Lessons Learned from Retrofitting a Psychrometric Facility for Testing of HVAC&R Equipment with Flammable Refrigerants

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ABSTRACT

Recently, there has been a push in the HVAC&R industry to transition to systems with environment-friendly, low Global Warming Potential (GWP) refrigerants, which is driven by current and future plans to phase out existing refrigerants. However, some of these low-GWP alternative refrigerants such as R290, R32, and R600a are flammable and further research and development are needed to optimize and verify the performance and safety of HVAC&R equipment that employ these alternative refrigerants. To facilitate these research and development efforts, one of the psychrometric testing facilities at the Ray W. Herrick Laboratories was retrofitted to be able to test and investigate equipment with flammable refrigerants. To fulfill the safety requirements for flammable refrigerants, various components of the test facility as well as the operational procedures to install, test, and operate test equipment were modified. Furthermore, as a part of the retrofit, the control hardware and software of the facility were also upgraded to make the control system more robust and provide better flexibility and automation in maintaining a wide range of temperature and humidity conditions. Finally, the psychrometric chambers were operated over a wide range of conditions to determine the operating envelope and demonstrate the ability to maintain test conditions based on the AHRI 210/240 standard. This paper documents the learning experiences that provide some guidelines for either a new or retrofit of an existing psychrometric facility for testing HVAC&R equipment with flammable refrigerants.

1. INTRODUCTION

The demand for air conditioners is increasing across the globe, especially in developing countries with hot climates, due to increasing standards of living, urbanization, electrification, and rising temperatures (IEA, 2018). For example, installed cooling systems in residential buildings around the world are expected to rise from around 3.4 billion in 2016 to more than 8 billion in 2050 (IEA, 2018). This will not only increase energy requirements but also peak electrical demand, thus putting a strain on the current grid infrastructure around the globe. Therefore, it is important to improve air conditioners' energy efficiency to reduce their energy, peak-load, and emissions impact. Further, refrigeration, air conditioning, and transportation air conditioning sectors account for around 80% of the global hydrofluorocarbons (HFCs) emissions (EPA, 2013). HFCs are powerful greenhouse gases (GHGs) with global warming potential (GWP) hundreds to thousands times more per pound than carbon dioxide (CO_2) and thus contribute significantly to climate change. With the growth of refrigeration and air conditioning demand across the globe, especially in the developing world with tropical climates, HFC emissions are projected to quadruple by 2030 (EPA, 2016). To reduce these GHGs emissions, there are various efforts on a national as well as global scale. For example, the Kigali Amendment to the Montreal Protocol (UNEP, 2016, 2019), establishes a global schedule to phase down HFCs (hydrofluorocarbons) refrigerants with low GWP (Global Warming Potential) alternatives over the next 30 years to reduce the direct emissions from air conditioning systems with some differences in timelines depending on national governing bodies. Improving both energy efficiency and transitioning to low GWP refrigerants could double the climate benefits of the Kigali Amendment (Park et al., 2019). However, typical refrigerants, such as R290, R32, and R600a, which provide an alternative to the current HFC refrigerants (e.g., R134a, R410A, and R404A) to meet these high energy-efficiency and low-GWP targets are flammable. So, further research and development are needed to optimize and verify the performance and safety of HVAC&R equipment that employ these alternative refrigerants. To facilitate these research and development efforts, one of the psychrometric testing facilities at the Ray W. Herrick Laboratories was retrofitted to be able to test and investigate equipment with flammable refrigerants. The motivation of this paper is to share the learning experiences from this retrofit process.

To safely test equipment with flammable refrigerants, a retrofit process was carried out where different components of the test facility, such as blowers, heaters, sensing, and control equipment, were upgraded with explosion-proof and intrinsically safe alternatives to eliminate any ignition sources. In addition, refrigerant monitoring systems were installed to detect any leakage in the test facility along with a dedicated ventilation system to reduce the refrigerant concentration in case of leakage. Details on these hardware retrofits to the test facility are discussed in the subsections below along with the key points related to the standard operating procedure for ensuring safe installation, operation, service, and testing of equipment with flammable refrigerants in test rooms. Furthermore, as a part of the retrofit, the control hardware, as well as the control architecture of the facility, were also upgraded to make the control system more robust and provide better flexibility and automation in maintaining a wide range of temperature and humidity conditions. As an example, the thermal expansion valves (TXVs) used for the refrigeration system were replaced with electronic expansion valves (EXVs) that are independently controlled, which gives flexibility for better superheat control. The overall control architecture for the test facility is presented along with an approach for tuning controller parameters. Finally, the psychrometric chambers were operated over a wide range of conditions to determine the operating envelope and demonstrate the ability to maintain test conditions based on the AHRI 210/240 standard. This paper documents the learning experiences that can provide guidelines for either a new or retrofit of an existing psychrometric facility for testing HVAC&R equipment with flammable refrigerants.

