Design and Commissioning of a Facility for Studying Next-Generation High Performance Building Technologies and their Interactions with Occupants

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ABSTRACT

Next-generation high-performance building technologies are envisioned where buildings are assembled on-site from factory-manufactured modular elements, which would lead to better quality control, less material waste, more predictable schedules, and consequent savings in cost and energy consumption. Prefabricated building elements would enable the cost-effective integration of climate-responsive building envelopes, localized thermal comfort delivery systems, and decentralized heating and cooling technologies such as wall-embedded micro-heat pumps, sensors, embedded intelligence, and networking, lowering the cost of resilient and decarbonizing technologies. These modular elements can integrate the smart technology needed to provide scalable, cost-effective solutions with autonomous, occupant-responsive, healthy, and sustainable features.

To explore and evaluate these new high-performance building technologies and study novel interfaces for their interaction with occupants, a new test facility has been designed and constructed. The facility has a modular construction layout utilizing reconfigurable thermally active panels for walls, floor, and ceiling. The interior surface temperature of each 3.05m × 1.22m (4 ft. x 10 ft.) panel can be controlled individually using a hot and cold water hydronic system. Based on the commissioning results, the controllability range of each panel surface temperature was achieved between 15°C to 35°C. This allows for formulating different climate zones, building type conditions, and enables studies on localized comfort delivery, occupant comfort control, active building materials, among others. This paper presents the overall design of the facility, controller tuning, and commissioning results.

1. INTRODUCTION

In the future, high-performance buildings are envisioned to feature advanced technologies that address sustainability, energy efficiency, modularity, and embedded intelligence. These next-generation buildings are expected to be designed for easy and fast on-site assembly using factory-manufactured modular elements. In comparison to conventional site-built homes, these factory-manufactured homes offer numerous advantages, such as accelerated construction time, customization options, and portability (Choi et al., 2019; Durdyev & Ismail, 2019; Khodabandelu et al., 2020). In addition, prefabrication modules can reduce material waste, energy use, and emissions of greenhouse gases during the construction process (Hong et al., 2016; Tavares et al., 2019; Ferdous et al., 2019). Moreover, these future high-performance, modular buildings should integrate new intelligent, localized, and energy-efficient comfort delivery systems, allowing occupants to control their surrounding space actively. Localized comfort systems can create a microclimate around occupants, providing accelerated comfort that can be conveniently adjusted to meet their personal needs leading to reduced energy use (Godithi et al., 2019; Wang et al., 2014). Also, Liu et al. (2021) have demonstrated that both energy and comfort can be improved through increased human-building interactions.

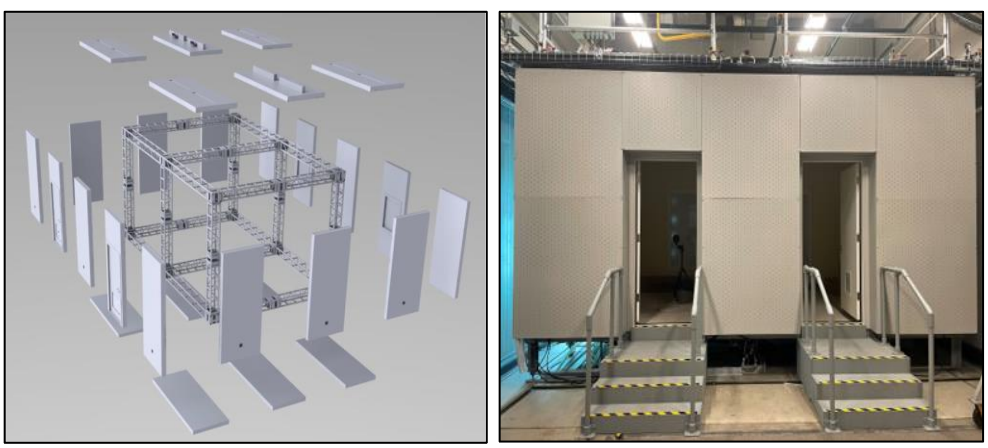
The development of the Human-Building Interactions Laboratory (HBIL) is motivated by an interest in studying the benefits of localized comfort delivery enabled by modular construction and advanced human-building interactions. Furthermore, HBIL is designed to be capable of integrating high-performance equipment, such as a wall-embedded micro heat pump (Wu et al., 2024) and embedded energy storage (Rathore et al., 2022), into the modular walls of this facility and studying its overall performance before integration within actual buildings. It can also be used to study advanced ways of interacting with buildings, such as through voice and/or visual wall-mounted devices (e.g., tablets, smart speakers, etc.). Finally, it can emulate conventional comfort delivery and environmental conditions representative of any climate within the U.S. to study occupant comfort.

Yadav (2022) discusses the design, construction, and installation of the HBIL facility and hydronic system design in detail. A radiant heating and cooling approach was chosen to provide localized thermal comfort delivery. Karmann et al. (2017) and Rhee et al. (2017) have shown that radiant systems have equal or better energy savings and provide better occupant comfort than conventional forced air-based systems. The test facility also has an air comfort delivery capability with ceiling or underfloor diffuser options for emulating forced-air comfort delivery and ventilation systems. This paper presents an overview of the design and installation of the HBIL facility, with a focus on the commissioning results of the overall system to demonstrate the facility's capabilities.

