Thermally Anisotropic Building Envelope Integration into Panelized Metal Construction: Laboratory Evaluation in Guarded Hot Box

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ABSTRACT

The Thermally Anisotropic Building Envelope (TABE) is an active building envelope system that can exchange thermal energy with a storage medium to reduce the building's energy demand. TABE redirects thermal energy along thin conductive layers in the building envelope to hydronic loops that are connected to thermal energy storage (TES), where it will be available to offset future energy demand when the conditions are favorable. TABEs can also be connected with a geothermal loop to reduce the building's heating and cooling loads. Due to the importance of thermally conductive metal layers to TABE function, this technology has potential for easy adoption into panelized metal construction. In this study, we illustrate the construction process of prototype metal panels containing TABE and the laboratory evaluation in Oak Ridge National Laboratory's rotatable guarded hot box. The thermal performance of the prototype panel was assessed for both baseline and operational cases and the total heat flow extracted from the panel by TABE was quantified.

INTRODUCTION

Hydronic radiant building envelope systems offer an innovative solution for improving energy efficiency and contributing to a greener building initiative (Zhou and Li 2020). Previous research has thoroughly explored the use of hydronic radiant heating and cooling systems embedded in the walls and floors to reduce energy consumption for space conditioning (Dréau and Heiselberg 2014). Further studies highlight the impact of hydronic systems embedded in building envelopes and emphasize the need for effective control strategies and specific material properties to ensure efficient heat distribution and thermal comfort (Krzaczek et al. 2019; Krajčík and Šikula 2020).

Traditional hydronic tube-enabled radiant wall systems usually adopt a relatively small spacing between the

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hydronic tubes, typically in the range of 4 to 6 in. (10 to 15 cm) on center, owing to the low conduction of envelope material. Since the spacing between hydronic tubes directly affects the evenness of temperature distribution, a smaller tube spacing results in more uniform heating or cooling across the wall surface. This leads to enhanced thermal comfort due to the reduced cold or hot spots within the space. Furthermore, this facilitates a prompt response to changes in heating or cooling demand. A short response time is necessary to maintain the living zone temperature within the desired setpoints, particularly under challenging climate conditions. While high thermal performance can be achieved with a small tube spacing, this can adversely affect installation, maintenance, and repairs. Systems with a small tube spacing are more complex and require additional access points, making maintenance and potential repairs more labor-intensive. Additionally, a small tube spacing typically results in higher installation costs due to the increased material and labor required.

To address the challenges of traditionally hydronic tube-enabled radiant wall systems, the Thermally Anisotropic Building Envelope (TABE) was developed. This system requires minimal tubing and modification to existing building envelope construction practices whilst delivering high thermal performance (Biswas et al. 2019). This technology utilizes conductive metal layers to laterally distribute heat between the hydronic tubes and along panel surfaces. The enhanced heat distribution provided by metal layers allows for a notable increase in hydronic tube spacing, expanding the range up to 16 to 32 in (40.6 to 81.3 cm) on center. Previous prototype TABE panels required tedious work adding multiple aluminum foil layers within the construction (Howard et al. 2023). This posed increases in production cost and limitations to widespread adoption. Noticing this obstacle, a new TABE design, or metal-skin TABE design, is explored that utilizes the conductive metal skins inherent to panelized metal construction. The new metal-skin TABE design requires minimal modification to existing panelized metal construction design and installation practices. The objective of this study is to detail the panelized metal-skin TABE design and experimentally assess its thermal performance using the Rotatable Guarded Hot Box (RGHB) hosted at the U.S. Oak Ridge National Laboratory (ORNL). The experimental study showed that the new TABE design achieves a high thermal performance.