2. FACILITY OVERVIEW

In this section, an overview of the test facility is provided along with a description of different components to maintain a range of temperature and humidity conditions in test rooms. In this test facility, there are two side-by-side psychrometric chambers to emulate various temperature and humidity conditions representing indoor and outdoor conditions for HVAC&R equipment testing. The rooms were originally designed and built for performance measurement of unitary air conditioners and heat pumps based on standards, such as AHRI 210/240 (AHRI, 2020), as well as testing of other equipment which requires a controlled environment in terms of temperature and humidity. Both rooms have the same internal dimensions, 13’6” (4.1m) wide, 19’6” (5.9m) long, and 9’5” (2.9m) high resulting in a total internal volume of 2500ft^3 (70.8m^3). The test rooms are capable of sustaining temperatures ranging from -20ºC (-4°F) to 52ºC (125ºF) and relative humidity ranging from 25% to 95% with operation tolerance of about 1°F and 1% RH. Figure 1 shows a schematic of one of the test chambers with its air handling unit (AHU) containing re-conditioning equipment to control the room air temperature and humidity. Each test room has two AHUs operating in parallel to provide flexibility in capacity and control. The test room air is circulated through an AHU using a variable-speed blower with the return air duct located near the test room ceiling and re-conditioned air is supplied to the test room with an under-floor air distribution system. There is around 12” (0.3m) of space between the ground floor of the chamber and the test laboratory ground floor for the under-floor air distribution system. Depending on the test room temperature and humidity setpoint, the test room return air in an AHU is first cooled down with refrigeration coils, followed by reheating using electric heaters, and then humidified using steam injectors. The air is cooled down below the required room temperature setpoint and then the temperature is controlled using heaters which respond relatively faster compared to cooling coils. Further, for humidity control, the air is first dehumidified by controlling the cooling coil temperature below the air dew point temperature and then humidified with steam injectors. In this way, both temperature and humidity are controlled to the required setpoint using feedback control for automation.

In both test rooms, cooling and dehumidification functions are fulfilled by direct expansion refrigeration coils which are driven by a single 90-ton screw compressor with R22 as a refrigerant. Figure 2 shows a simplified schematic of the overall refrigeration circuit for both test rooms. In each psychrometric chamber, cooling in the air loop is provided through two sets of fin and tube heat exchangers which function as evaporators for the refrigeration system. Each evaporator coil is divided into three parallel circuits, one representing around 20% and the other two circuits representing around 40% of the total coil cooling capacity. Figure 3 shows a detailed piping and instrumentation schematic of a single cooling coil with three circuits. Depending on the required capacity, solenoid valves are used to engage the right configuration of circuits in the evaporator, providing 5 possible capacities ranging from 20% to 100% in 20% increments. Each cooling coil circuit refrigerant outlet superheat (SH) is controlled with an electronic expansion valve (EXV), which was retrofitted from a thermostatic expansion valve (TXVs) for better controllability and the future possibility of changing the working fluid from R22 to a more environmentally friendly alternative. The two test rooms are usually controlled at different temperature conditions, thus requiring different evaporating temperatures for cooling coils based on cooling and dehumidification requirements for each test room. Each coil evaporating temperature is controlled by controlling the refrigerant pressure using a pressure regulating (CDA) valve downstream of the cooling coil, which was also retrofitted from a mechanically controlled version to an electrically controlled valve for better controllability. For defrosting the cooling coils, hot gas bypass from compressor discharge is used. During retrofitting, valves and piping needed for hot gas defrost were added to replace the previous electric resistive heaters system for defrosting. Further, check valves were also installed at appropriate locations to ensure the right refrigerant flow direction when activating different sets of cooling circuits or hot gas bypass for defrosting. For humidity control, the evaporating temperature of the cooling coil is kept below the air dew point temperature to continuously de-humidify and then add the required amount of steam using steam injectors.

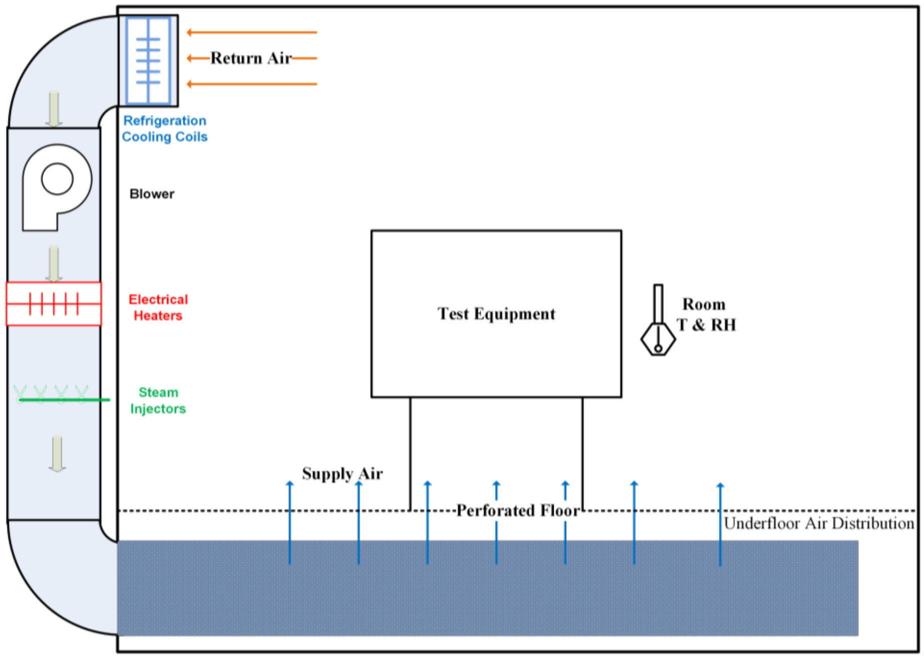

Figure 1. Schematic showing airflow through the re-conditioning system of psychrometric chambers