2. FACILITY OVERVIEW

2.1 Design Overview of the Facility and Thermo-active Panels

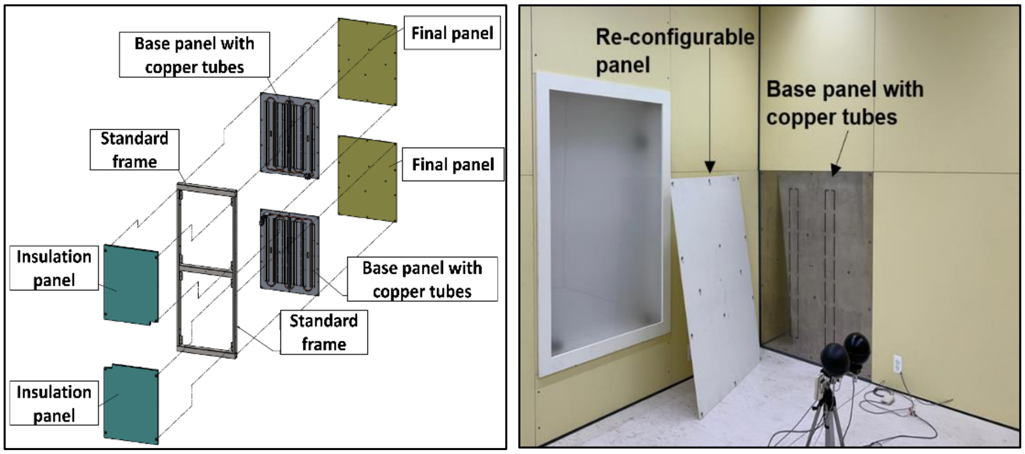
To demonstrate modular characteristics and enable fast construction, the facility is designed for assembly by using manufactured modular panels which are supported by a truss or frame structure with overall interior dimensions of 6.1m × 3.65m × 3.04m (20 ft. × 12 ft. × 10 ft.) (length x width x height). Figure 1a illustrates this modular construction layout, which consists of 24 modular panels. All the panels and components were manufactured and provided by a local vendor. They were able to set up and assemble the facility on-site within only four days. Figure 1b shows the completed final installation of the HBIL.



a) b)

Figure 1: (a) Modular construction layout; (b) facility final build of the HBIL

The facility is designed to test different thermal comfort delivery methods, including radiant heating or cooling from test room surfaces. The ability to control interior surface temperatures also allows for emulating external wall conditions associated with summer cooling or winter heating scenarios. Figure 2a shows an exploded view of the panel. It consists of a steel structure frame on which the base panel with hydronic piping using copper tubes is mounted. On the interior side, the surface treatment panel is attached using magnets on the base panel and from the rear side, the insulation pane is screwed into the steel structure. The panel surface temperature can be independently controlled by supplying water at the desired temperature to the hydronic piping within the base panel. This panel design was tested thoroughly to evaluate the minimum and maximum achievable surface temperatures at a steady state and the dynamic responses to achieve required setpoints. These test results and additional panel design details can be found in Yadav (2022). Figure 2b shows the final wall panels inside the HBIL. The removable interior panel enables testing of alternative materials and surface treatments.



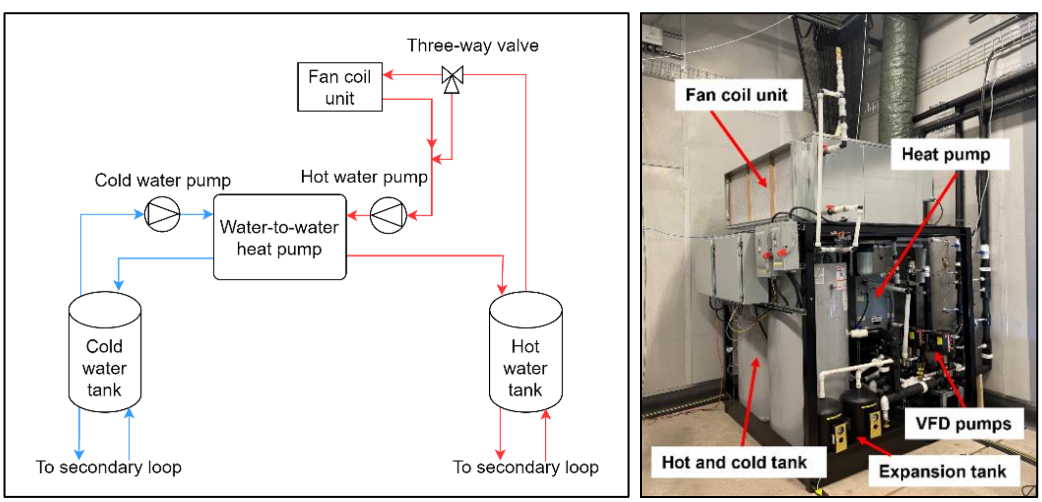
a) b)

Figure 2: (a) Panel exploded-view; (b) Panel final build.