METHODOLOGY

The metal-skin TABE prototype design is shown in Figure 1. It had a wall area of 62.4 ft^2 (5.80 m^2) with dimensions of 7.9 x 7.9 ft (2.4 x 2.4 m) and included three hydronic tubes spaced at 32 in (81.3 cm) on center for both the interior and exterior faces of the panel (6 tubes in total). All hydronic tubes were connected in parallel to a chiller water source maintained at temperatures achievable by a low-grade thermal source. Following instrumentation, the panel was installed in the RGHB and was tested for both a baseline case (no fluid flow present in TABE) and an operational case (fluid flow present in the TABE). Performance was assessed for both cases using heat flow data collected from the TABE panel and the fluid.

Metal-skin TABE Panel Construction

The TABE panel included five main layers: the outer metal skin, a half-inch XPS insulation layer, a 2-inch XPS insulation layer, an additional half-inch XPS insulation layer, and an interior metal skin. All hydronic loops were run vertically through cutouts in the half-inch XPS insulation layers on both the exterior and interior sides of the panel. Several steps were taken to prepare and assemble the panel for experimental evaluation. First, a 2 in (5.08 cm) XPS insulation board was prepared with thermocouples installed on both its inner and outer surfaces for temperature monitoring. Then, 0.5 in (1.27 cm) XPS insulation was added with vertical sections cut out for fitting metal pipe carriers used to hold the TABE hydronic loops (Figure 2a). Metal pipe carriers served to encase each hydronic loop in a thermally conductive surrounding and efficiently exchange heat between the PEX tube and the metal skins. These sections and hydronic tubes were secured in place with aluminum tape (Figure 2b). After assembly, the metal-skin TABE layers, through fasteners and metal edging profiles were then used to sandwich the panel and provide structural rigidity. To add extra structural integrity, small aluminum strips were fastened to cover the tubes and carriers (Figure 2c). Lastly, metal skins were fastened into place to complete the panel assembly process (Figure 2d).

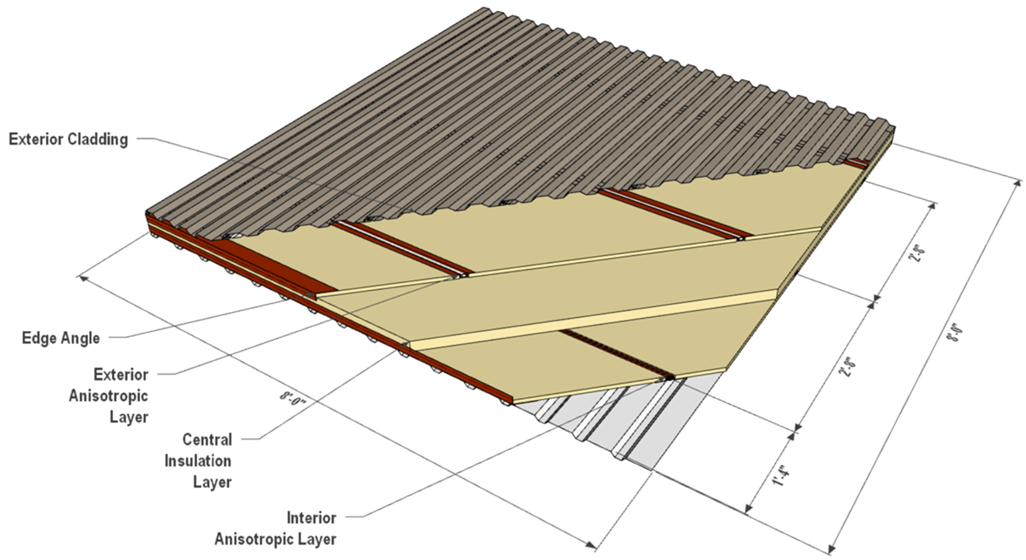


Figure 1 TABE prototype panel design for RGHB testing.