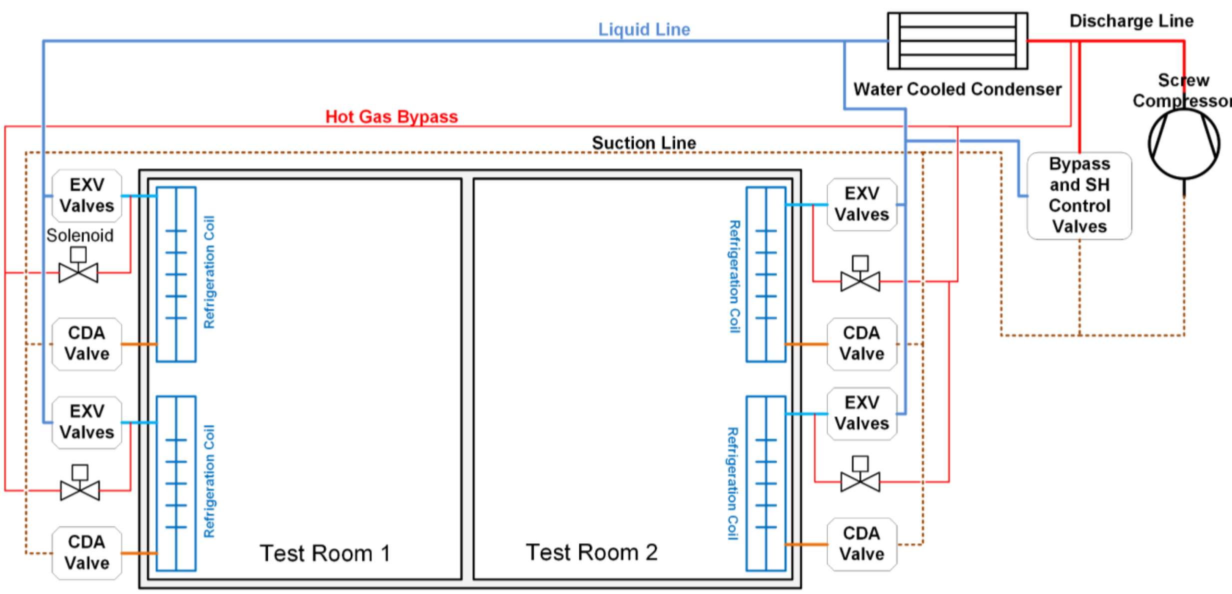

Figure 2. Schematic showing the piping and instrumentation of the refrigeration system providing cooling and dehumidification to the psychrometric chamber

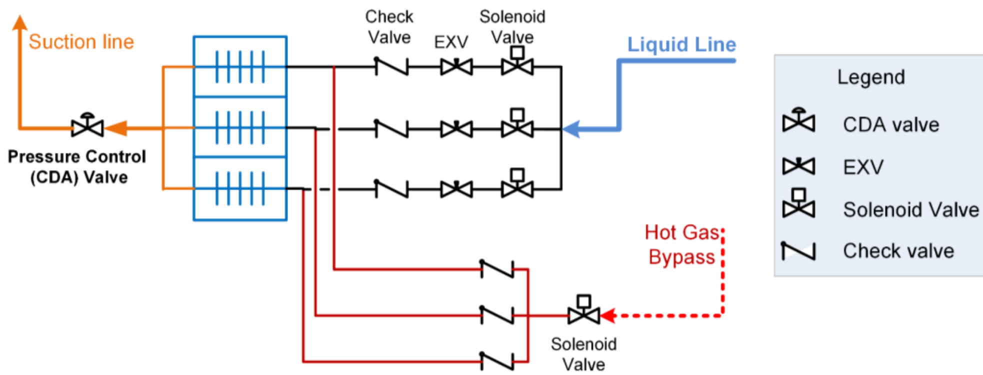

Figure 3. Schematic of a single refrigeration coil piping and instrumentation

The heat on the high-pressure side of the refrigeration system is rejected to a water-cooled shell and tube heat exchanger which acts as a condenser. Based on the required cooling capacity in both rooms, the capacity of the screw compressor is controlled using its slider mechanism which controls the compressor suction mass flow rate to meet part-load conditions. In situations when the compressor is running at minimum capacity and the required cooling capacity is still lower than desired, the compressor is artificially loaded using a pressure controlled hot gas bypass valve between the compressor discharge and suction line. Further, the compressor suction SH is controlled by a TXV between the condenser outlet and the compressor suction line. The capacity of heaters is controlled using a silicon controlled rectifier (SCR). For humidification, steam humidifiers are installed in the AHU. High-pressure steam from the building supply is throttled down using a regulator and then pneumatically controlled steam valves are used to control the flow of steam entering the air stream.

3. RETROFITS FOR FLAMMABLE REFRIGERANTS

This section describes the modifications made to the test facility hardware as well as its operation in order to safely test HVAC&R equipment with flammable refrigerants up to A3 flammability classification as per ASHRAE standard 34 (ASHRAE, 2019b). For this, as per safety standards ASHRAE 15 (ASHRAE, 2019a) and EN 60335-2-40 (CENELEC, 2003) guidelines, five key areas needed to be addressed as outlined below.

1. Refrigerant leakage monitoring
2. Ventilation system
3. Ignition sources
4. Grounding
5. Temperature and airflow monitoring

1. Refrigerant monitoring and ventilation system

- For each test chamber, a refrigerant monitor was installed to sense any refrigerant accumulation in the room in case of leakage. For each refrigerant monitor, the air sampling points are spread throughout the test room for a uniform and representative sampling. Further, one of the two blowers in each test room AHU is always running at least at minimum speed to continuously circulate and mix the air in the room to reduce the overall refrigerant concentration at the leakage point and also for better sampling by the refrigerant monitor for early detection. The room refrigerant sensor is set to sound the alarm and initiate the room ventilation below 25% of the lower flammable limit (LFL) for the refrigerant. The LFLs for different refrigerants are provided in ASHRAE 34 standard (ASHRAE, 2019b).
- A dedicated mechanical ventilation system was also installed in each test room as per ASHRAE standard 15 (ASHRAE, 2019a) to purge the air from test chambers to the outdoor environment outside the building in case of leakage. The mechanical ventilation system is required to exhaust an accumulation of refrigerant due to refrigerant leaks or a rupture of the system to an extent that will keep refrigerant concentrations below the flammability limit. Based on the test room volume, the system needed to be capable of removing the air from the psychrometric chambers at the required minimum airflow rate of not less than 201.28 cfm (94.15 l/s). The installed exhaust fan can pull 600 CFM at 0.5” wc static pressure head. The installed ventilation system has normally closed dampers and the ventilation activates either when a researcher/technician is working in the chamber or when the refrigerant monitors indicate an increase in the refrigerant concentration above the set

threshold. The ventilation system is hardwired to run based on the door opening and with the refrigerant monitor alarm.