2.2 Hydronic System Design and Installation

To control each panel's surface temperature, a hydronic system was designed and built to provide cold and hot water for the overall test facility. The hydronic system for HBIL is divided into two sections: primary and secondary loop. The main purpose of the primary loop is to maintain the cold and hot water temperature in respective tanks (100 gallons) from where it is supplied to each panel in the test facility through a secondary loop. Figure 3a shows the primary loop schematic and Figure 3b shows the equipment skid. A water-to-water heat pump is utilized to generate both hot and cold water. Cold tank temperature is maintained from 10 to 15°C and the heat absorbed by the heat pump is rejected into the hot tank. The hot tank water temperature is maintained from 30 to 40 °C utilizing the heat rejected from the heat pump along with a supplementary electric heater. In addition, a fan coil unit (FCU) was also installed in series on the heat-pump condenser side to reject any excess heat when the facility is running mainly in cooling mode and the heating load is low. A three-way valve is used to control hot water flow, directing it either into the FCU or directly into the heat pump. This helps avoid unnecessary heat loss caused by water moving through the FCU when it is not in use. The water from the heat pump evaporator and condenser side is circulated through the cold and hot tank respectively, using single-speed pumps.

Table ***1*** summarizes the key equipment with specifications.



a) b)

Figure 3: a) Primary loop schematic and b) equipment skid of the hydronic system

Table 1. HBIL equipment details

No.	Equipment	Specifications
1.	Hot water tank with a heating element	120 Gallon-4.5 kW Heating Element
2.	Heat Pump	Water to Water 17.2 kW 208-230V
3.	Fan Coil Unit (FCU)	Horizontal Direct Drive-VFD-23.2 kW
4.	Primary Loop Pumps (Single Speed)	20 GPM, 15 psi, 0.75 HP
5.	Secondary Loop Pumps (VFD)	30 GPM, 33 psi, 1.5 HP

In the secondary loop, hot and cold water is circulated from corresponding tanks to each panel's 3-way mixing valve inlet using variable speed pumps. The hot and cold water pumps were selected based on pressure drop estimations for the secondary loop. The secondary loop consists of a main supply pipe branched into four sub-loops through a supply manifold and a main return pipe returning to the respective tanks via a return manifold. Figure 4 shows a schematic of the secondary hydronic loop. There are four subloops: two for walls, one for the ceiling, and one for the floor. Each sub-loop supplies cold and hot water to 6 panels. A reverse return configuration is adopted for each subloop to balance the flow in each panel of the subloop. Each subloop has a bypass valve controlled to maintain a stable differential pressure across the supply and return lines. Temperature, pressure, and flow sensors are installed at various locations in the main loop and subloops to monitor flow distribution and system operation.

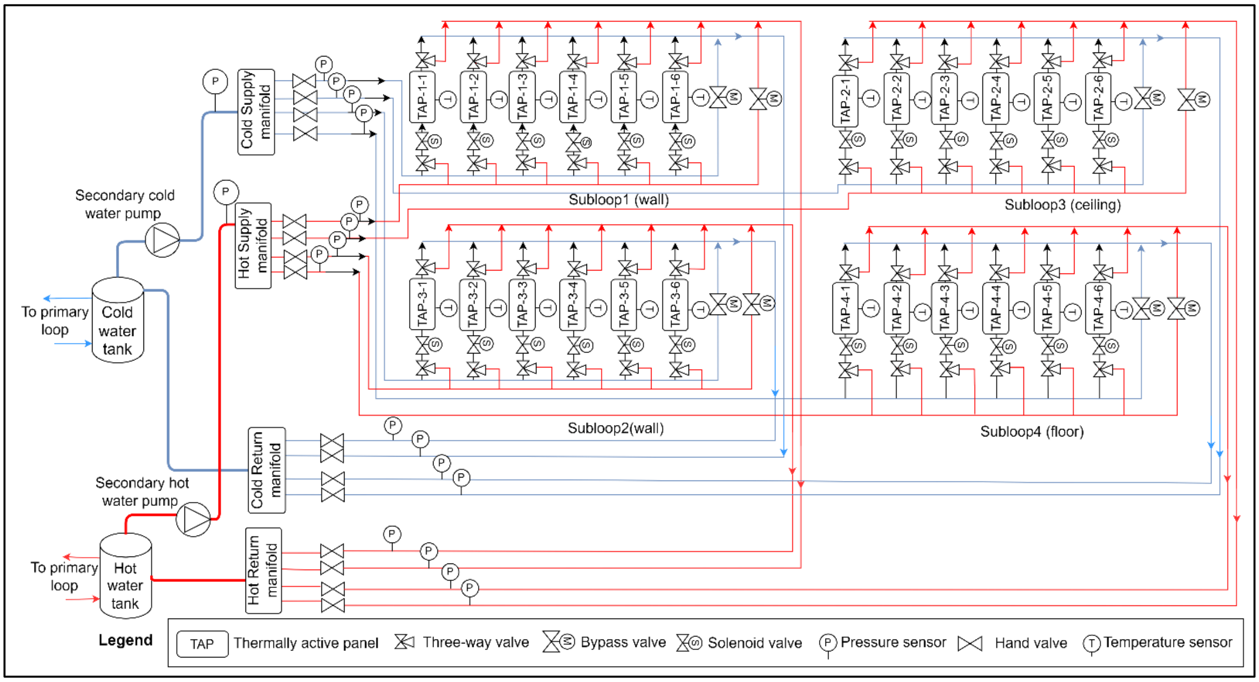
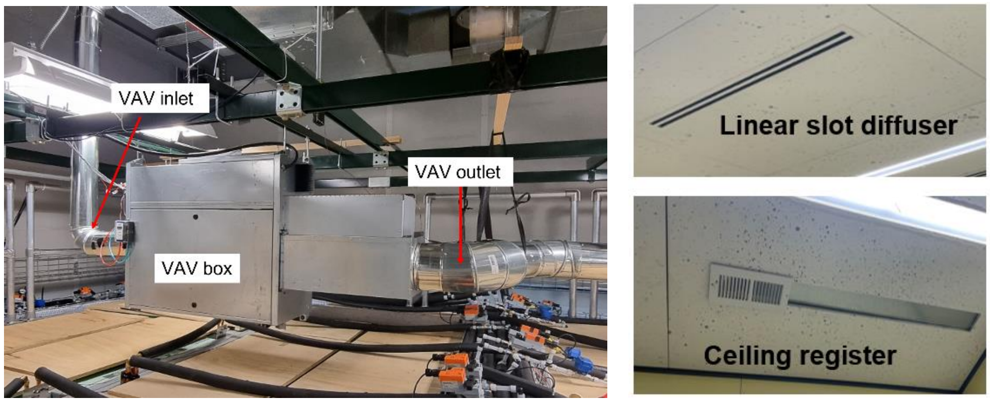


