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Hydronic Shell: An Affordable Solution for Multifamily Deep Energy Retrofit

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January 2025

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Buildings and Transportation Science

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January 2025

Prepared by
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managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR2272

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ABSTRACT

Approximately 42% of multi-family buildings in the United States have do not have insulation as required by the building codes. Envelope retrofits of these buildings are needed to improve their thermal performance, provide thermal resilience, and enable a pathway to electrification of space heating systems. Hydronic shell (HS) is a retrofit technique where a stud wall layer is added to a masonry wall along with a convective coil and a fan coil unit fitted in the façade cavity which can provide both heating and cooling to the space. The HS system serves a dual purpose of 1) retrofitting the building envelope and 2) retrofitting the HVAC system and enabling electrification of space heating. The electrification of space heating is possible from the installation of a combination of hydronic system/fan coil unit system which uses a central heat pump as a source of heating water in the cavity between the existing wall and retrofit insulation layer. This study evaluates the performance of the HS system at varying outdoor conditions mimicked by a climate chamber and hot water supply temperature from a water bath. During the ramp-up period, the indoor chamber temperature could be increased from 66 ºF to 69.5 ºF within an hour using heating water at 120 ºF when the outdoor chamber temperature was at 0 ºF. When the indoor chamber temperature was maintained within a deadband, variation in cavity air temperature was mostly influenced by the duration when water was flowing through the cavity convector. It was seen from the testing that the hydronic system alone without use of fan in the system is able to maintain the space temperature at coldest outdoor condition used in the experiment (0 ºF) even at lowest hot water supply temperature chosen (90 ºF). During the ramp-down period, the fastest decline in temperature took 6.4 hours from temperature to drop from 69.6 ºF to 66 ºF which shows tremendous potential of thermal resilience and peak load shifting.

1. INTRODUCTION

The rising threat from climate change resulted in the Paris Agreement which has a target of "*holding the increase in the global average temperature to well below 2 ºC above pre-industrial levels*" (United Nations Framework Convention on Climate Change 2015). The U.S. Department of Energy has a goal to reduce the greenhouse gas (GHG) emissions in buildings, 65 % by 2035 and 90% by 2050 compared to the 2005 baseline (U.S. Department of Energy 2024). Electrification of buildings with heat pumps is one of the key strategies for reducing the on-site fossil fuel-based heating system. The electrification of buildings end-uses currently using fossil fuel will enable the use of renewable energy sources like wind and solar for these end-uses. However, the electrification of buildings will significantly increase the electrical load in heating dominated climate (Mumme et al. 2022).

According to the 2020 residential energy consumption survey there are approximately 32 million multi-family buildings in the U.S. , approximately 42% of these buildings are poorly insulated or do not have any insulation (US EIA 2020). A study shows that for multi-family buildings in the United States, approximately 85% of the building's primary energy use can be explained by the variance in the building envelope thermal properties (Hu et al. 2022). This study also suggests three technologies from Finland that can be used in the United States to improve building energy efficiency in cold and very cold climate regions which are improving building envelope thermal properties, use of efficient heat recovery ventilation systems, and use of heat pump systems in well-insulated buildings. Appropriate retrofits are needed for buildings with low thermal performance to prevent/alleviate any stress on the electric grid. Energy-efficient buildings also play a crucial role in both building and grid resilience i.e. lowering the potential of outage during extreme weather (Li et al. 2024) and keeping the space habitable for a reasonable duration during any outage (Lee et al. 2024). A study on the thermal refurbishment of residential buildings based on energy simulation shows for old apartment buildings façade retrofit is the most effective retrofit action compared to retrofitting roofs, floors, or windows (Ponechal, Jandačka, and Ďurica 2024).

Studies discussed above focus either on building envelopes or equipment retrofits. The Hydronic Shell (HS) system discussed in the next section is a solution that can meet the target of envelope target in tandem with equipment retrofit/building electrification. It is a solution that was developed and optimized for a typical affordable multifamily housing typology with simple rectilinear geometry, masonry wall and punched windows. In this work, we evaluate the thermal performance of the HydroBox HVAC unit and the hydronic convective coil within the façade cavity, including the heat transfer and thermal storage capabilities of the masonry wall that represents the existing wall of a retrofitted masonry building. A full-scale Hydronic Shell façade panel with integrated HVAC components was built and tested in the heat and moisture (HAM) chamber at ORNL (Boudreaux et al. 2019) for performance testing. The ultimate objective of the technology demonstrate that the Hydronic Shell solution can enable space heating electrification retrofits of multifamily buildings in cold climates with the use of an exterior hydronic heating panel.

2. TECHNOLOGY DESCRIPTION

Hydronic shell is a retrofit technique where a stud wall layer is added to a masonry wall along with a convective coil and a fan coil unit fitted in the façade cavity as shown in Figure 1. The retrofit envelope includes an R-25 wall layer with and triple pane window. The integrated HVAC unit will turn on/off a valve to start/stop water flow in the cavity convector and the HydroBox equipped with a variable-speed fan. The cavity convector will be used as the primary source to heat/cool the space and the fan in the fan coil will be a secondary unit which is activated when the cavity convector cannot meet the space heating/cooling needs. The water coming to the cavity convector and HydroBox will be pre-conditioned using a heat pump.

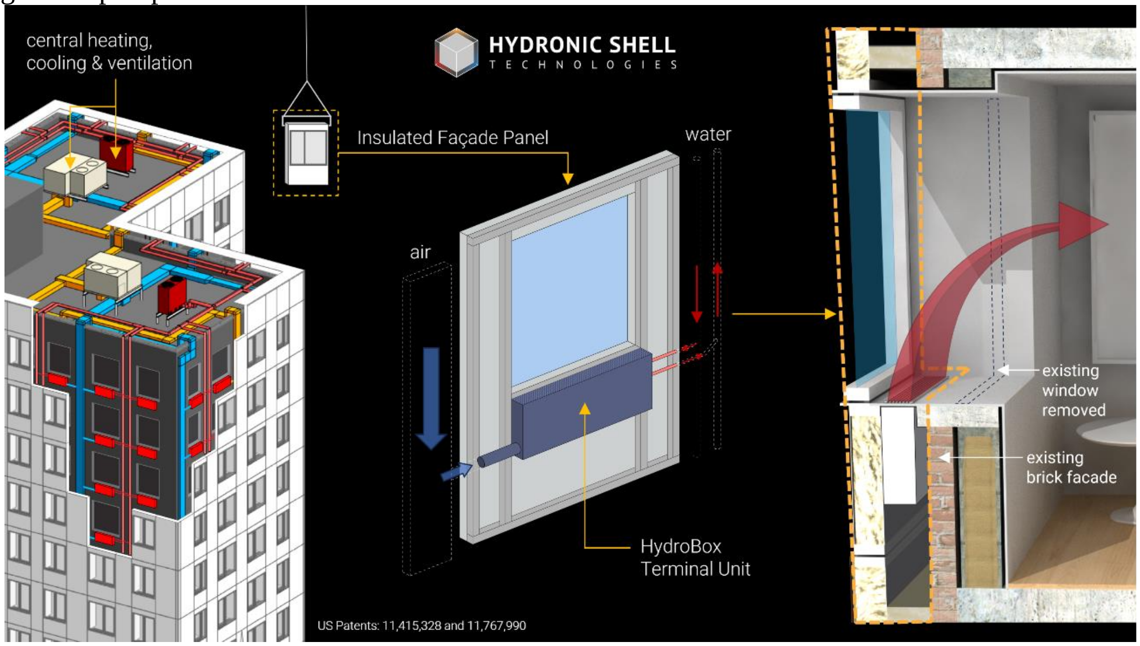


Figure 1. Hydronic Shell system added to the Masonry Facade

3. EXPERIMENTAL EVALUATION METHODOLOGY

Experimental testing was carried out in the heat and moisture (HAM) chamber of ORNL. The following tasks were executed as part of the experimental testing.