- Further, in case of leakage detection by the refrigerant monitor, the test facility as well as test unit high and low voltage power are shut off automatically by the safety equipment control system with shunt trip breakers. Note that all key components related to safety are independently controlled by the hardwired safety control system and are not controlled by the psychrometric chambers control program. However, refrigerant sensor status monitoring capabilities are provided to the psychrometric chamber control to allow the user to shut down the test system safely in case of leakage. In addition, an emergency stop button was added outside the test room to completely shut down the test rooms as well as the test unit power. Once the alarm is triggered and the room equipment is off, the operator has to manually reset the alarm condition before the room can return to normal operation. If the alarm status is still active when the alarm reset is pressed, the room remains locked out to ensure safety.

2. Removing ignition source, electrical upgrades, and grounding

- Different components were retrofitted with explosion-proof alternatives to remove any ignition sources in the test room.
  - Wherever possible, electrical disconnects were moved outside the test rooms and electrical connections inside the psychrometric chambers were replaced with explosion-proof connectors.
  - Lighting fixtures were also replaced with explosion-proof lighting fixtures.
  - Blowers located in the air-handling units and the airflow measurement device were replaced with direct drive explosion-proof blowers.
  - Electric heaters in the AHU duct, as well as its wiring, were replaced with explosion-proof alternatives.
  - Each test room sensor to measure the temperature and relative humidity was also replaced with an explosion-proof and intrinsically safe alternative.
  - The previous cooling coil defrosting system utilizing strip heaters on the coil was replaced with a hot gas bypass system utilizing high-temperature refrigerant from the compressor discharge
- A designated electrical grounding wire was installed to prevent and avoid sparks generated by the test equipment or due to the discharge of static electricity.
- When someone is working inside the psychrometric chambers, sparkless tools need to be used in addition to an explosion-proof refrigerant charging, recovery, and vacuuming system.
- Any penetrations between the test room and outside to route wires, pipes, etc. were sealed to contain refrigerant leaks and flames inside chambers.

3. Temperature and airflow monitoring

Temperature monitoring at critical locations was added to the psychrometric chambers. During the testing of any HVAC&R system inside the test rooms, the air temperature after the AHU electric heaters shall not exceed 194°F (90°C) (CENELEC, 2003). The outlet air temperature is always monitored with redundancy and is used as an input to the appropriate safety systems to shut off the heaters if it exceeds the limit. Further, the surface temperature of electric heaters should be at least 100°F below the flammable refrigerant auto-ignition temperature. For this, each heater's surface temperature is monitored by a standalone hardwired control panel with high-temperature limit switches to shut off the heater if its surface temperature exceeds the limit of 400°F. In addition, the airflow in each AHU is monitored with an airflow switch which needs to be activated before the heaters are powered up to ensure airflow over the heaters whenever in operation.

In addition to the retrofits to the test facility, a standard operating procedure was also developed to ensure safe installation, operation, service, and testing of equipment in the test rooms. Some of the key points are discussed below.

- **Instrumentation:** Any test unit instrumentation which requires entry into the refrigerant circuit, such as pressure sensor taps, service valves, etc., should be done outside the test rooms in a well-ventilated area in order to avoid using a brazing torch inside the test rooms whenever possible. Before any brazing, the interior of the unit cabinet must be checked for the presence of refrigerant using a hand-held refrigerant monitor. In addition, the absence of refrigerant in the refrigerant circuit should also be verified by purging the system with nitrogen at least at 10-15 psig. Any potential isolated segments in the refrigerant circuit, such as between check valves, TXV, EXV, solenoid valves, etc., must be identified and a service port should be installed in that segment.
- **Leakage check:** Prior to moving the test unit inside test rooms, it must be checked for any possible leakages. A leakage test should be performed by pressurizing the test unit at design pressure with nitrogen as well as in

vacuum pressure below 500 microns. The test unit should be able to hold the high pressure and vacuum for at least 15 minutes without any decay in pressure.

- **Test unit installation:** After moving the test unit to test rooms, a new line set should be installed, and the line set should have mechanical protection at critical locations to prevent any accidental damage that may result in a leak. It is recommended to use mechanical unions to install the line set rather than brazing. If that is not possible, then test rooms must be ventilated and the absence of refrigerant in the test room must be verified with the refrigerant monitor as well as a hand-held refrigerant sensor before doing any work that involves brazing. While working on the test unit inside the test room, the ventilation fan should always be ON and any power to the test room equipment should be OFF.
- **Power connection:** Proper Lock-Out/Tag-Out (LOTO) procedures must be followed. In addition, the test system (outdoor unit, indoor unit, and line sets) must be grounded per NFPA 70, Article 250 (NFPA, 2020). Electrical connections should be only completed after LOTO and verifying the grounding, for example, checking the ground path from both the condenser fan motor (motor mounting nut) and the compressor suction tube to the room ground wiring.
- **System evacuation, refrigerant charging, and recovery:** Figure 4 shows a schematic of a charging station built to connect the test unit's low- and high-pressure sides to different components for pressure leakage check, vacuuming, refrigerant charging, refrigerant recovery, and purging. After the test unit and its line set installation, the leakage check should be performed again, first at high design pressure with nitrogen. Then, the test system should be evacuated using a flammable refrigerant rated vacuum pump and it should be ensured that the system holds the vacuum prior to charging the system with refrigerant. Further, before refrigerant charging, proper system grounding must be completed as per NFPA 77 (NFPA, 2019) to eliminate the potential for a static discharge during the refrigerant charging process. In addition to the other system components discussed above, the refrigerant tank must also be grounded to ensure a balance of electrical potential. During the refrigerant charging process, a hand-held refrigerant sensor should be used for early detection in case of leakage at any valves. Once charging is completed, the lines external to the test unit system should be purged with nitrogen using a vent line that opens to the atmosphere external to the building. When refrigerant from the test unit needs to be recovered, a cold recovery tank with a recovery machine for flammable refrigerants should be used.