Figure 4: Schematic of the secondary hydronic loop

2.3 Air System Design

A variable air volume (VAV) box was installed and integrated with the HBIL. It was mounted on top of the HBIL and connected to an air handling unit (AHU) of the room in which the facility is located as shown in Figure 5a. The VAV inlet draws air from the AHU, and the outlet supplies the air to the HBIL. The fan and heater of the VAV box provide flexibility in controlling the flow rate and temperature of the air supplied to the HBIL. The VAV outlet is divided into two ducts, which direct airflow to a linear slot diffuser and a ceiling register at the corners of the room (Figure 5b), emulating either commercial or residential applications respectively.



a) b)

Figure 5: a) VAV box and b) linear slot diffuser and ceiling register of the air system

3. CONTROL SYSTEM DESIGN AND CONTROLLER TUNING

3.1 Overview of Control System

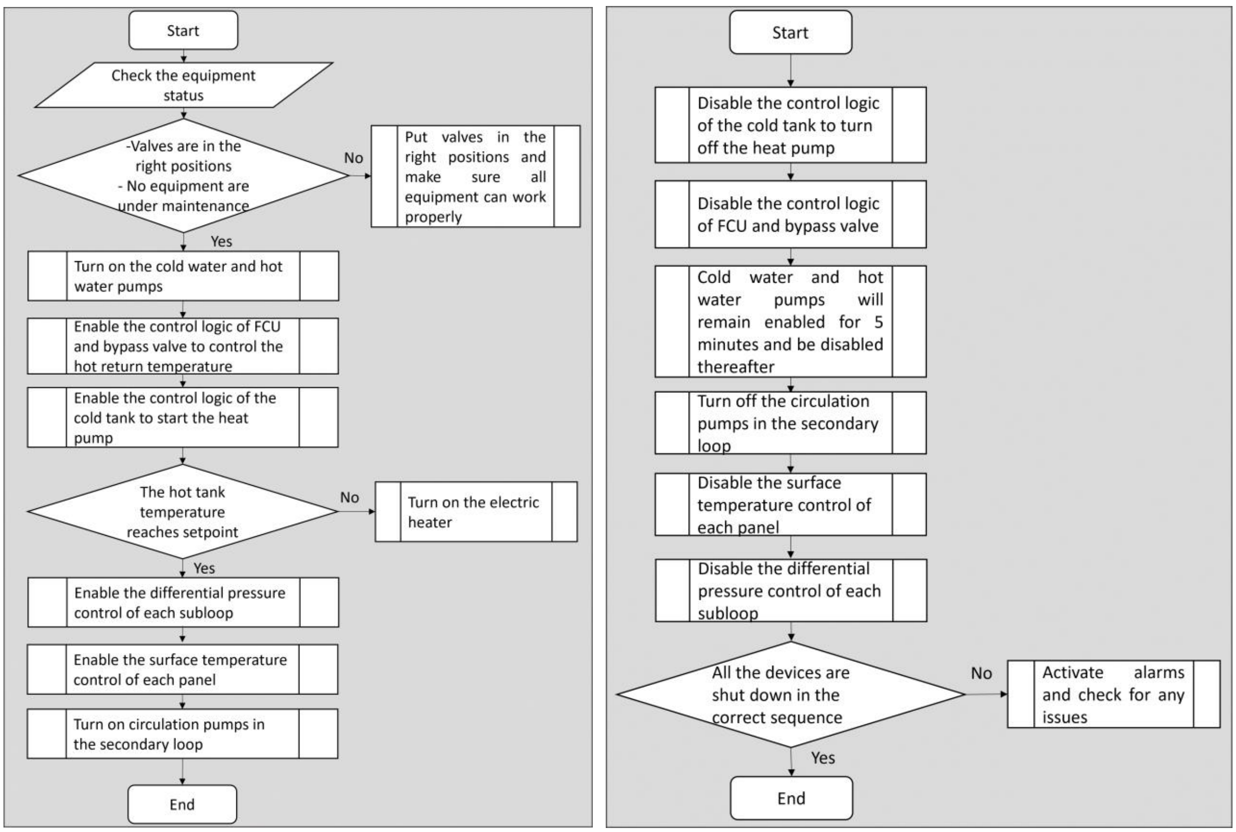
A control system was designed to enable automated operation of the hydronic system, maintain designed setpoints of the system (e.g., cold and hot tank temperatures, panel surface temperatures) mentioned in Section 2.2, and run the system safely. Actuators, sensors, and other equipment (e.g., three-way valve, pressure sensor, pump, heat pump, etc.) are all connected to PLCs (Programmable Logic Controllers). They are fully programmable, and thus, different control logic can be implemented. The control logic of the hydronic system was programmed based on a designed set of control sequences. Figure 6a shows the control sequence to start and operate the whole system. First, the status of all devices is checked to ensure that none are under maintenance. Additionally, all valves must be correctly positioned (e.g., the isolation valve of the tank should be opened before operating the system). Next, the cold and hot water pumps are activated to circulate water through the heat pump. Then, the control logic for the FCU and the three-way valve is enabled to regulate the hot return temperature based on the setpoint. Following this, the control logic for the cold tank is enabled to start the heat pump, which will turn on and off to maintain the cold tank's water temperature. If the hot tank's water temperature does not reach the setpoint, an electric heater will be activated to provide supplementary heating. Once the primary loop operates properly, the differential pressure control for the bypass valve in each sub-loop and the surface temperature control for each panel are enabled. Finally, the circulation pumps in the secondary loop are activated to circulate water through each panel.