3.1 TEST APPARATUS (HAM CHAMBER)

HAM chamber (Figure 2) has two chambers named indoor chamber and climate chamber in between which a frame with an 8 ft × 10 ft opening can be inserted. The opening of the frame is used to build/install a test wall of interest. The temperature, relative humidity, and pressure of both indoor and climate chambers can be controlled. For this test, the climate chamber temperature was controlled using the native controller for the HAM chamber, and the indoor chamber was controlled using the HS system which is discussed in the upcoming sections.

Figure 2. HAM chamber with indoor chamber (left) and climate chamber (right)

3.2 DATA COLLECTION AND MONITORING

Several variables were monitored and the data was collected at 1-minute intervals for the analysis. A list of instruments/sensors that were used for the testing is listed in Table 1. Data acquisition (DAQ) systems were used to log the relevant data from the sensors/instruments listed in the table. A DAQ system was also used for on/off control of the valve to control the water flow into the Hydrobox.

Table 1. Sensors and instruments used for the experimental testing

Sensor/Instrument	**Description/Purpose**	**Model**	**Range**	**Accuracy**
Water bath/circulator	Heat the water and circulate it inside the Hydrobox	Sahara AC200-S14P	Ambient +23 to + 302 (ºF)	± 0.018 ºF (temperature stability)
Water flow sensor	Monitor the water flow rate	Omega FTB602	0.08 to 2.38 (gpm)	± 1%
Thermocouples	Measurement of air temperatures, surface temperatures, water inlet and outlet temperatures	Omega Type-T Thermocouples	-328 to 500 (ºF)	1.8 ºF or 0.75%
Relative humidity sensor	Monitor the relative humidity in the cavity between the existing and retrofit wall layer	Honeywell HIH-4000	0 to 100 (% RH)	± 3.5%
Heat flux sensors	Installed to measure heat flux in the wall surface facing the indoor chamber	HFS50	-21°F to +300 (°F)	± 5%

3.3 TEST ARTICLE PREPARATION

First, an 8 ft × 10 ft test wall was prepared which included an "existing" masonry façade and retrofit overclad façade. The HVAC system including the cavity convector and fan coil unit was attached to the interior side of the retrofit overclad façade. The "existing" masonry façade is shown in Figure 3, where several thermocouples were added to monitor the air and surface temperatures in the 6" cavity between the brick wall layer and R-25 insulation-filed stud wall layer.

Figure 3. Wall representing "existing" masonry wall with one CMU layer and a brick layer: before installation of the hydronic shell

Next, the hydrobox and exterior retrofit wall layer were added to the wall to represent the changes that will be made by the hydronic shell system. First, the hydrobox was fastened to the wood frame wall used for the exterior stud wall (Figure 4). Then, the exterior retrofit wall layer was installed maintaining a 6-inch distance from the brick wall. The finished test wall after installation of the hydrobox and exterior retrofit wall layer is shown in Figure 5. The thermocouples and heat-flux were added to the exterior surfaces of the wall (indoor and outdoor side) for monitoring surface temperature and heat flow rate. The layout of sensor instrumentation in the indoor side wall surface is shown in Figure 5.

Figure 4. Installation of hydrobox

Figure 5. Wall after installation of hydrobox and insulation layer

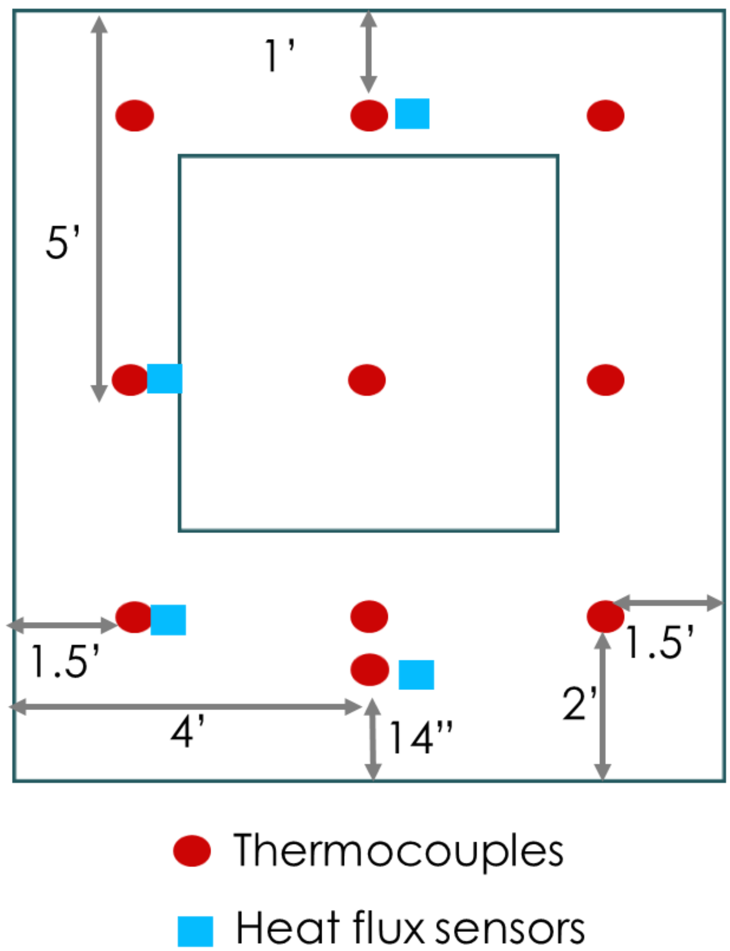


Figure 6. Layout of thermocouples and heat flux sensors on the indoor side

Next, for the testing, a Campbell Scientific CR1000 data logger was set up for the measurement and control of different variables. This data logger was used for the measurement of the water flow rate and for controlling the fan and valve inside the hydrobox. The inlet and outlet port from the hyrdobox was connected to PEX tubes and routed from the windowsill to the indoor side of the test wall (Figure 7). As shown in Figure 7, an Omega FTB602 water flow sensor was installed in the piping going to the inlet of the hydrobox to measure the water flow rate. A Sahara AC200-S14P water batch was connected to the hydrobox as shown in Figure 8. The water bath can heat an operating fluid up to 180 ºF. For our testing, we used distilled water as the operating fluid. The hydronic loop with water bath, piping, and hydrobox was operated to check if the capacity of the internal pump in the water bath was enough to circulate the water in the hydronic loop and for any potential leakage. The internal pump was able to circulate water through the loop which eliminated any need for an external pump to circulate the water and no leakage was present in the hydronic loop. A couple of relays have also been added inside the box containing the CR1000 data logger to control the on/off position for the fan/valve inside the hydrobox.