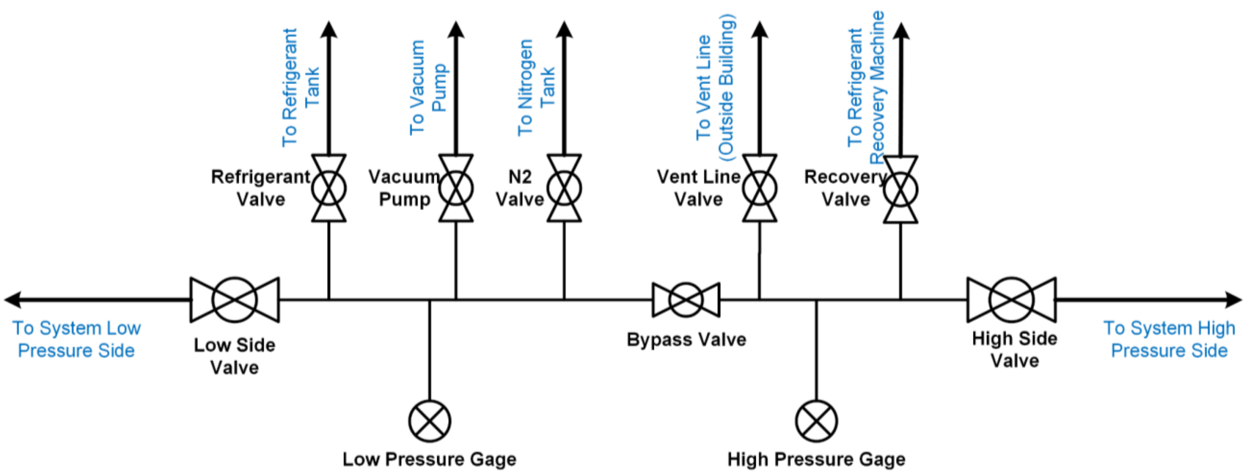

Figure 4. Schematic of charging station

- **Additional personnel safety**: If the test room contains a system charged with a flammable refrigerant, all personnel entering and working in the test rooms must wear a personal oxygen sensor and anti-static wrist strap assembly whenever working on electrical connections, servicing instrumentation, or charging/recovering refrigerant from the test unit. The power supply to all room equipment must be shut off and ventilation equipment must be in operation anytime personnel are in the room and the door may not be closed while the personnel is occupying the chambers.
- **Leakage response:** In case of leakage detection by the refrigerant monitor, no one should enter the test room under any circumstances while the alarm is active, and the operator should also confirm that no one is inside the test rooms and the ventilation system is ON. It should also be verified that the room and test unit power was

automatically shut off, if not, it must be shut off manually with the emergency switch located outside the test rooms. Then the operator should contact the technical shop and safety personnel for further assistance.

4. FACILITY CONTROL APPROACH AND CONTROLLER TUNING

In addition to the retrofits discussed above for testing systems with flammable refrigerants, the test facility control hardware and software were also upgraded from the previous generation for better flexibility in the control design and implementation to achieve test room stable operation across varied conditions. The temperature and humidity control for the psychrometric chambers involves controlling different components mainly based on single-input and single-output (SISO) controllers for each actuator. As outlined in section 2, each test room has two AHUs, each with a cooling coil, blower, electric heater, and steam injector. Further, each cooling coil has three refrigerant circuits that can be independently turned on and off. The test room temperature control is achieved by cooling the air below the room temperature setpoint using cooling coils and then reheating the air with electric heaters. Similarly, for humidity control, the circulated air in each AHU is first dehumidified by maintaining the cooling coil temperature below its dewpoint temperature and then adding humidity using steam injectors. Depending on the capacity of the unit being tested, it is chosen whether to operate both AHUs or just one for a certain test condition and how many cooling coil refrigerant circuits to open. Figure 5 shows a schematic of the evaporating temperature setpoint calculation approach for each cooling coil within the indoor (ID) and outdoor (OD) test rooms. In cases where humidity control is required for a test room, the cooling coil refrigerant saturation temperature setpoint is maintained around 10℃ below the room air dew point temperature setpoint. Otherwise, it is maintained around 10℃ below the room air dry-bulb temperature setpoint. The 10℃ temperature difference is the default value which can be changed by the user based on the testing requirement, such as employing a low coil temperature during pull down. The cooling coil evaporating temperature setpoint is then converted to the corresponding saturation pressure setpoint for the R22 refrigerant. Each cooling coil has a pressure regulating (CDA) valve as shown in Figure 3, which is controlled using a PI (Proportional - Integral) controller to maintain the cooling coil refrigerant pressure measured upstream to the CDA valve to its setpoint. In addition, an EXV for each refrigerant circuit of the cooling coil is also controlled using a PI controller to maintain the refrigerant outlet superheat (SH) at a setpoint of 8℃.

