requirement for ducted systems) would be achieved with R-37 or R-39 insulation depending on the test method, and 95% (the assumed value for radiant ceiling panels with components in unconditioned space in 2021 IECC) would be achieved with R-56 insulation.

If the radiant ceiling panel system is entirely within conditioned space, the 2021 IECC would assume a delivery effectiveness of 100%, which would require an attic insulation level greater than R-79 to achieve.

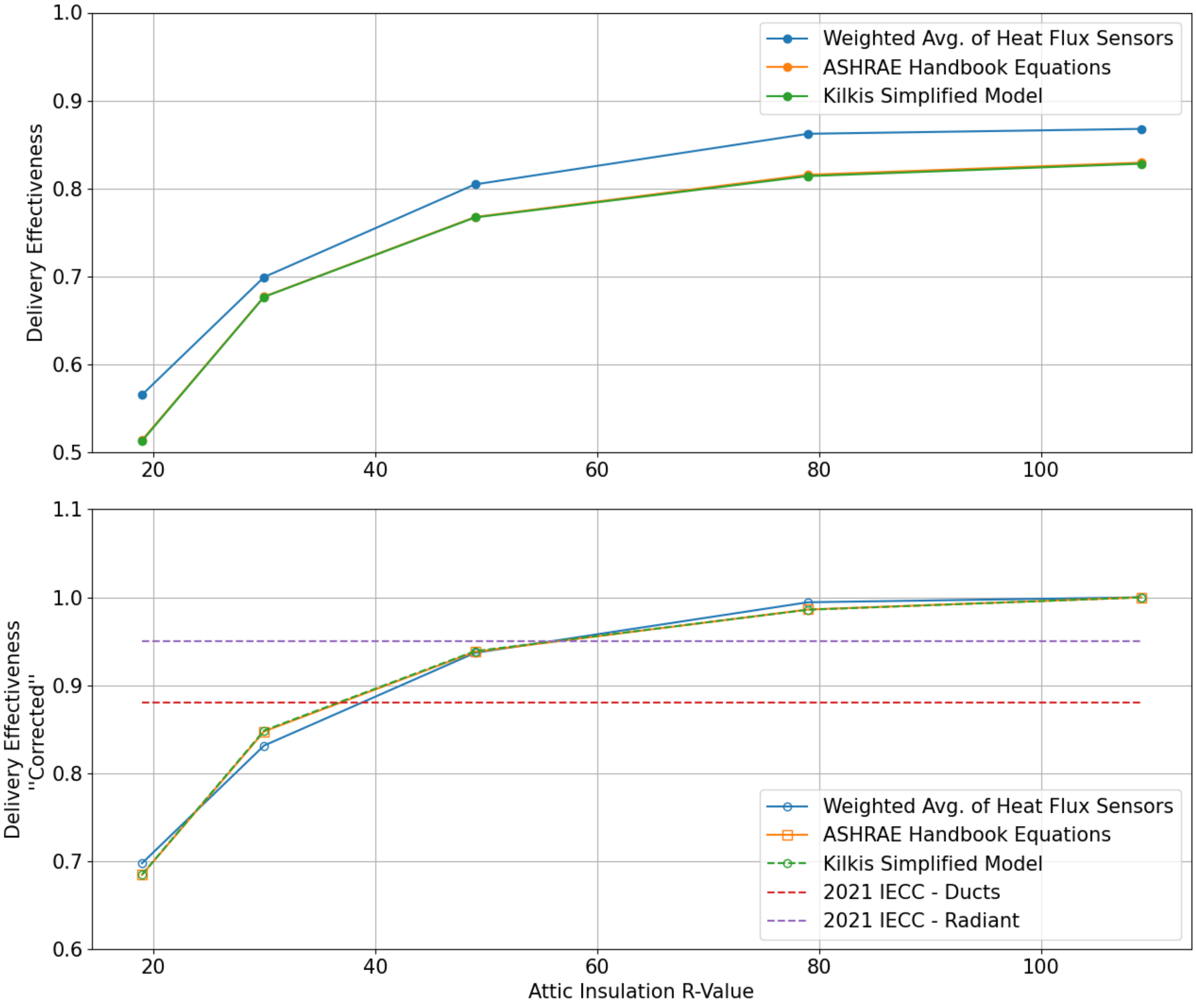

Figure 19. Delivery effectiveness from measurements (top) and corrected for edge effects (bottom) compared to IECC prescriptive requirements

3.3 EnergyPlus Analysis

As described in Section 2, an EnergyPlus model was developed to determine if the model predictions were in alignment with lab test results. Various model inputs were adjusted to make boundary conditions consistent at steady state, as shown in Figure 20. T_{attic} represents the attic space in the test chamber, T_{shop} is the ambient temperature of the laboratory, T_{indoor} represents the indoor space in the test chamber, and $T_{water\text{-}in}$ is the temperature of the water entering the radiant ceiling panel.