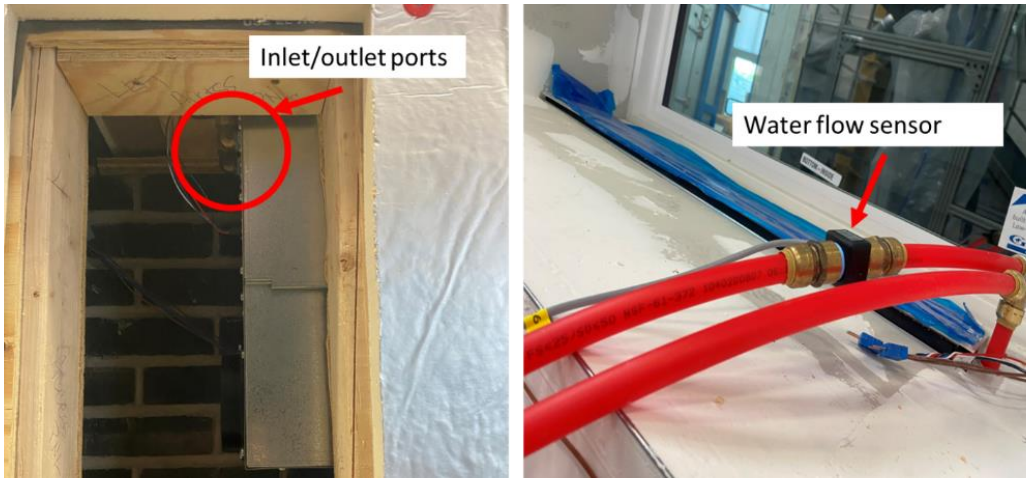


Figure 7. Hydrobox inlet and outlet port (left); Pex tubes connected to the Hydrobox routed from window sill (right)

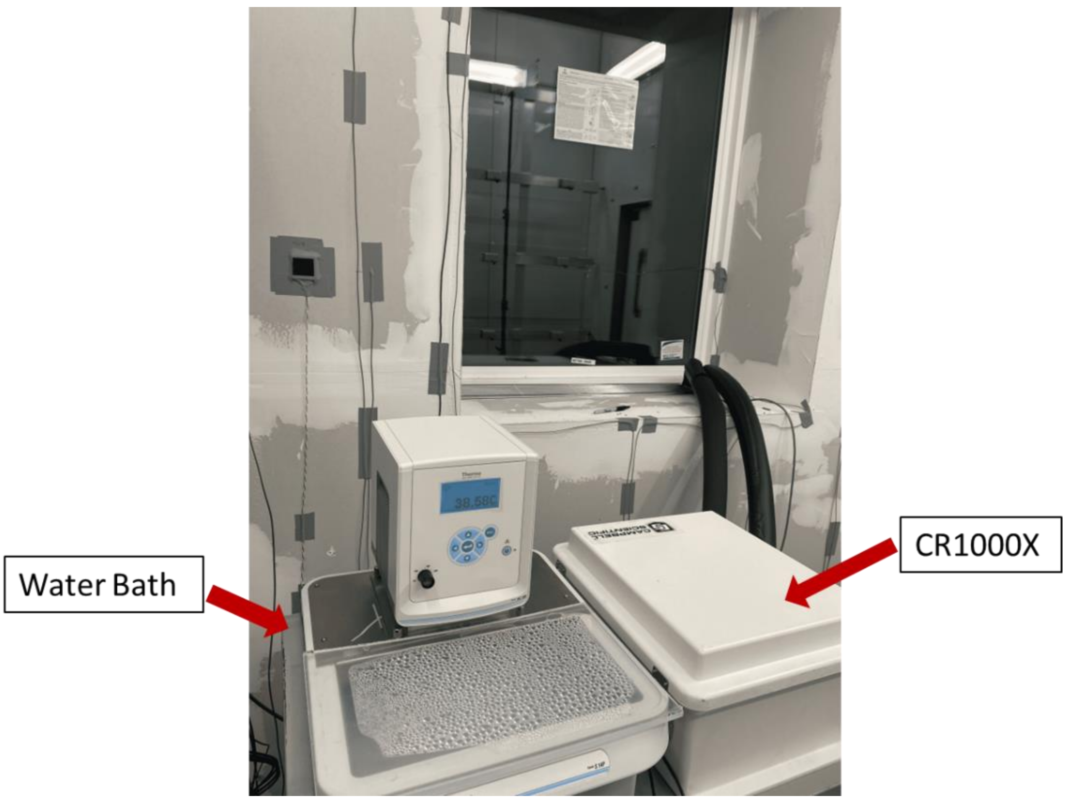


Figure 8. Test wall inside the HAM chamber with water bath and data logger for testing.

3.4 TEST VARIATIONS

The climate chamber was controlled to vary the outdoor temperature and the water bath was controlled to vary the hot water supply temperature. Different tests and the respective variables used for the testing are listed in Table 2. The tests were conducted to see how the indoor temperature, cavity temperature and surface temperatures were impacted by climate chamber temperature and supply water temperature. Test9 was conducted to check the impact in indoor and cavity temperature when the water was constantly supplied to the Hydrobox instead of switching it On/Off. The medium speed for the pump was used for the first three tests because, at 30 ºF climate chamber temperature, the indoor chamber temperature had very low or no heating requirement. The wall insulation > R-25 and the internal heat gain from the water bath in the indoor chamber could be the reasons that there is no heating requirement at 30 ºF climate chamber temperature.

Table 2. List of tests and their corresponding variable

Test	Supply water temperature (°F)	Climate chamber temperature (°F)	Pump speed
Test1	90	30	Med
Test2	105	30	Med
Test3	120	30	Med
Test4	90	10	High
Test5	105	10	High
Test6	90	0	High
Test7	105	0	High
Test8	120	0	High
Test9*	105	0	High

**In this test water is supplied constantly unlike turning On/Off that was done for other tests*

The indoor chamber temperature was controlled by turning on/off the valve, thus leaving the supply water flow on/off. The valve was controlled to maintain an indoor chamber temperature of 70 ºF with a deadband of 0.5 ºF. Figure 9 shows the relationship between the indoor room temperature and the supply water flow rate. The figure shows that the supply water flow is on until the temperature reaches 70 ºF + 0.5 ºF and turns off until the temperature drops to 70 ºF - 0.5 ºF.