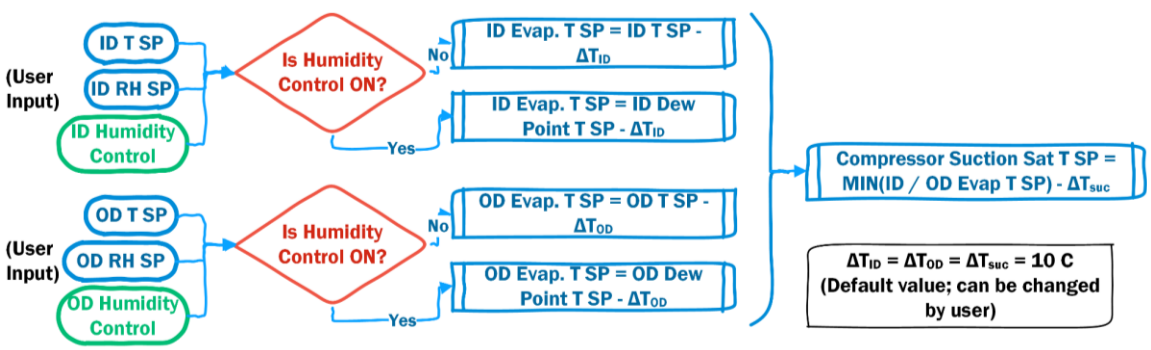

Figure 5. Schematic showing the evaporators and compressor suction saturated temperature setpoint calculation approach

Both test room cooling coils are driven by a single variable-capacity screw compressor and the compressor suction pressure setpoint is maintained based on a refrigerant saturated temperature setpoint of around 10℃ below the minimum of both room's cooling coil evaporating temperature setpoints as shown in Figure 5. A PI controller is used to modulate the compressor slider position in order to control its measured suction pressure to the setpoint. The slider allows modulation of the compressor capacity from 15% to 100%. In case the required cooling capacity would lead to a compressor capacity that is below 15%, then a bypass valve from compressor discharge to suction is mechanically controlled to artificially load the compressor. In addition, there is also a TXV from the water-cooled condenser outlet to the compressor suction to maintain the compressor suction SH. The bypass valve and TXV are engaged based on the activation of solenoid valves that are installed upstream of these devices. Further, the blower in each AHU has a variable frequency drive, which provides another degree of freedom to control the coil cooling rate by varying the airflow. The combination of the control of the compressor, blowers, pressure regulating valves, and expansion valves cools and dehumidifies the room air circulating in the re-conditioning system AHU. Then, heaters in each test room AHU are controlled using an SCR based on a PI controller to maintain the test room temperature to its setpoint.

Similarly, steam injectors valves are controlled based on another PI controller to maintain the test room absolute humidity ratio to its setpoint. In case of defrosting required for a cooling coil, refrigerant flow through all EXVs is stopped by shutting off the solenoids upstream of the EXVs, and a hot-gas bypass solenoid is opened to circulate the high-temperature refrigerant from compressor discharge through the cooling coil until defrosting is completed. During defrosting, the AHU blower is stopped to minimize its effect on room temperature conditions.

For the overall test facility re-conditioning system, feedback control responses of different actuators (e.g., CDA valve, EXV, and compressor slider) are coupled at the system level. Therefore ideally a multiple-input and multiple-output (MIMO) controller would be best suited for this system. However, developing and tuning a robust MIMO controller for this non-linear system requires detailed modeling efforts, which was not possible at the time due to limited system test data available. So, for overall test facility control, different actuators are independently controlled with a single-input and single-output configuration either using digital on/off control (e.g., solenoid valves) or using PI feedback controllers for continuous control using analog output (AO) signals from the test rooms PLC (Programmable Logic Controller). Table 1 summarizes the different control variables and corresponding actuators controlled using a PI controller. Further, to avoid instabilities in control with the SISO configuration for this coupled system, the system dynamic response was studied with experimentation, and the control response rate of highly coupled components was set differently based on an importance hierarchy. For example, the opening of the CDA valve as well as the EXV openings affect the evaporating pressure, so, to avoid instability issues, the CDA valve control was slowed down compared to the EXV controls as cooling coil SH control is more critical for compressor safety.

Table 1. Control variables and corresponding actuators controlled using a PI controller

No.	Control Variable	Control Actuator
1	Room Temperature	Heater SCR
2	Room Humidity	Steam Injector Valve
3	Cooling Coil Evaporating Pressure	Pressure Regulating (CDA) Valve
4	Cooling Coil Refrigerant Circuit Outlet SH	EXV
5	Compressor Suction Pressure	Compressor Slider

To control the test facility conditions across a wide range, all the different PI controller gains or parameters were tuned. Deriving the gains for PI controllers for this kind of coupled system is often challenging and can be time-consuming with a relatively slow responding system such as this thermal system, especially if addressed solely with a trial-and-error approach. Here, a semi-empirical approach was followed for tuning the PI controllers' gains, deriving initial reasonable values of PI gains using a system identification and simulation approach based on actuator step response data and then fine-tuning those gains manually to the required performance. This cut down the time required for tuning all the different controllers considerably, however, significant time was still needed given the complexity of the system and number of actuators. Figure 6 shows the outline of the approach used for tuning PI controller gains.