Figure 6b shows the control sequence to stop the system. First, the control logic for the cold tank is disabled to shut off the heat pump. Next, the control logic for the FCU and the three-way valve is disabled. After that, the cold water and hot water pumps will continue to operate for 5 minutes before stopping to prevent ice build-up in the evaporator and recover extra energy. Then, the circulation pumps in the secondary loop are turned off. Following this, the surface temperature control for each panel and the differential pressure control for the bypass valve in each sub-loop are disabled. Finally, all devices should be checked to ensure they are shut down in the correct sequence. For example, the cold water and hot water pumps must not be turned off while the heat pump is still running. If irregular operation is detected, the control system should activate alarms to report the issue.

3.2 Feedback Controller Tuning

A single-input and single-output (SISO) configuration, employing either on/off or Proportional-Integral (PI) feedback controllers for various control outputs, was implemented for overall facility control. Table 2 summarizes the major control variables and corresponding outputs controlled using a PI controller.

Using a trial-and-error approach to tune the PI controller gains or parameters for controlling the test facility conditions across a wide range can be challenging. This process is often time-consuming, especially for a relatively slow-responding system like the radiant system adopted in the HBIL. Therefore, a semi-empirical approach was utilized to tune the PI controllers' gains. At first, the step response of each control output was obtained based on experiments. Taking control of panel surface temperature with a three-way valve as an example, the control output signal to the three-way valve was manually changed in multiple steps between 0 to 100% opening position while keeping other control variables affecting the panel surface temperature as stable as possible. After each step change in the control signal, data were continuously collected until the panel surface temperature stabilized. Next, this step response data was used to build a plant model using the MATLAB system identification toolbox (Mathworks, 2024). This model captures the dynamic response of the panel surface temperature to the control input signal applied to the valve. Then, the plant model was incorporated into a MATLAB Simulink model (Mathworks, 2024), along with a PI controller, to simulate the system response based on an input reference setpoint profile. This simulation model facilitated the tuning of the PI controller gains using the MATLAB Control System Toolbox, ensuring the desired system response across various operating conditions. These initial PI gains provided good starting points, which were then implemented into the system. The system's response was evaluated through further testing, and if deemed unsatisfactory, the control gains were manually fine-tuned until the desired response was achieved. The tuning results and PI controller performance will be detailed in the next section.



a) b)

Figure 6: The system control sequence to a) start system and b) stop system

Table 2. Control variables, corresponding actions and objectives

No.	Control Variable	Control Output	Objective
1.	Secondary loop head pressure	Circulation pump speed	Maintain stable head pressure
2.	Subloop differential pressure	Subloop bypass valve	Maintain stable pressure drop across each subloop
3.	Panel surface temperature	Three-way valve at each panel	Control panel surface temperature
4.	Hot return temperature of heat pump	FCU speed	Reject excess heat and maintain stable hot return temperature