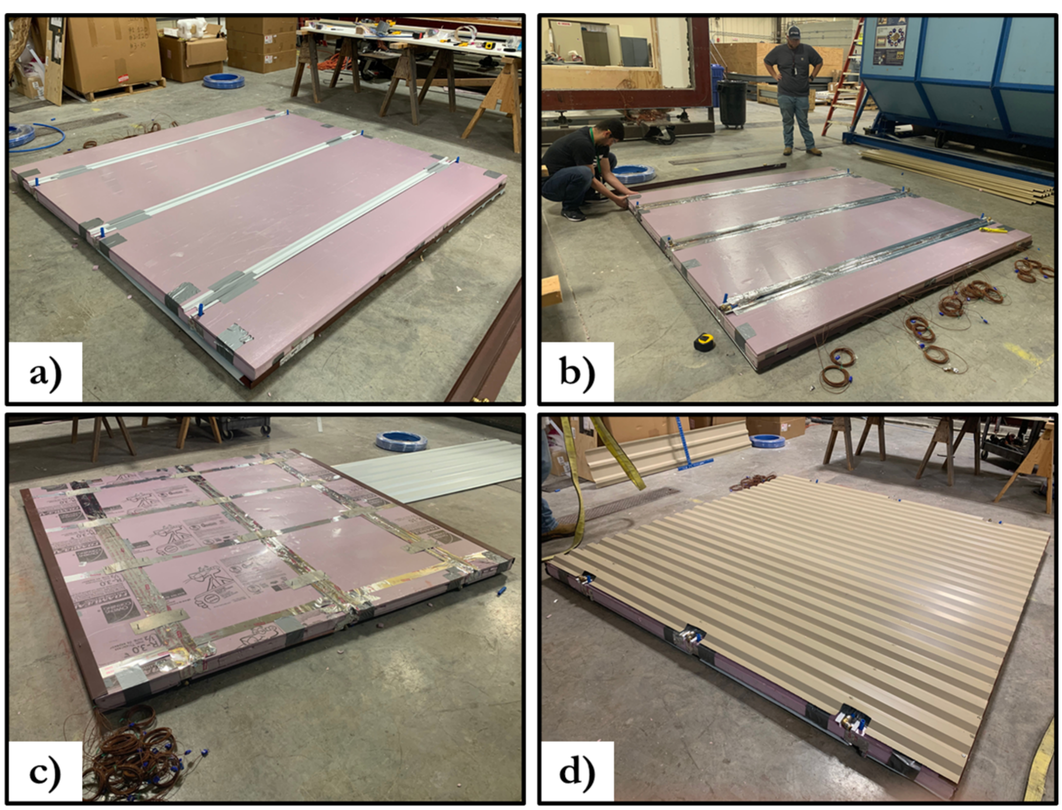


Figure 2 (a) Metal pipe carriers inserted between gaps in 0.5 in XPS insulation, (b) Aluminum tapes applied to secure hydronic loops within pipe carriers and promote thermal contact, (c) Edge angles, aluminum strips, and through fasteners utilized to sandwich panel, and (d) metal skins applied on both interior and exterior of panel.

Test Setup

After assembly, some trimming was required to fit the panel into the frame for testing. Once appropriately sized and placed into the frame, closed-cell spray foam was used to seal any gaps and channels through the metal cladding profiles to prevent convection. All hydronic loops in the TABE panel were connected to a chilled water source that was maintained at temperatures reflecting that achievable with low grade thermal energy sources (thermal energy storage or geothermal loop) (Figure 3a). Instrumentation of the TABE panel included 60 thermocouples to monitor temperature at each layer of the construction, thermocouple probes to monitor fluid inlet and outlet temperature from hydronic loops, flowmeters to monitor fluid flowrate at the inlet to each hydronic loop, and proportional valves to precisely control the flowrates through each hydronic loop (Figure 3b). Following completion of the panel construction and instrumentation, the panel was prepared for testing in the RGHB (Figure 3c).