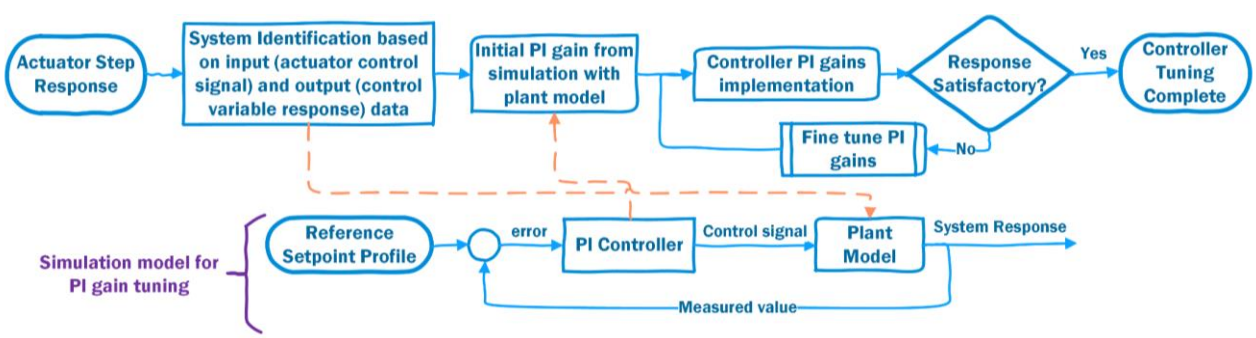

Figure 6. Schematic outlining the individual PI controller tuning approach

Here, an example of tuning the PI controller for heaters is discussed for a better understanding of the tuning process outlined in Figure 6. As discussed before, the heaters are controlled based on a PI feedback controller to maintain the test room temperature to its setpoint defined by the user. The heating capacity of the heater is controlled using a silicon-controlled rectifier (SCR) which is controlled based on an analog control (voltage) output (AO) signal from the test room PLC. Each SCR linearly varies the heater capacity from 0 to 100% corresponding to a 0 to 10V AO signal from the PLC. The heater PI controller in the PLC was implemented to output a 0 to 10V signal to control the room temperature to the setpoint based on feedback from the actual measured value of the temperature inside the test room obtained using an RTD (Resistance Temperature Detector) sensor. The first step in the tuning process is to understand the system (plant) dynamic response with the control output signal to an actuator by collecting step response test data. For this example, the control output signal to heater SCR was varied manually in multiple steps between 0 to 10V in increasing and decreasing order while keeping the other control variables affecting the room temperature as stable as possible. After each step change in the control signal, data was collected until the control variable (temperature) reached a stable value. The step response data is then utilized to develop a plant (system) model using the MATLAB system identification toolbox (Ljung, 2019) capturing the test facility room temperature dynamic response to the control input signal to the SCR. Then the plant model is used in a MATLAB Simulink (MathWorks, 2019b) model with a PI feedback controller to simulate the system response based on an input reference setpoint profile. This simulation model then allows tuning the PI controller gains using the MATLAB control system toolbox (MathWorks, 2019a) based on the desired system response across varied operating conditions. These PI gains provide good initial guesses which are then implemented into the actual system and its response is verified with further testing. If the response is not satisfactory, control gains are fine-tuned manually until the desired response is achieved. In this fashion, control parameters for different PI feedback controllers were tuned to get the desired temperature and humidity control response for both test rooms in addition to other intermediate control variables, for example, the cooling coil evaporating pressures. In this overall tuning approach, to get good initial PI gains, it is critical to get the system step response data across its operating range and select an appropriate linear or non-linear model form in the system identification process to get the best possible model fit. Further, some understanding of the actuator response and its effect on the overall system control variable is also helpful in selecting the appropriate model form.

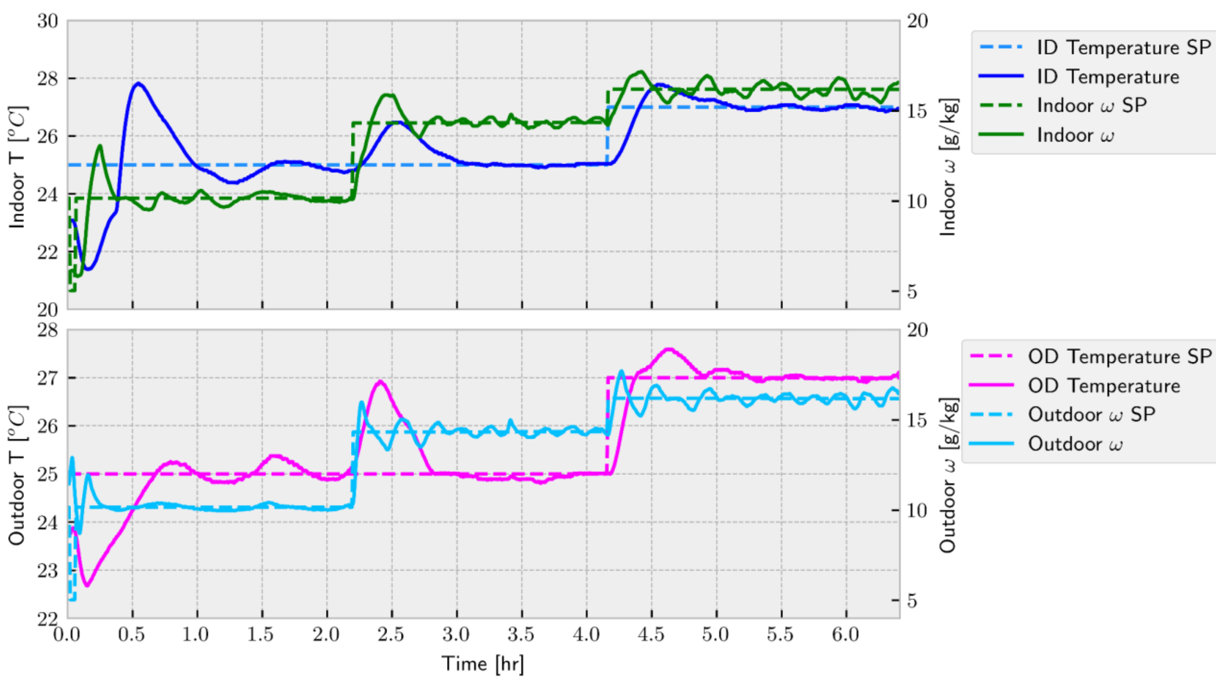

Figure 7. Indoor and Outdoor test room temperature and humidity control response with initial PI gains