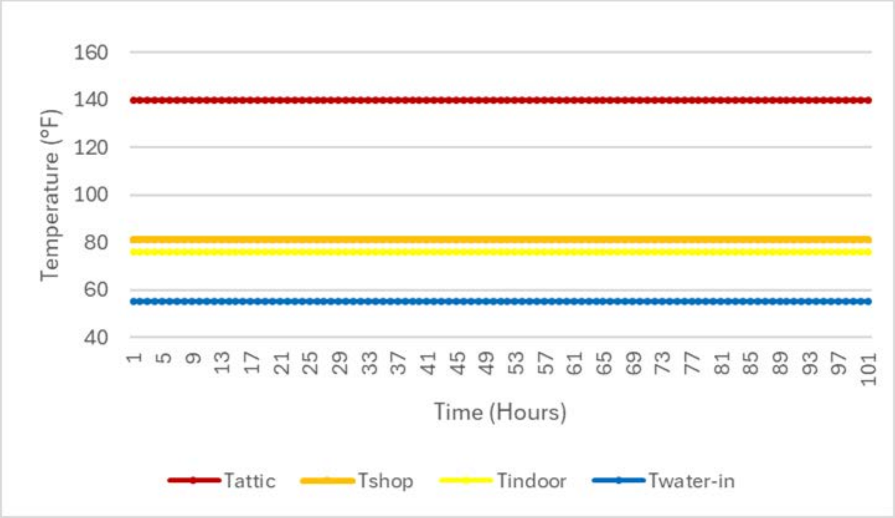

Figure 20. EnergyPlus model temperature calibration

However, the autosizing option for EnergyPlus resulted in a radiant ceiling panel flow rate that was only 15% of what was applied during lab tests. Because of difficulties matching other test conditions if the flow rate was forced to match, and approximating the test chamber as an interior zone of a larger model, we decided to leave the flow rate as it was and focus on the trends in delivery effectiveness as a function of attic insulation. The delivery effectiveness predictions for the five tested insulation levels are shown in Figure 21.

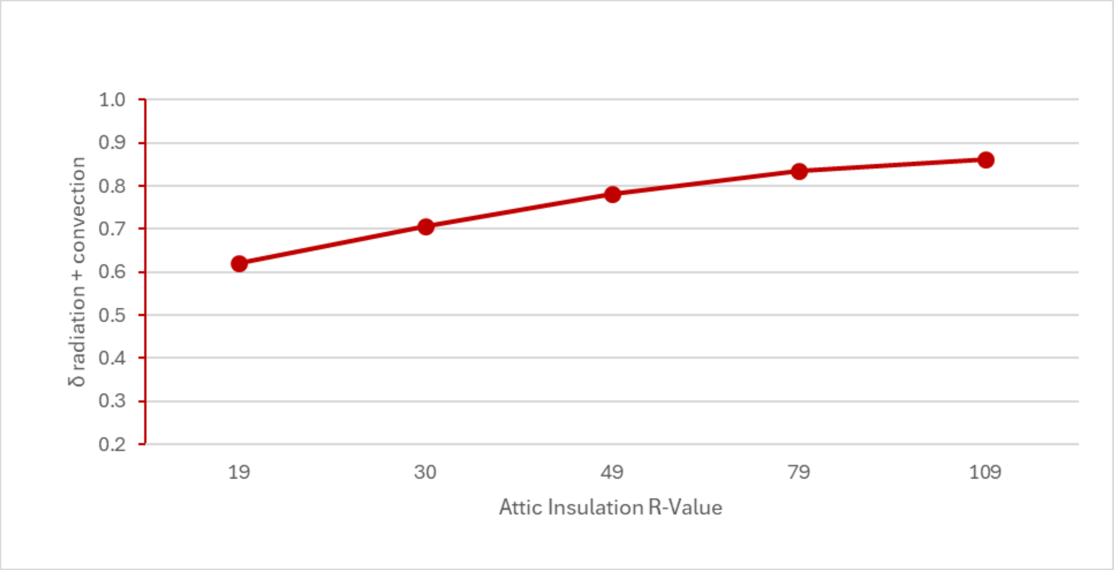

Figure 21. Delivery effectiveness predicted by the EnergyPlus model

A comparison of the modeled delivery effectiveness to the test results is provided in Figure 22. The measured values were adjusted for edge losses, and the modeled values did not require adjustment because the Low Temperature Radiant System Model in EnergyPlus has adiabatic edges according to the engineering reference manual (U.S. Department of Energy 2023), as shown in Figure 23.