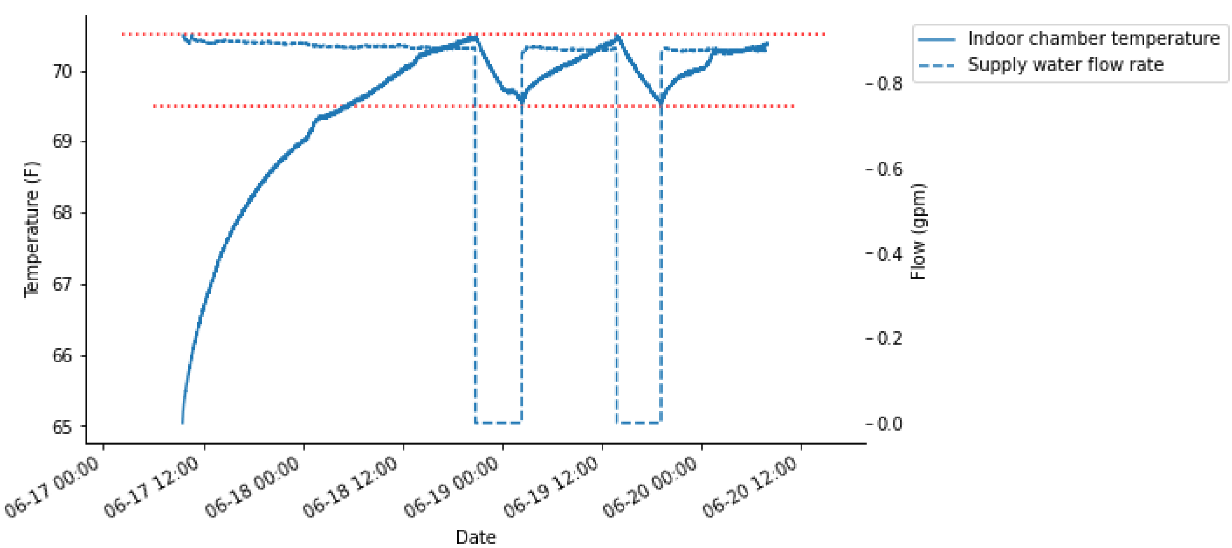


Figure 9. Indoor chamber temperature and supply water flow rate (Test4)

4. RESULTS

For each of the tests, the data was broken into the following three parts

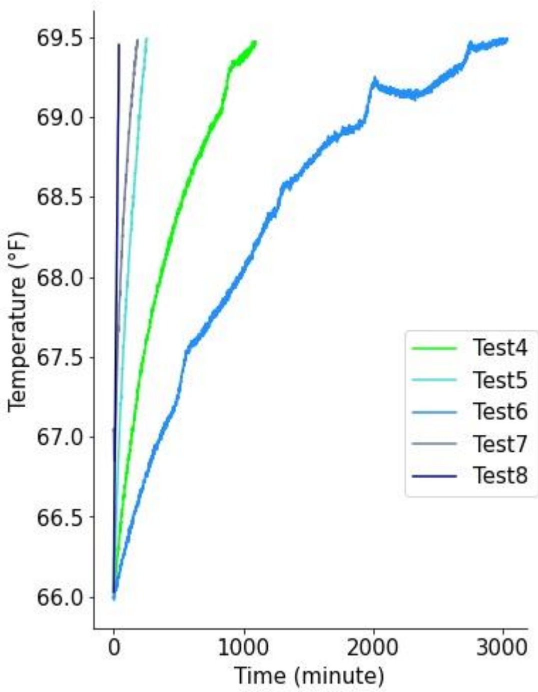
- Ramp-up: The period when the heater starts until the indoor room temperature reaches the lower limit of temperature setpoint deadband.
- Cycling: The period when the indoor room temperature is higher than the lower limit of temperature setpoint deadband. Here, the temperature of the room cycles as a result of turning on/off of water flow rate using valve control.

- Ramp-down: The period when the heater is turned off and the indoor room temperature is allowed to drop.

4.1 CHAMBER TEMPERATURE

4.1.1 Ramp-up and ramp-down

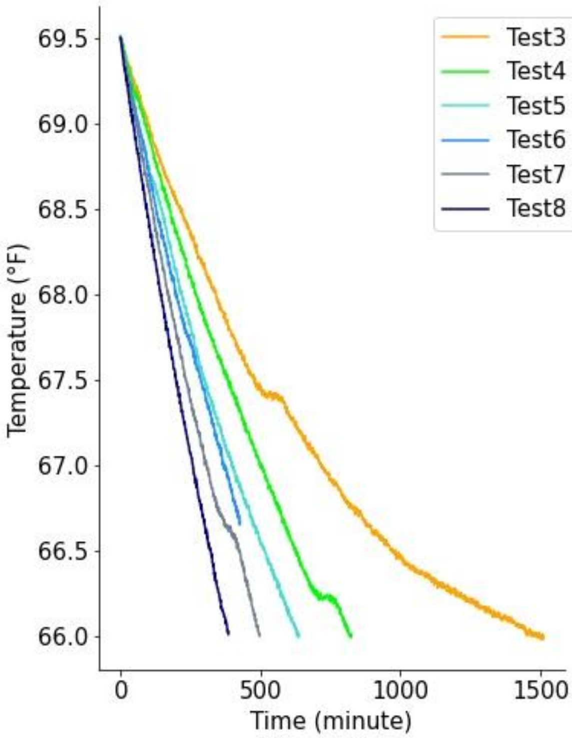
The ramp-up and ramp-down operation was performed for a few tests to see the temperature rise and decline at different outdoor chamber temperatures. The Hydrobox fan was turned on only for ramp-up operation of Test9 which is discussed in later section, for all other tests discussed in this section the fan was left off. The results for temperature increase and temperature decrease during this operation are shown in Figure 10 and Figure 11. Figure 10 shows the slowest rise in temperature (approximately 50 hours to raise the temperature from 66 ºF to 69.5 ºF) for Test6 with the lowest climate chamber temperature (highest higher heating energy demand) and lowest water temperature (slowest heating rate). The second slowest rise in temperature was seen for Test4 (which took approximately 18 hours) with a chamber temperature of 10 ºF. For other tests, the temperature rise was comparatively faster with the fastest temperature rise for Test8 which uses hot water at 120 ºF.



Test	Climate chamber temperature (°F)	Water temperature (°F)	Rate of change (°F/hr)
Test4	10	90	0.19
Test5	10	105	0.82
Test6	0	90	0.07
Test7	0	105	0.79
Test8	0	120	5.0

Figure 10. Temperature rise for different tests (left); Climate chamber temperature, heating water temperature, and rate of temperature change for each test (right).

Figure 11 shows that the slowest decline in temperature is for Test3 because of the higher climate chamber temperature compared to other tests. Test4 and Test5 with climate chamber temperature at 10 ºF also have a slower decline in temperature compared to the tests using 0 ºF as climate chamber temperature. The fastest decline in temperature happens for Test8 for which it took 386 minutes (6.4 hours). Thus, it can be seen that the retrofitted walls can be used to provide thermal resilience in the event of an outage even at very cold outdoor temperatures of 0 ºF.