4. COMMISSIONING RESULTS AND DISCUSSIONS

4.1 Overall Panel Performance

The thermal performance of different panels was assessed for cooling and heating modes by evaluating the maximum and minimum surface temperature (15°C to 35°C) that can be achieved with the given supply of cold and hot water temperatures for typical indoor space conditions. Each panel has a thermocouple embedded into the interior MDF board to measure interior surface temperature. In the performance assessment tests, cooling mode was initiated with water from the cold tank circulated through the hydronic circuit at the panel back until the surface temperature reached a setpoint. After that, the system was switched to heating mode, and hot water was circulated through the panel hydronic circuit until the design temperature was reached. Figure 7 shows the test results for three wall panels. The surface temperatures of all panels were able to reach temperatures below 15°C in cooling mode and 30°C in heating mode. On the primary loop side, the cold-water supply temperature from the cold tank was maintained between 10°C to 15°C and the hot water supply temperature was maintained around 35°C. Although not explicitly shown in Figure 7, the panel surface temperatures could reach 35°C by activating the tank heating elements to increase the hot water supply temperature. Therefore, the design goal for the panel surface temperature controllability range was achieved. Moreover, Figure 7 demonstrates the overall good performance of the PI controller. When the temperature setpoint changes, there is an initial surface temperature overshoot and some oscillations. The surface temperature stabilizes within 0.5 to 1 hour, depending on the magnitude of the setpoint change. This thermal response is much faster compared to typical high thermal mass radiant systems, which may have response times falling within the range of 9 to 19 hours (Ning et al., 2017). This capability enables HBIL to emulate radiant systems with either high or low thermal mass.

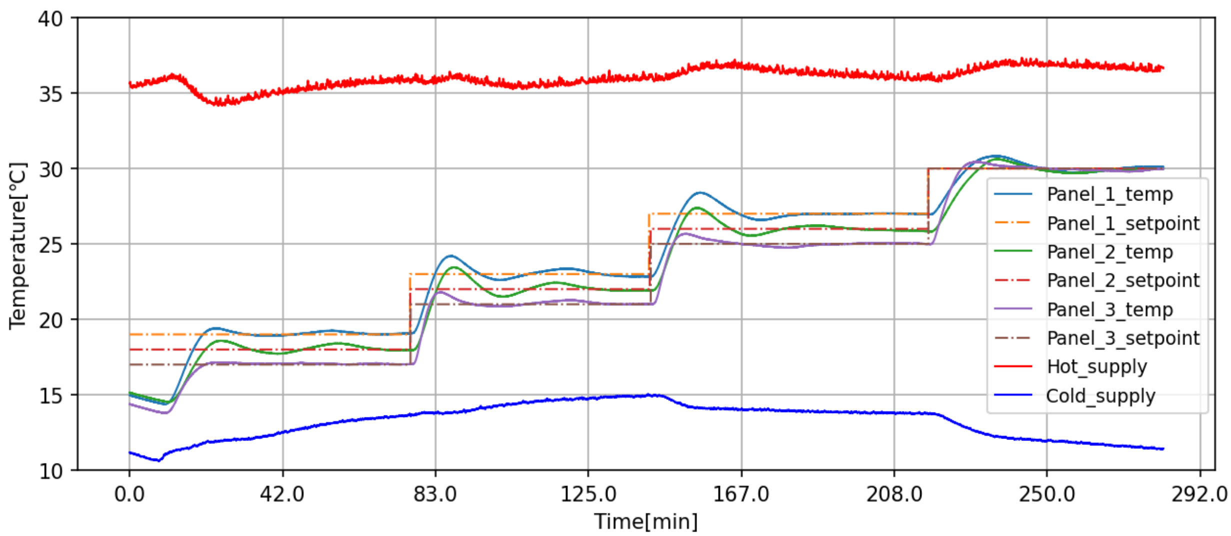
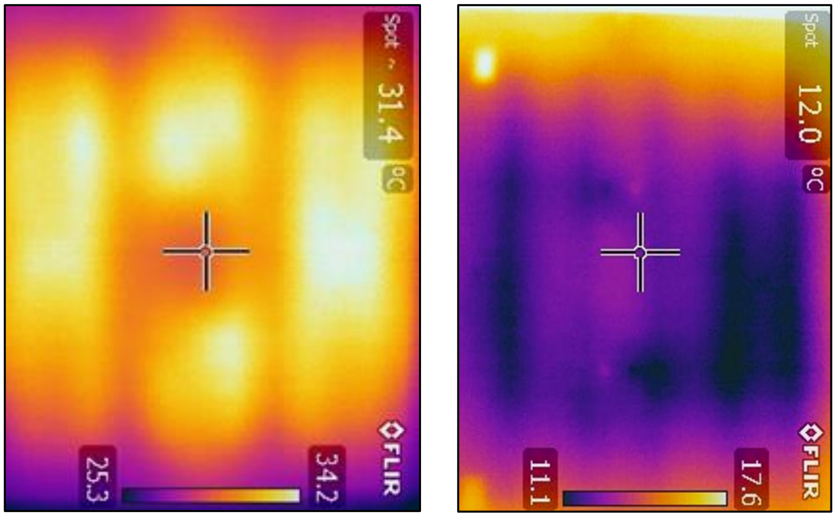


Figure 7: Controllability of panel surface temperature

In addition to the controllability range of panel surface temperature measured at the center of each panel, uniformity in the panel surface temperature is also crucial for the test facility application. To evaluate the surface temperature distribution of the panels, thermal images were taken during steady-state conditions. Figure 8 below shows thermal images of a panel in heating and cooling steady-state conditions. It visualizes the non-homogeneous distribution of the panel surface temperature. The spot temperature shows the central temperature, 31.4°C in heating mode and 12°C in cooling mode. The surface temperature distribution in the heating mode is from 25.3°C to 34.2°C and the cooling mode is from 11.1°C to 17.6°C based on the legend in the thermal image. Except at the edges, the surface temperature in most areas is around or above the spot temperature in heating and lower or around the spot temperature in cooling mode. Overall, the panel surface temperature distribution is relatively uniform and shows good performance except at the edges which is undoubtedly due to edge heat transfer.