Figure 7 shows the temperature and humidity control responses for the indoor and outdoor psychrometric chambers with initial PI gains derived from the simulations based on the plant model developed with step response data. The upper subplot shows the indoor (ID) temperature setpoint (SP) and its actual measured value referenced to the left vertical axis, and the indoor humidity ratio (ω) setpoint and its measured value referenced to the right vertical axis. Similarly, the lower subplot shows the outdoor (OD) temperature and absolute humidity ratio variation. Overall, both test rooms showed reasonable control response for temperature as well as humidity with some overshoot in temperature control and oscillations in humidity control. The increase in both room temperatures around 2.1 hours into the test when the humidity setpoint was increased while keeping the room temperature setpoint constant was due to additional heat added into the test rooms associated with superheated steam introduced for increasing humidity. The test room cooling coils take some time (~30 min) to bring back the air temperature to its setpoint. To further improve the control response, both test rooms' PI gains were manually fine-tuned with updated results shown in Figure 8. At the beginning of the test, initial PI gains were used similar to the ones used in Figure 7, then PI gains for the temperature as well as humidity controller were manually tuned until stable operation was achieved at around 3.5 hours into the test. Both test rooms' operation was verified at different operating conditions required by the AHRI 210/240 (AHRI, 2020) standard and some further controller fine-tuning was done to achieve acceptable controllability over a wide operating range.

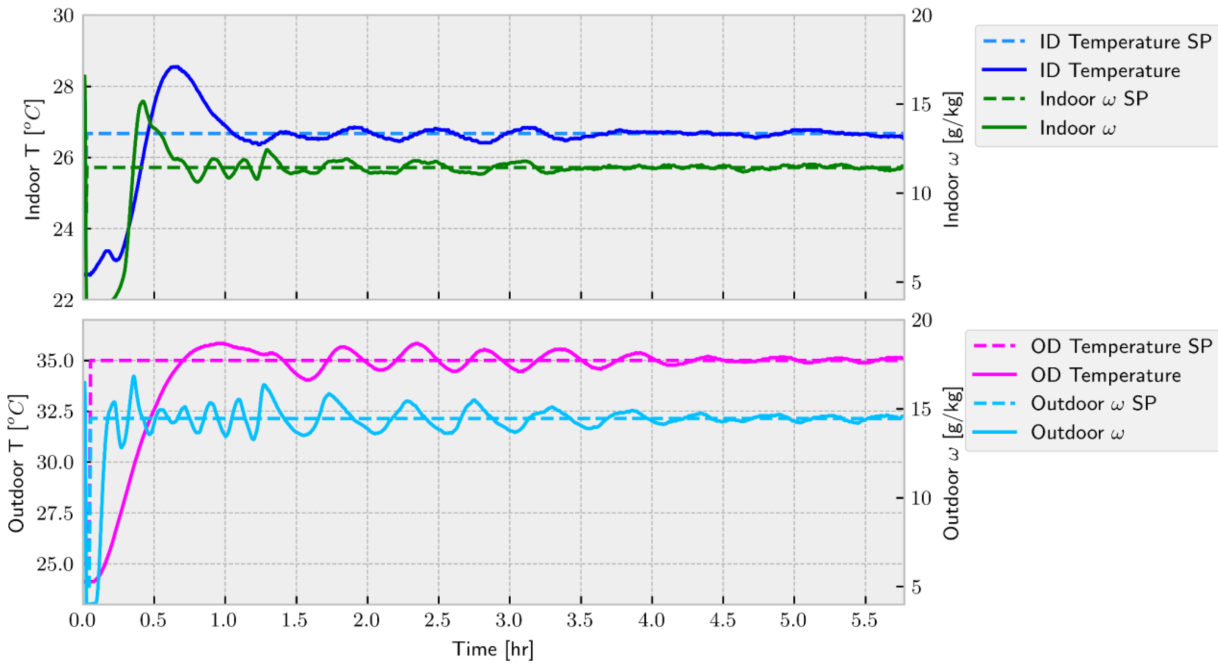

Figure 8. Indoor and outdoor test room temperature and humidity control response during and after manual fine-tuning

5. CONCLUSIONS

This paper presented lessons learned from retrofitting a psychrometric test facility used for testing HVAC&R systems with flammable refrigerants up to A3 flammability classification as per ASHRAE 34 (ASHRAE, 2019b). During the retrofitting process, five different areas were addressed to safely test equipment with flammable refrigerants which are related to a refrigerant leakage monitoring system, a ventilation system, removing ignition sources, grounding to avoid any sparks or static discharge, and temperature and airflow monitoring. In addition to the hardware and control retrofits to the test facility, a standard operating procedure was also developed and documented to ensure the safe installation, operation, service, and testing of equipment with flammable refrigerants in test rooms. Further, the test facility control hardware and software were also upgraded from the previous generation for better flexibility in the controls design and implementation for test room stable operation across varied conditions. The control architecture for the test facility was developed based on using PI feedback controllers for different actuators in order to control temperature and humidity in the test rooms. In this paper, the overall test facility control approach was presented along with an approach utilized for tuning controllers. Finally, both test rooms' temperature and humidity control responses were shown. One of the possible future tasks is to implement a multiple-input and multiple-output (MIMO) control approach for this coupled system rather than the single-input and single-output (SISO) configuration implemented currently to further improve its control and operation.

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