Test	Climate Chamber temperature (°F)	Rate of change (°F/hr)
Test3	30	0.14
Test4	10	0.25
Test5	10	0.33
Test6	0	0.4
Test7	0	0.42
Test8	0	0.54

Figure 11. Temperature decline for different tests (left); Climate chamber temperature and rate of temperature change for each test (right).

4.1.2 Cycling

Figure 12 shows the cycling of the indoor chamber temperature and corresponding water flow rate for tests with varying combinations of climate chamber temperature and water temperature. The Hydrobox fan was left off during all the time when the indoor chamber was cycling between the deadband of the temperature setpoint. The figure shows at 30 ºF climate chamber temperature, the water temperature at 90 ºF needs to be supplied almost one-third of the time to maintain the indoor room temperature. When the water bath is at 105 ºF, this supply needs to be there for a very short duration. The water at 90 ºF takes a longer time to raise the temperature from 69.5 ºF to 70.5 ºF when the climate chamber is at 10 ºF (Test4) compared to the climate chamber at 30 ºF (Test1). This phenomenon occurs even though the flow rate at Test4 is higher than the flow rate at Test1.

It can also be seen that the duration of the hot water supply increases as the climate chamber temperature reduces. For example, at 0º F climate chamber temperature, the hot water supply at 90 ºF is ON for most of the duration but still it is not able to raise the temperature above ~69.75 ºF.

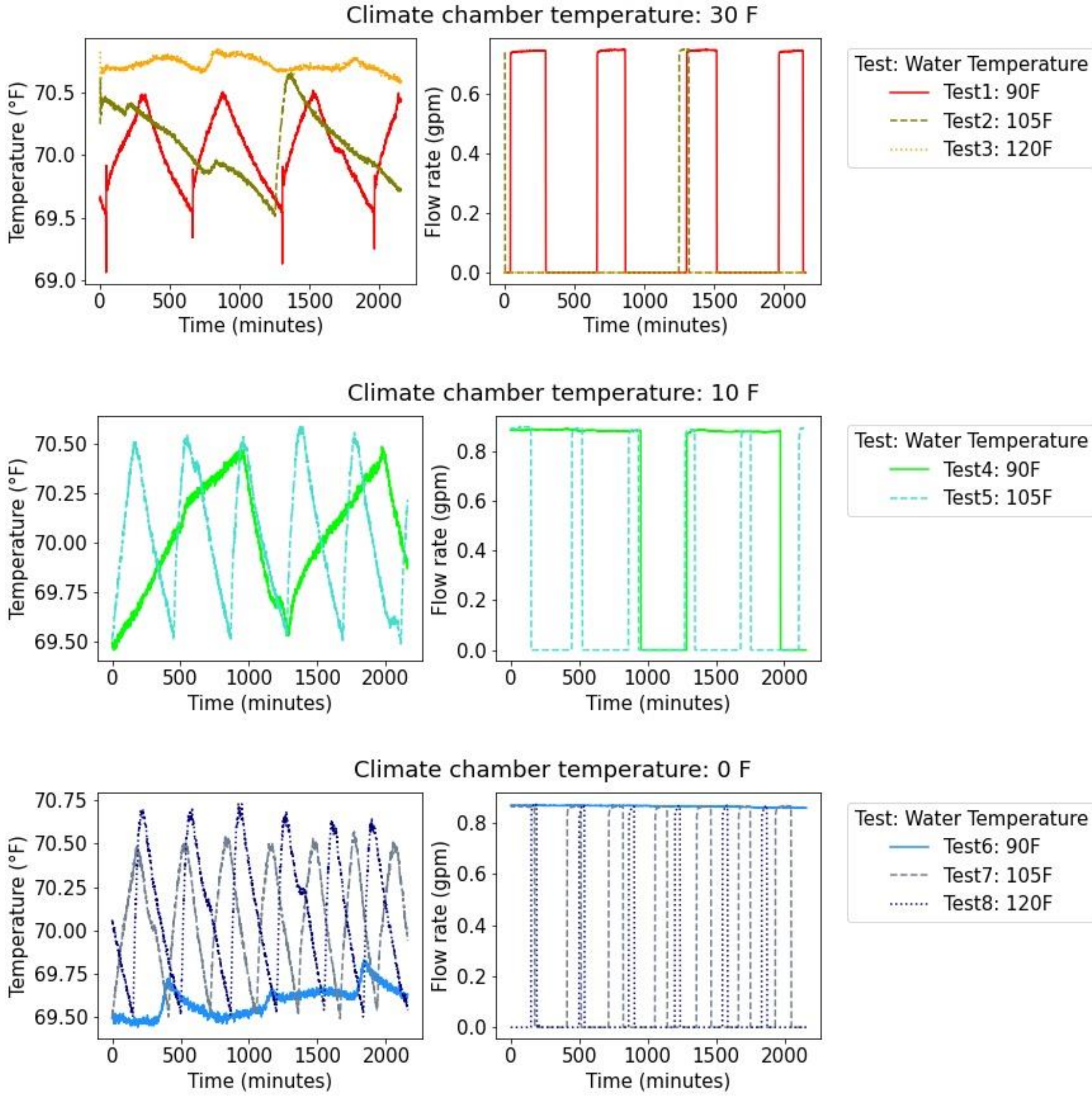


Figure 12. Indoor chamber temperature and supply water flow rate at varying climate chamber temperature and supply water temperature

4.2 HEAT FLUX AND SURFACE/AIR TEMPERATURES

4.2.1 Cycling

The results for heat flux from the indoor chamber towards the climate chamber, at the indoor chamber side wall surface, are shown in Figure 13. This result is shown for the period when the indoor room temperature is cycling with the deadband of ± 0.5 ºF for a 70 ºF temperature setpoint. It can be seen that for a given climate chamber temperature, the average heat flux is generally higher for higher hot water temperatures. This occurs because, at higher hot water temperatures, the water bath operates for less amount of time resulting in lower cavity temperature (Figure 14). Hence, there is higher heat transfer from the indoor side towards the cavity.