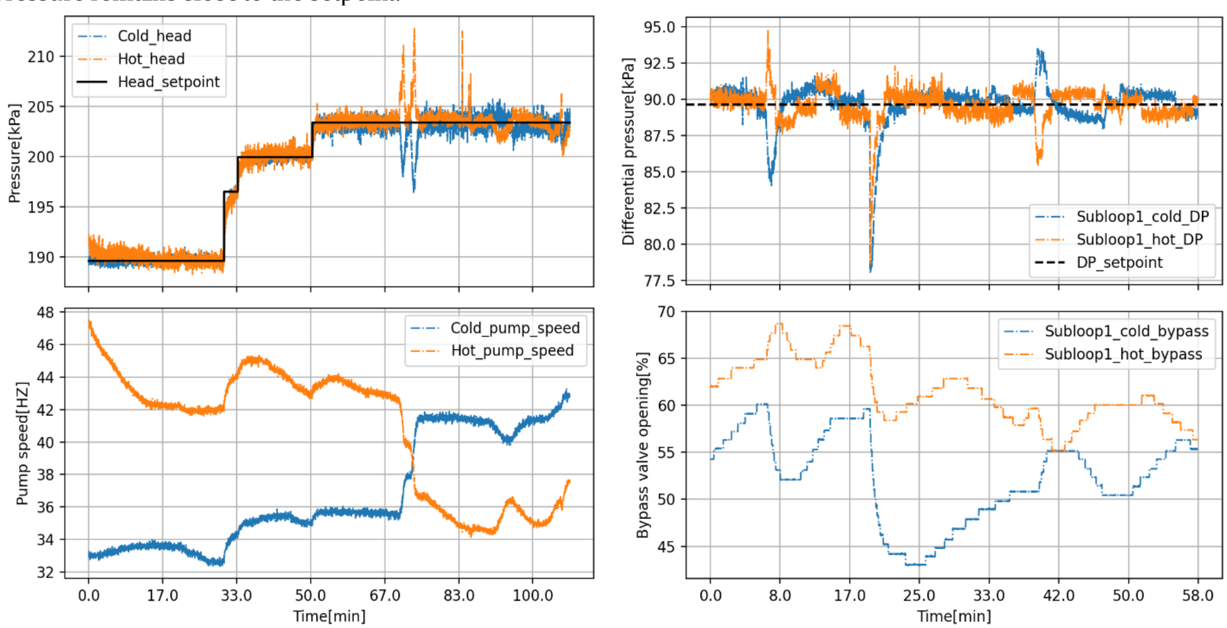


a) b)

Figure 8: Thermal images of panel under steady state: a) heating mode; b) cooling mode

4.2 Performance of Head Pressure PI Controller

The supply head pressure of the secondary loop is regulated by adjusting the circulation pump speed within the loop. It is crucial to maintain the head pressure of both the hot and cold-water loops at the same setpoint to prevent potential backflow within the system. This precaution is necessary because the system does not employ check valves, and the hot and cold water are mixed through a three-way valve at each panel. A difference in pressure between the cold and hot loops could lead to backflow issues. Figure 9a illustrates the performance of the PI logic in controlling the supply head pressure. It can be observed that both the cold and hot loops maintain the same setpoint for head pressure. As the setpoint changes, the head pressure measurement shown in the upper plot effectively follows the setpoint by adjusting the pump speed, as shown in the lower plot. Sudden increases and decreases in pressure are attributed to changes in the panel surface temperature setpoint and adjustments in the opening of the three-way valves, which subsequently impact the head pressure. Nevertheless, the PI controller effectively modulates the pump speed to ensure the head pressure remains close to the setpoint.



a) b)

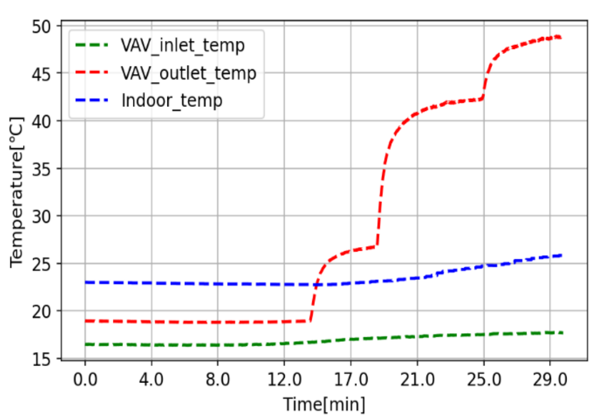
Figure 9: a) Head pressure control; b) Differential pressure control

To ensure an even distribution of water flows into each subloop, the pressure drop across each subloop should be equal. However, each subloop often operates under different conditions. For instance, the floor subloop and the interior wall subloop have different surface temperature setpoints, leading to varying three-way valve openings and pressure drops in each subloop. These differences in pressure drops and uneven water distribution affect control stability and panel surface temperature control. Therefore, a bypass valve and a differential pressure sensor were installed in each subloop, as shown in Figure 4, to maintain consistent pressure drops for each subloop by modulating the valve openings. Figure 9b illustrates the performance of the PI logic in controlling the differential pressure of one subloop. Sudden changes in pressure are due to changes in the panel surface temperature setpoint and adjustments in the three-way valves, which subsequently impact the differential pressure. Nevertheless, the PI controller can effectively adjust the bypass valve to ensure the differential pressure follows the setpoint.