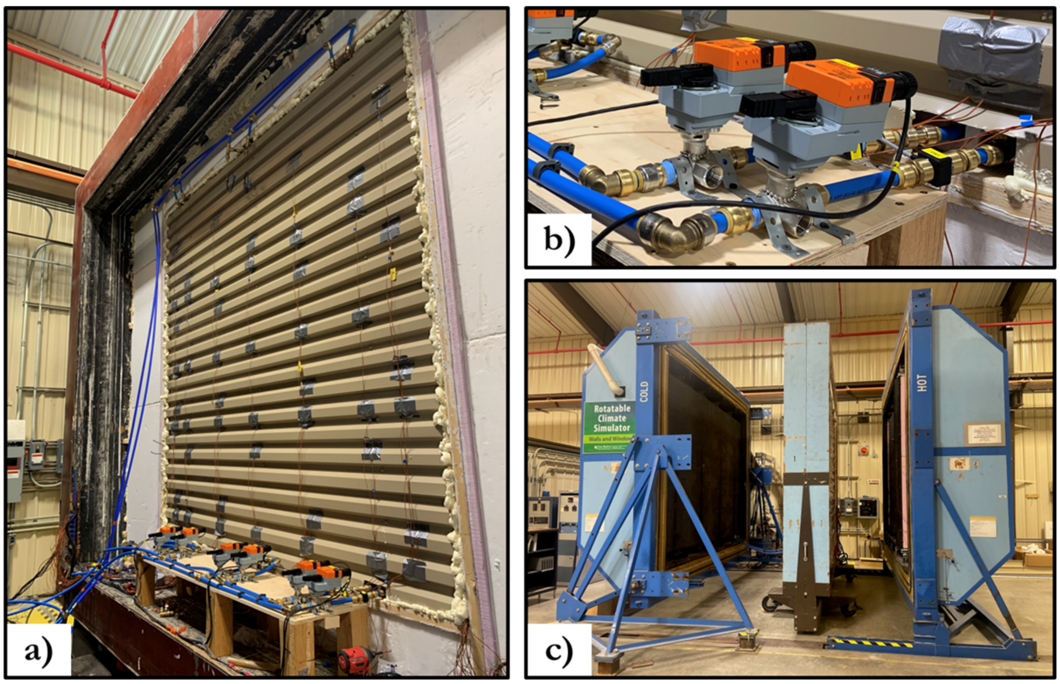


Figure 3 (a) Completed and instrumented TABE panel, (b) Flowmeters and proportional valves utilized to regulate flow in the TABE hydronic loops, and (c) RGHB utilized for TABE testing.

ORNL operates and maintains a guarded hotbox for assessing the thermal resistance (R-value) and thermal transmittance (U-factor) of full-size wall and window assemblies. This hotbox conforms to ASTM C1363 standards (ASTM 2019). The TABE panel assembly was mounted in the specimen frame, which measured 13 ft. (3.96 m) long by 10 ft. (3.05 m) high. The specimen frame, along with the test assembly, was then positioned between two identical "clamshell" chambers. These chambers are known as the climate (cold) chamber (CC) and the metering/guard (hot) chamber (MC). By placing the test wall assembly between these chambers, independent temperature control was achieved on each surface, creating a temperature differential across the specimen. Firstly, testing was done to establish performance of the panel for a baseline case (no fluid flowing in the hydronic loops). After this performance had been assessed, fluid flow was introduced to the hydronic loops and performance data was collected for the operational TABE system.

RESULTS AND DISCUSSION

Data collection for the RGHB study of the TABE prototype panel spanned several weeks. It was imperative to allow sufficient time for the system to reach steady-state conditions before any meaningful analysis could be conducted. For this analysis, data was carefully extracted from two specific 24-hour periods during which the system had achieved stable and consistent behavior. The first of these periods (baseline case) had no fluid flowing through the TABE hydronic loops. This established a reference point for the system's thermal performance. The second 24-hour period was characterized by the introduction of water flow through the TABE hydronic loops (operational case). The water entered the system at a temperature of 59°F (15°C) , and it was delivered at a flow rate of 0.5 gpm (3.79 l/min). This condition represented an operational TABE case and was utilized to assess the performance of this technology.