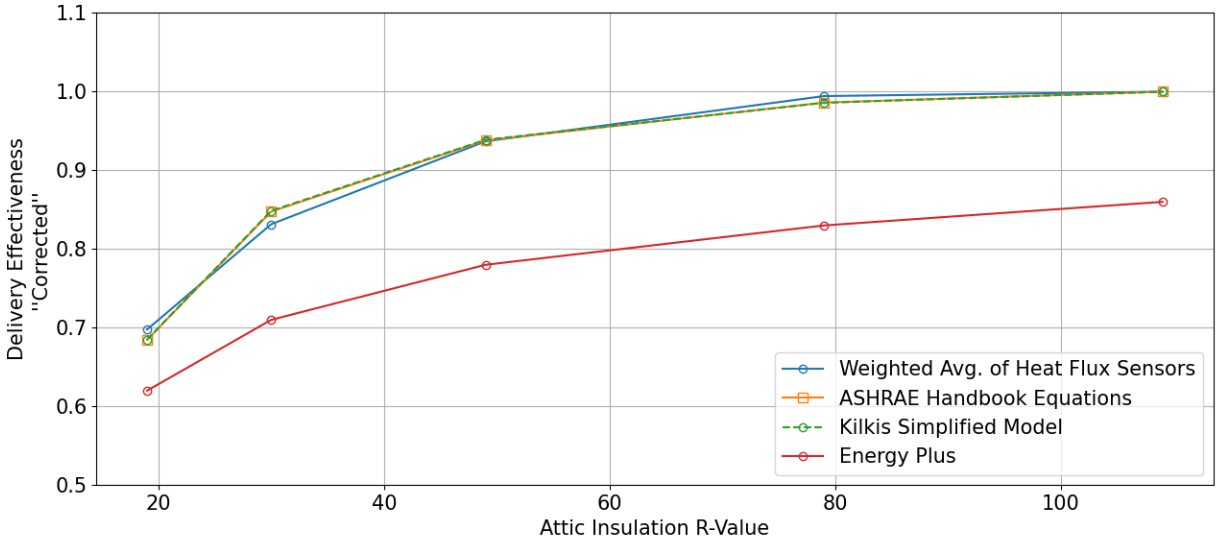

Figure 22. Modeled versus measured delivery effectiveness

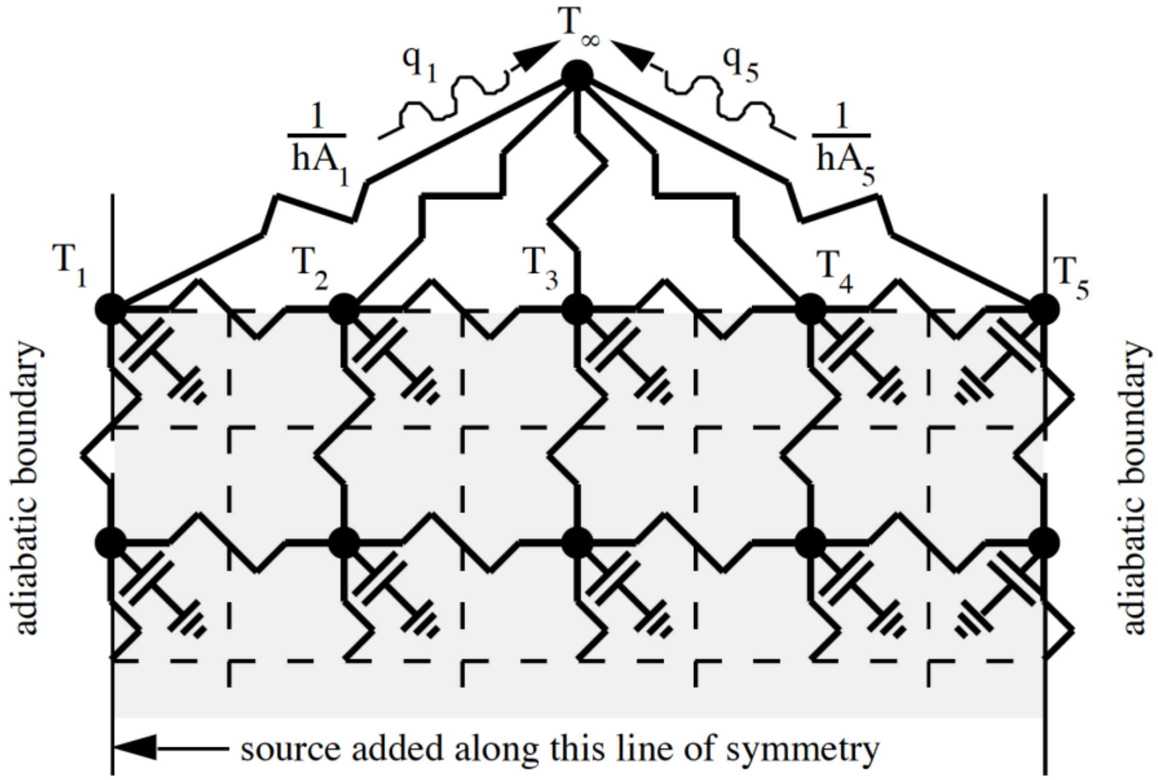

Figure 23. 2D node example for a low-temperature radiant system (U.S. Department of Energy 2023)