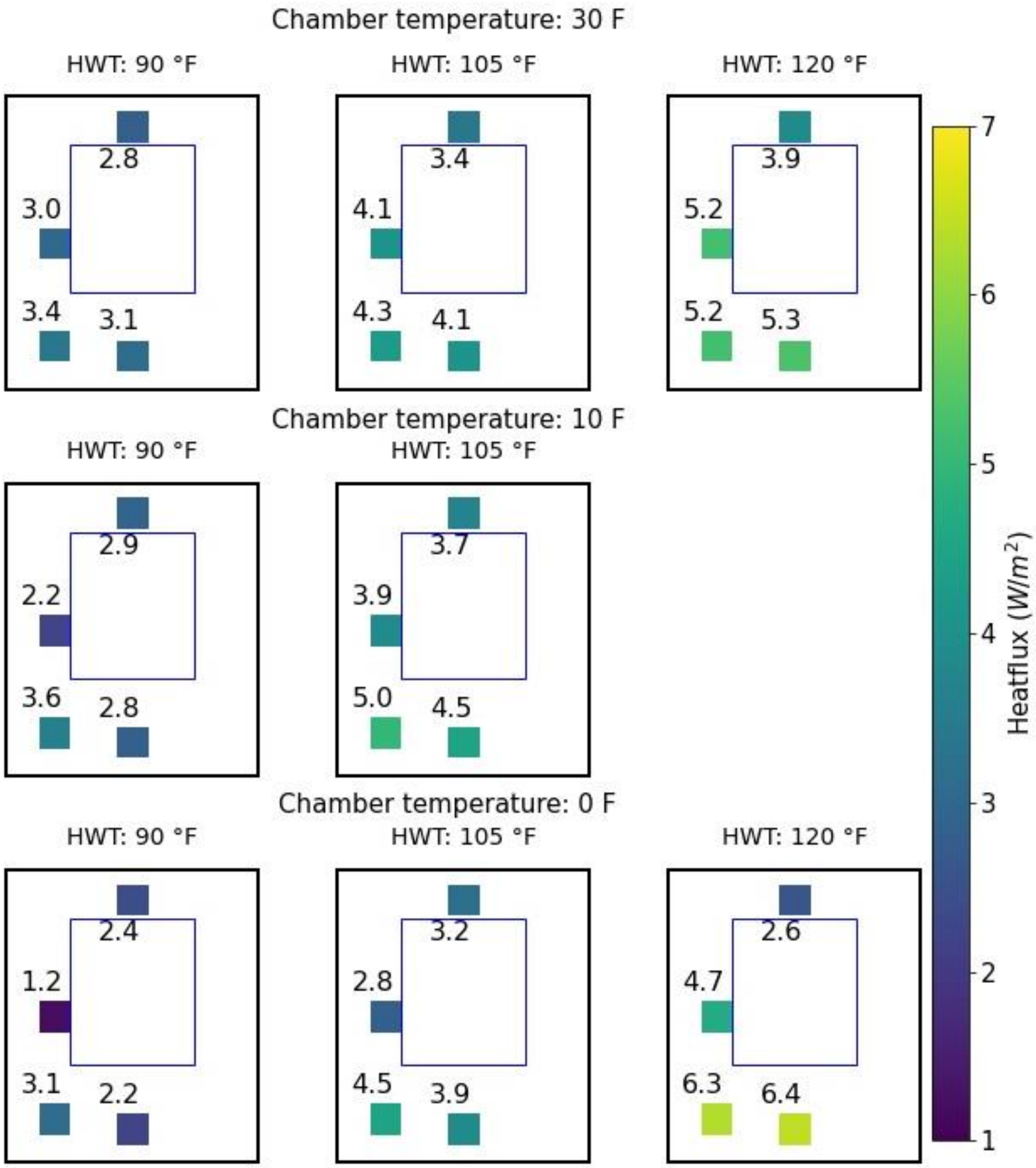


Figure 13. Average heat transfer during the cycling period (Note: HWT=heating water temperature)

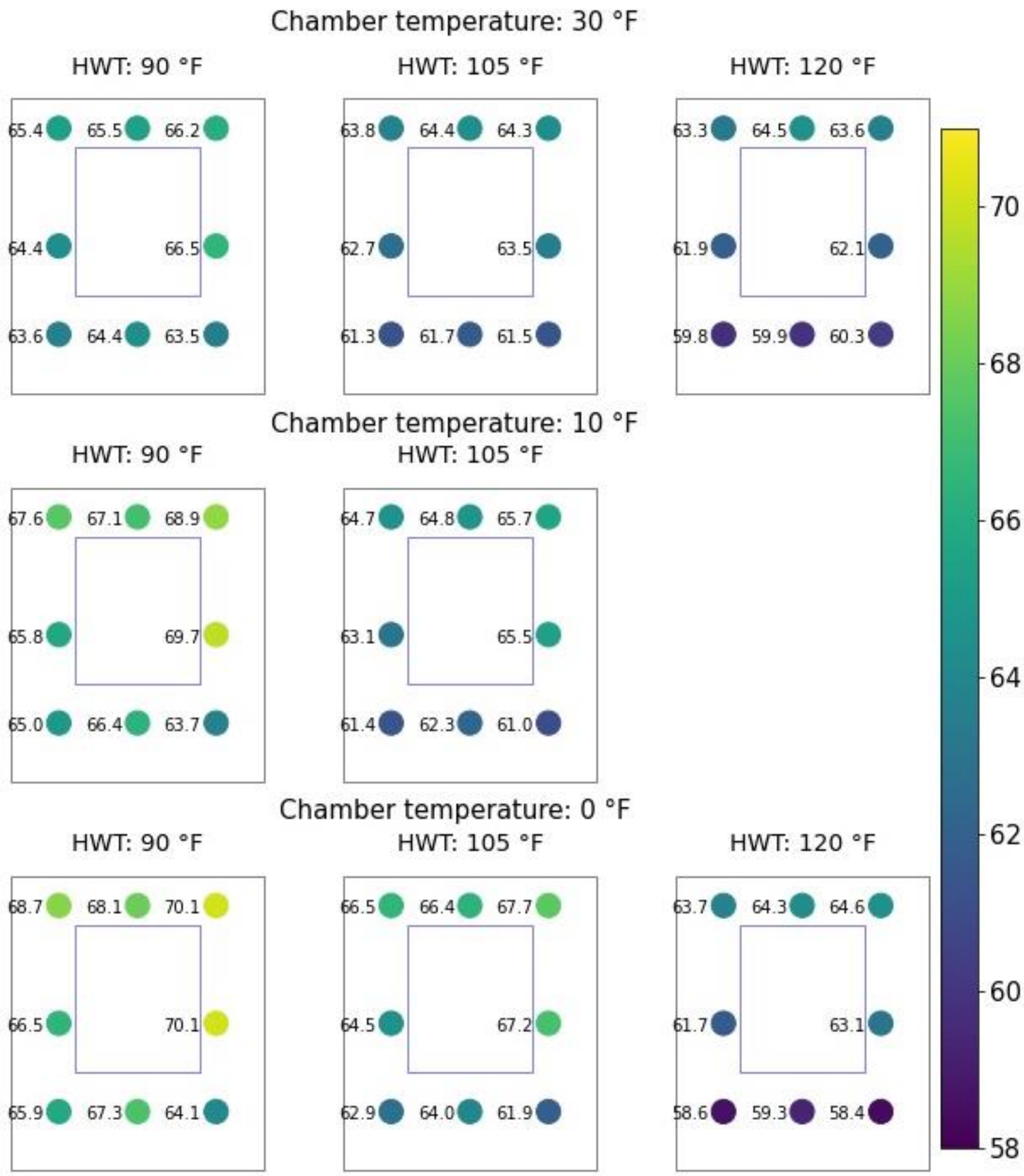


Figure 14. Average cavity air temperature during the cycling period

Figure 15 shows the distribution of temperature at various locations in the wall surface facing the indoor chamber. The distribution shows the wall surface temperature is evenly distributed in comparison with cavity air temperature (Figure 14) where more variation is seen. The window surface temperatures (at the center of the grid) have higher differences at different climate chamber temperatures. This heat transfer from the window might be one of the reasons for the requirement of higher heating at lower climate chamber temperatures.