4.3 VAV Box Performance

The airflow rate of the VAV box can be adjusted by controlling the fan speed, allowing a range from 85 m³/h to 510 m³/h. The outlet air temperature of the VAV box is controlled by adjusting the heater's capacity using a silicon-controlled rectifier (SCR). Figure 10a shows VAV test results that demonstrate the system capability. The supply temperature range of the VAV box was tested at an airflow rate of 340 m³/h. During the test, the VAV inlet air temperature from the AHU was maintained at approximately 17°C, and the VAV outlet temperature initially remained around 19°C without the operation of the VAV heater. The slight increase in the VAV outlet temperature was due to the heat generated by the VAV fan. At the 14-minute mark of the testing period, the heater was turned on at partial load, and its capacity was subsequently increased. As a result, the VAV outlet temperature eventually reached around 49°C. Additionally, the HBIL indoor air temperature began to rise once the heater was activated. The test results demonstrated that using a VAV box with a heater can effectively emulate conventional central air comfort delivery systems (e.g., air-to-air heat pump, gas furnace) or ventilation systems with a wide range of supply air temperatures and airflow rates.

In addition to the functionality test of the VAV box, PI controls for the VAV outlet temperature and airflow were also implemented to provide high-fidelity system emulation. Figure 10b demonstrates a case with the implemented PI controllers. In the current controller setting, the heater capacity is regulated based on the room's indoor temperature setpoint (i.e., how much heater capacity is needed to maintain a stable indoor temperature), while the VAV fan speed is controlled based on the outlet air temperature setpoint (i.e., adjusting the fan speed to maintain a stable outlet temperature). Overall, both the indoor temperature and the VAV outlet temperature show good control performance, with some overshoot and small oscillations. Future fine-tuning will be conducted to reduce oscillations and further improve the control performance. The implemented PI controllers facilitate the emulation of more advanced heat pump systems, such as variable-speed heat pumps or two-stage heat pumps with an electrically commutated motor (ECM) on the indoor fan and an auxiliary heater with a SCR. Therefore, the performance comparison of different forced air systems can also be evaluated using the HBIL to understand their respective pros and cons.



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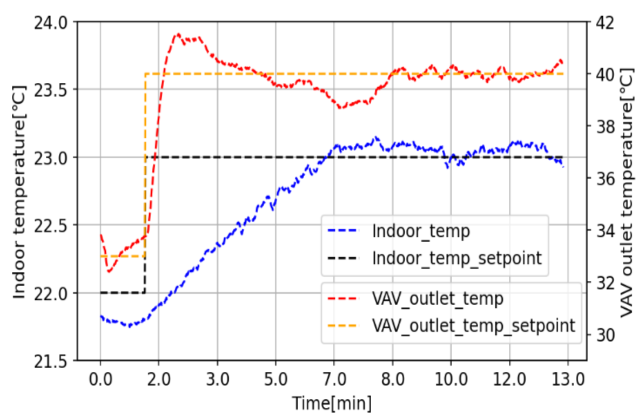

b)

Figure 10: a) VAV box test results; b) The control performance of the VAV outlet temperature and HBIL indoor temperature

5. CONCLUSION

This paper presented the design, controller tuning and commissioning results of a novel Human Building Interactions Laboratory. Based on the commissioning results, the controllability range of each panel surface temperature was demonstrated to be between 15°C and 35°C, which meets the test facility design specifications. The summarized key features of the HBIL facility include:

- Modular design with thermo-active panels emulating residential and commercial spaces.
- Radiant and natural convective heating and cooling via floor, ceiling, and walls.
- 3-way mixing valve to supply desired mixed water temperature to each radiant panel and achieve independent temperature control. The controllability of each panel surface temperature ranges between 15°C and 35°C.
- Capability of emulating various outdoor conditions by setting different surface temperatures.
- Reconfigurable medium-density fiberboard interior panels with removable magnetic attachment, and embedded thermocouples.
- A dedicated VAV box with an electric heater is used to supply air to the indoor space to emulate conventional central air comfort delivery or ventilation. The controllability of supply air temperature is between 19°C and 49°C and airflow ranges from 85 m^3/hr to 510 m^3/hr.

To further enhance the control and operation of the facility, a future task could implement a multiple-input and multiple-output (MIMO) control approach for this system, instead of the single-input and single-output (SISO) configuration currently implemented. Furthermore, new human-building interfaces, such as wall-mounted tablets and voice assistants, will be installed to conduct occupant-centered research to improve occupant comfort and well-being.

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