The model predicted much lower delivery effectiveness, but this may have resulted from the flow rate being lower than the test conditions. More noteworthy is the fact that the delivery effectiveness had not leveled off with an insulation level of R-109 and appeared to be a long way from reaching 100%. This seems to be at odds with the physical reality, and we are uncertain where the remaining cooling energy in the model is being lost. It is possible that the edges are not truly adiabatic in the modeling software, or the large temperature rise associated with the low flow rate is having a larger effect than we would expect.

The chamber and surrounding laboratory space is not a building in outside ambient conditions, and using a building simulation tool like EnergyPlus proved more problematic than expected. Key challenges related to modeling the test chamber in EnergyPlus included:

- The chamber interior and attic were represented as two interior zones in a larger commercial building model.
- Effects from surrounding zones were minimized, but there was some heat transfer between them, including radiation effects.
- Two-dimensional edge effects could not be modeled.
- The fins connecting the radiant ceiling panel tubes could not be modeled because the thermal conductivity was too high and the thickness was too small for the EnergyPlus materials library.
- The conduction upward from the gypsum board adjacent to the radiant ceiling panel was larger than the sum of the radiation and convection from the interior space.
- Auto-sizing resulted in low radiant ceiling panel flow rates, and turning off auto-sizing made it impractical to match all conditions without extensive trial and error.
- Radiant panel control options were limiting when trying to match all boundary conditions.

4 Conclusions

This project successfully evaluated radiant ceiling panel delivery effectiveness in cooling mode at multiple insulation levels. Challenges were encountered when attempting to quantify edge effects around the radiant ceiling panels, which were much more impactful in a small test chamber than they would be in a real house with larger rooms. However, these edge effects were accounted for through a combination of lab tests and calibrated modeling using THERM.

Key findings from this study include the following:

- Edge effects in the BSRL test chamber caused approximately 13%–17% loss in delivery effectiveness.
- After adjusting for edge effects, the test results indicate that R-56 attic insulation would be required to meet the assumed 95% delivery effectiveness for radiant ceiling panels with components in unconditioned space in the 2021 IECC. R-37 to R-39 attic insulation would be necessary to meet the delivery effectiveness assumption of 88% for ducted systems in the 2021 IECC. If the panels were entirely within conditioned space, the 2021 IECC would assume a delivery effectiveness of 100%, which would require an attic insulation level greater than R-79 to approach.
- All three methods for determining downward heat transfer from the radiant ceiling panels based on measured data yielded similar values for delivery effectiveness.
- The Kilkis and ASHRAE methods give very similar results for total downward heat transfer, despite resulting in very different values for the convective and radiative components.
- EnergyPlus modeling of the test chamber and radiant ceiling panels identified some limitations and areas for improvement in the software. Although the model predicted lower delivery effectiveness, even with very high attic insulation levels, the uncertainties surrounding the alignment of the model with test geometries and boundary conditions reduced our confidence in the results.

5 Recommendations

This project identified that there are issues with how EnergyPlus models radiant ceiling systems, and with delivery effectiveness assumptions used for radiant systems in IECC, but additional work is needed to provide specific recommendations needed to update EnergyPlus and IECC parameters.

Recommendations for future study include the following:

- Additional laboratory testing in heating mode, and in cooling mode under a few more operating conditions (flow rate, inlet water temperature, attic temperature, and interior space temperature), with increased barriers to edge effects near the radiant ceiling panel mounting structure.
- Additional laboratory testing using radiant ceiling panels designed to be installed within the ceiling plane, such as the prefabricated panels manufactured by Messana.
- A deeper dive into the methods used in EnergyPlus to model radiant systems to make specific recommendations to address the limitations and issues found in

> this project. Although it is not reasonable to expect a building modeling tool to work seamlessly for an environmental chamber, it may be helpful to provide users with a greater ability to “lock in” certain variables to match test conditions, but there would be a risk that the model could become over constrained from a thermal balance standpoint.

Additionally, IECC does not currently have installation requirements for radiant systems. From these tests, it is clear that the IECC should have increased attic insulation requirements when radiant ceiling systems are installed, in order for the IECC delivery effectiveness assumptions to remain valid.

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