Test data extracted from these two distinct periods was instrumental in evaluating two key aspects of the RGHB study. First, it allowed for the assessment of the effective R-value of the panel under baseline conditions and comparison to total R-value of panel insulation. Second, it provided valuable insights into the performance of the TABE system when fluid flow was introduced. This data collection and analysis were integral to understanding the panel’s thermal behavior under various use cases.

Heat Flow Balance, Losses, and Corrections

During collection of TABE panel test data from RGHB, several critical factors needed to be considered. Losses associated with heat flow through the panel were taken into account. It was essential to ensure that the final heat flow data accurately represented the panel's thermal performance. One significant aspect to address was the heat loss through the perimeter of the test panel frame. It was crucial to account for frame losses, and these losses had to be subtracted from the raw heat flow values. To calculate these frame losses, characterization panel test data was utilized, where a panel with a known R-value (characterization panel) was placed in the RGHB. This data allowed for frame losses to be quantified based on the air temperature gradient across the TABE test panel.

Although the metering area totaled 8 x 8 ft. (2.44 x 2.44 m), the panel had to be slightly trimmed to allow for clearance when fitting the panel into the frame (7.9 x 7.9 ft (2.4 x 2.4 m)). To prevent any potential gaps between the panel's perimeter and the test frame, gaps were carefully sealed with spray foam. The area sealed with spray foam introduced its own heat flow path, which was unrelated to the TABE panel's thermal performance. Therefore, this additional heat flow needed to be subtracted from the raw heat flow values.

By accounting for these losses, heat flow values were obtained that would genuinely reflect the heat flow through the TABE panel itself. Figure 4 shows the magnitude of losses subtracted from the raw heat flow data and the corresponding corrected heat flow data This process ensured that the data collected was precise and representative, allowing for a more accurate assessment of the panel's thermal characteristics in both the TABE baseline and operational cases.

With the corrected heat flow ($\dot{Q}_{corrected}$), the effective R-value of the metal-skin TABE panel (R^{eff}_{panel}) was evaluated using Equation 1:

$$R^{eff}_{panel} = \frac{A_{panel}\left(T_s^{MC} - T_s^{CC}\right)}{\dot{Q}_{corrected}} \tag{1}$$

where, A_{panel} is the area of the panel, T_s^{MC} and T_s^{CC} are the panel surface temperatures on the MC and CC sides, respectively.

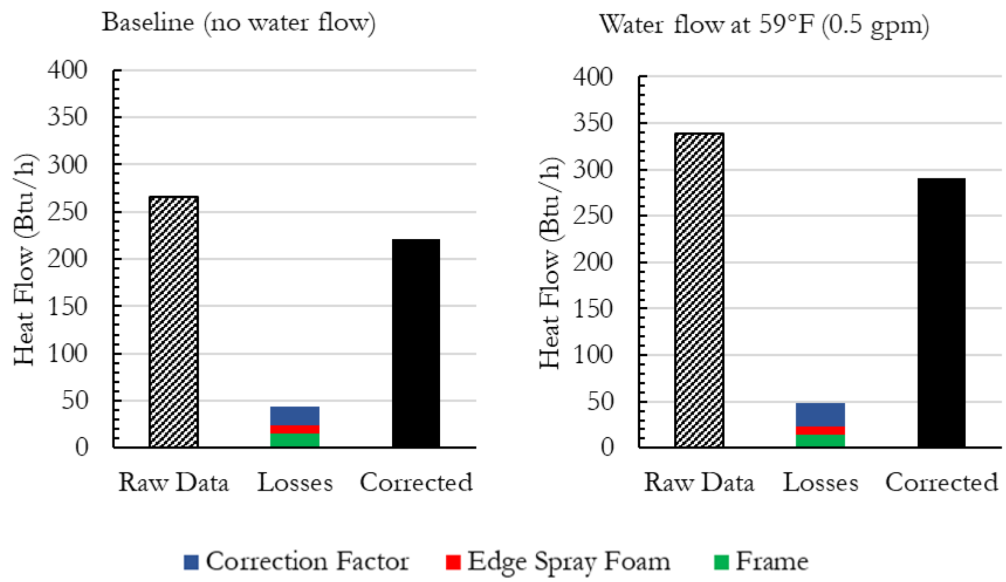
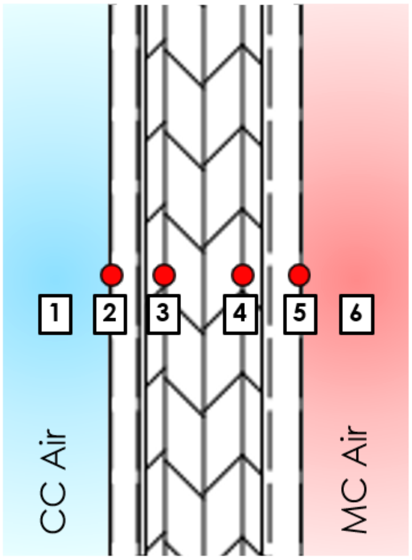