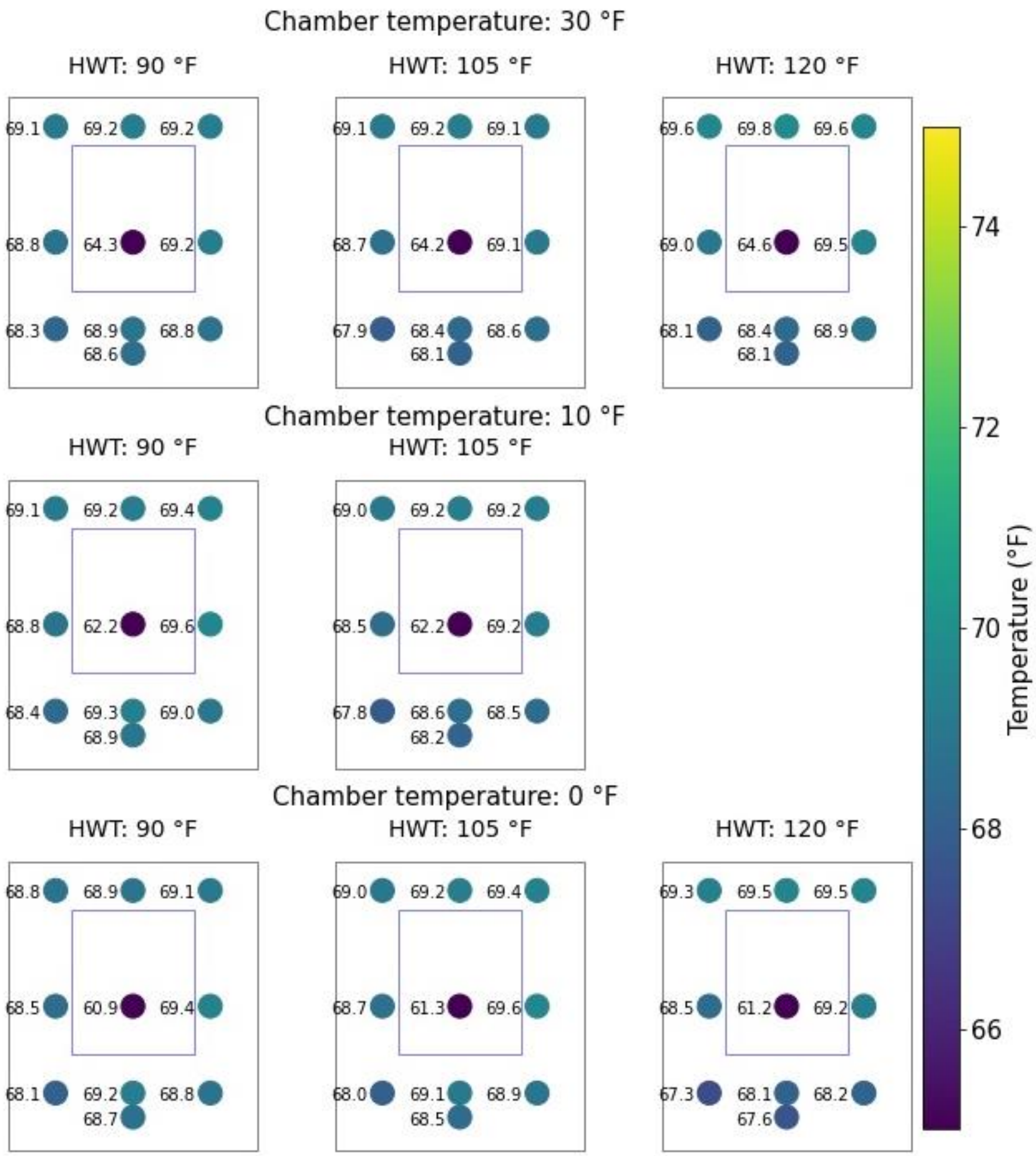


Figure 15. Average indoor side surface temperature during the cycling period

4.3 DELIVERED ENERGY CONSUMPTION

The delivered energy consumption result is calculated for the ramp-up and cycling period. During the ramp-down period the water bath was turned off so there was no energy consumption. The energy consumption was calculated based on the temperature difference of supply water from return water, water flow rate, and energy consumption from fan (whenever applicable). Note that the energy consumption for the pump is not calculated and the internal heat gain in the indoor chamber from the water bath was not monitored in this study.

4.3.1 Ramp up

For ramp-up, the total energy consumption for raising the temperature of the indoor chamber from 66 ºF to 69.5 ºF was calculated as shown in Table 3. The energy consumption needed for ramp up is higher for lower chamber temperature which results in higher heating load in the indoor chamber. The energy consumption was highest while using hot water at 90 ºF for heating and lowest while using 120 ºF for heating. One of the reasons for this might be prolonged periods when the wall would be exposed to outdoor conditions (climate chamber weather) for a longer duration taken by water at 90 ºF to ramp up the temperature compared with higher temperature supply temperature for hot water. The table also lists Test9 where a fan is used for forced convection to increase the rate of heating. This test is identical to Test7 in terms of boundary conditions except for the fan operation. It can be seen that by using the fan the temperature can be ramped up faster (Figure 16) and with lower energy consumption (Table 3). In Figure 16, for Test9 once the temperature reaches 69 ºF and the fan is turned off, the rate of ramp-up of temperature reduces.

Table 3. Energy consumption for the ramp-up period for different tests

Test	**Energy consumption (Wh)**	**Climate Chamber temperature (ºF)**	**Water temperature (ºF)**
Test4	1865	10	90
Test5	953	10	105
Test6	5119	0	90
Test7	714	0	105
Test8	301	0	120
Test9*	443	0	105
* for ramp-up the Hydrobox fan was ON at full speed until the indoor temperature reached 69 unlike other tests where they were OFF			