Figure 4 Losses in heat flow through TABE panel during RGHB testing for baseline and water flow cases.

Once the necessary corrections to the heat flow data were completed, focus shifted towards evaluating the performance of the system in baseline conditions. This assessment aimed to determine the effective panel R-value, a crucial factor in understanding the panel's thermal behavior. To achieve this, ASTM C518 standard (ASTM 2021) tests were conducted on each of the insulative layers within the system. These tests were instrumental in determining the temperature-dependent thermal conductivity of each individual layer. Temperature data collected from the RGHB experiments (Figure 5) was then averaged across each insulation layer, and this information was subsequently integrated with the results from the C518 tests. This combination allowed calculation of the R-value for each insulation component. These individual R-values were then aggregated, creating a comprehensive picture of the overall thermal performance of the panel. This comprehensive value was then compared to the panel's effective R-value, which was calculated using data from the RGHB experimental study (Figure 6). This comparison provided a meaningful assessment of how well the actual performance aligned with the expected thermal behavior. Effective panel R-value was found to be slightly over R-2 lower than the expected total insulative value of R-14.3. This is a reasonable results after accounting for the expected thermal bridging due to the hydronic loop placement and through-fasterners in the TABE assembly.



Number	Description	Baseline Temp (°F)
1	CC Air	66.9
2	Panel Exterior (CC)	68.1
3	Panel Interior (CC)	78.1
4	Panel Interior (MC)	101.8
5	Panel Exterior (MC)	111.2
6	MC Air	113.3

Figure 5 Temperature averages through cross-section of TABE prototype panel.

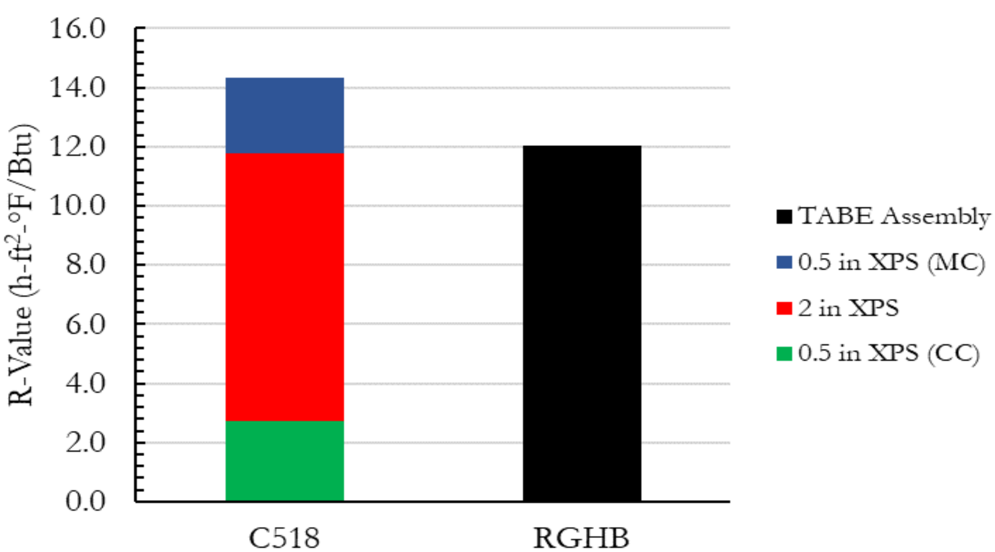


Figure 6 Comparison of C518 determined R-values of insulation layers and TABE panel effective R-value.

The assessment of the panel's R-value was not applicable when the hydronic loops were operational. In this specific case, a flow of water at 59°F (15°C) was circulated through the hydronic loops, maintaining a flow rate of 0.5 gpm (3.79 l/min). The RGHB experimental chambers were purposed as follows for this study. The CC side effectively mimicked indoor air conditions and the MC side mimicked summer outdoor conditions including heat gain due to solar radiation. The primary objective of this experimental case was to demonstrate that fluid flow through the hydronic loops had the capability to extract more heat than what was absorbed from the 'outdoor conditions' on the

MC side. The desired outcome was to achieve a net heat removal effect on the CC side, effectively illustrating that the TABE panel could contribute to cooling the indoor space. The results of this experiment, as depicted in Figure 7, demonstrated the successful attainment of this objective. These results indicate that the given TABE panel design was capable of generating a net heat removal effect on the indoor environment. This result holds significant implications, as it highlights the potential of the TABE system to save substantial amounts of cooling energy during operation, which is particularly valuable in hot summer conditions.

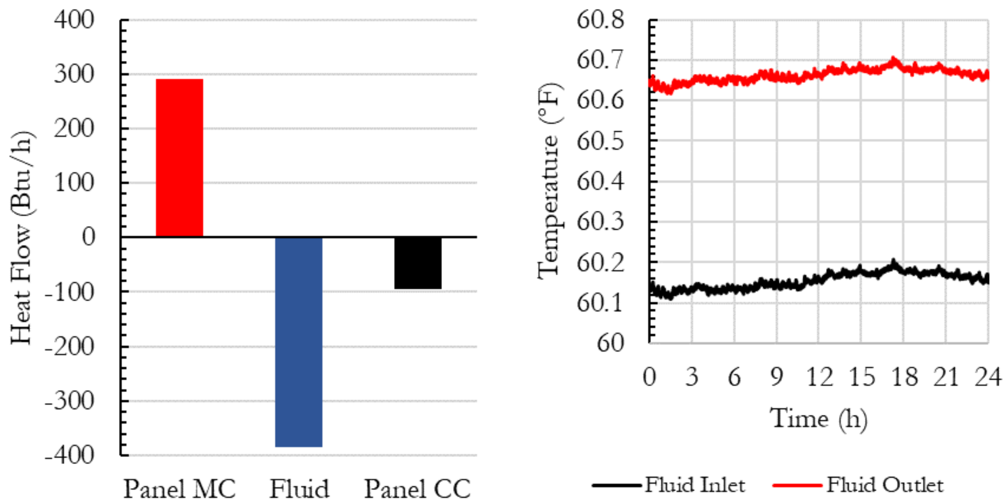


Figure 7 Heat flow through operational TABE panel given constant fluid flowrate and inlet temperature.

CONCLUSION

Results obtained from testing conducted in the RGHB provided valuable insights into the performance of the TABE panel utilizing panelized metal construction. When fluid flow was introduced into the hydronic loops, the TABE system demonstrated the capability to extract significant heat from the panel resulting in a net negative heat gain on the opposing surface. Overall, this research shows that new metal-skin TABE technology has the potential to significantly enhance energy efficiency, reduce cooling energy consumption, and improve thermal comfort within building envelopes. By addressing limitations in both traditional hydronic systems and previous TABE designs, this latest prototype demonstrates metal-skin TABE's potential as a promising solution for sustainable and efficient building design, opening the door to a greener and more comfortable future in the realm of construction and thermal management.

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