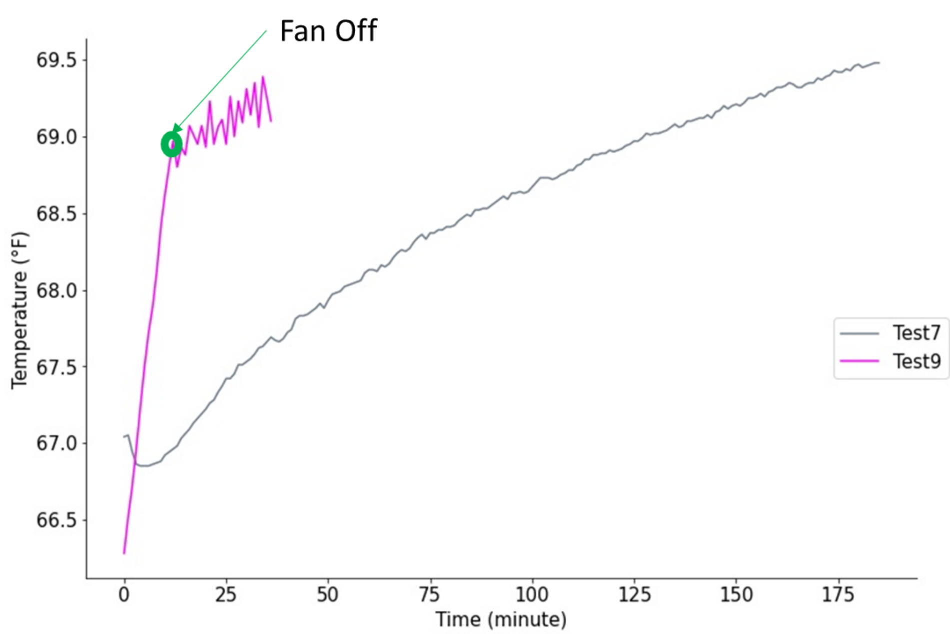


Figure 16. Indoor chamber temperature during the ramp-up period for Test7 and Test9

4.3.2 Cycling

Table 4 lists the energy consumption for 1 and ½ days for the cycling period for each of the tests. The energy consumption is higher for the lower chamber temperature as expected. The energy consumption for the same climate chamber temperature is higher for lower water temperatures. One of the reasons for this is at lower water temperature the hot water flow is present for a longer duration (Figure 12). Another reason is that internal load from the water bath to the indoor side is higher when heater is at higher temperature compared to water heater at lower temperature. The table also shows if the hot water supply is left continuously ON (Test9), then the energy consumption is almost twice compared to the case when it is cycled at the same boundary conditions (Test7). Figure 17 shows the rise in temperature of indoor chamber/cavity air for Test9 with a continuous hot water supply for approximately four days. The indoor chamber temperature rises to 74.4 ºF and the average cavity air temperature rises to 76 ºF. This higher temperature means it will take a longer time for the temperature to drop to 66 ºF than those seen in Figure 11 if such a mode of operation is chosen.

Table 4. Energy consumption for cycling period of 1 and ½ days for different tests.

Test	Energy consumption (Wh)	Climate Chamber temperature (ºF)	Water temperature (ºF)
Test1	1307	30	90
Test2	260	30	105
Test3	0	30	120
Test4	2468	10	90
Test5	1882	10	105
Test6	3059	0	90
Test7	2859	0	105
Test8	1548	0	120
Test9*	6684	0	105
*for cycling the hot water supply was provided continuously unlike for other tests where it was modulated to maintain indoor temperature at 70±0.5 ºF			

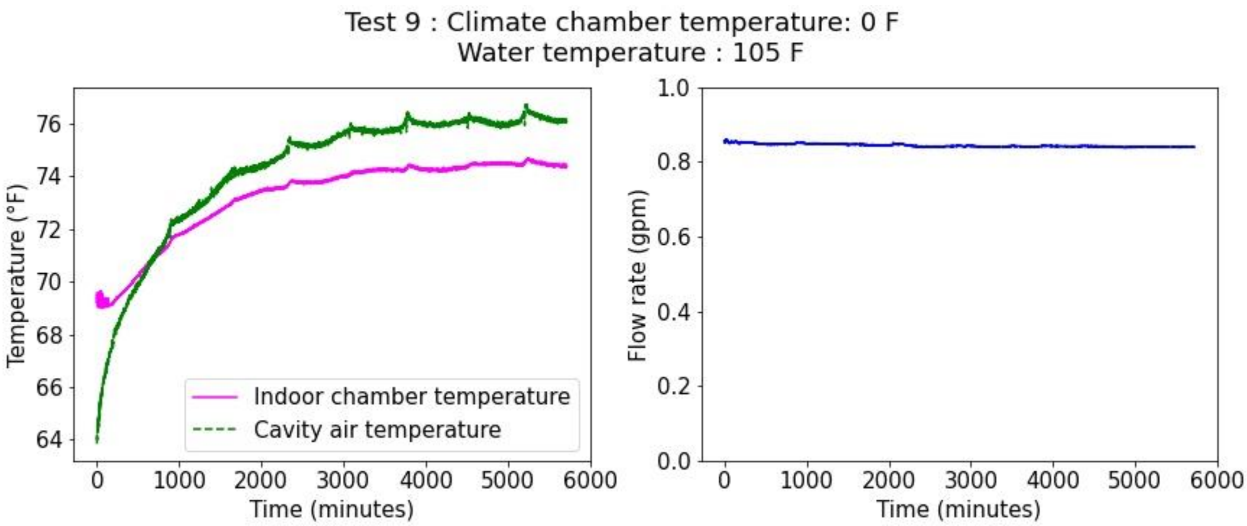


Figure 17. Indoor chamber/cavity air temperature and water flow rate for Test9 (Climate chamber 0 ºF and hot water temperature of 105 ºF)

5. SUMMARY

A wall representing an HS system retrofit over an existing masonry wall was built and tested in the HAM chamber at ORNL. The testing was done to evaluate the thermal performance of the system at different outdoor temperatures simulated by the climate side of the HAM chamber and hot water supply temperature. While elevating the temperature of the chamber from 66 ºF to 69.5 ºF at 0 ºF climate chamber temperature, the water at 90 ºF heated the chamber at a rate of 0.07 ºF/hr. For the same conditions, the heating of the chamber was significantly faster (5 ºF/hr) when the supply water was at 120 ºF.
The results also showed that in between the deadband of temperature setpoint, the water at higher temperatures showed higher cycling and less duration of water flow to the cavity convector. This also resulted in lower energy consumption by the system when supplying water at higher temperatures. At 0 ºF climate chamber temperature the energy consumption for hot water at 90 ºF was 3,059 Wh, which was 1,548 Wh for water at 120 ºF. During the ramp-down period, the fastest decline in temperature took 6.4 hours from temperature to drop from 69.6 ºF to 66 ºF which shows tremendous potential of thermal resilience and peak load shifting.

One of the limitations of the study is that the water bath supplying hot water to the cavity convector was located inside the indoor chamber, and the potential internal load due to heat loss from the water bath to the indoor room was not accounted for. Another limitation was that the energy consumed by the water bath pump was not accounted for, which would have resulted in higher energy consumption proportional to the duration of operation of the water bath which was higher at supply water at 90 ºF.

6. ACKNOWLEDGEMENTS

This material is based upon work supported by DOE's Office of Science and BTO. This research used resources of ORNL's Building Technologies Research and Integration Center (BTRIC), which is a DOE Office of Science User Facility. This manuscript has been authored by UT-Battelle LLC under contract DEAC05-00OR22725 with DOE. The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes.

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