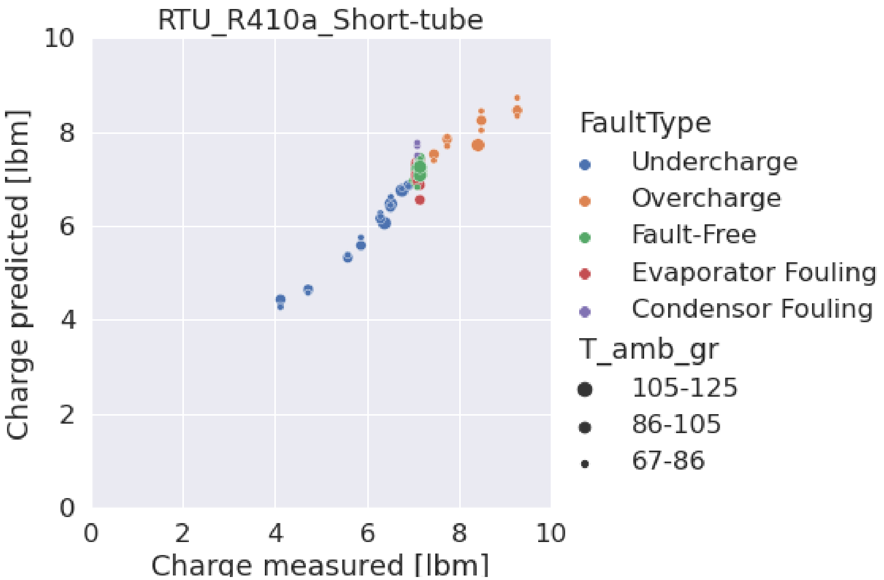
Virtual Sensor-based FDD and Control Suite for Widespread Adoption of Residential Embedded-FDD Heat Pumps



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WBS: 3.2.2.58, FOA/Lab Call Number: L095-1573

Project Summary

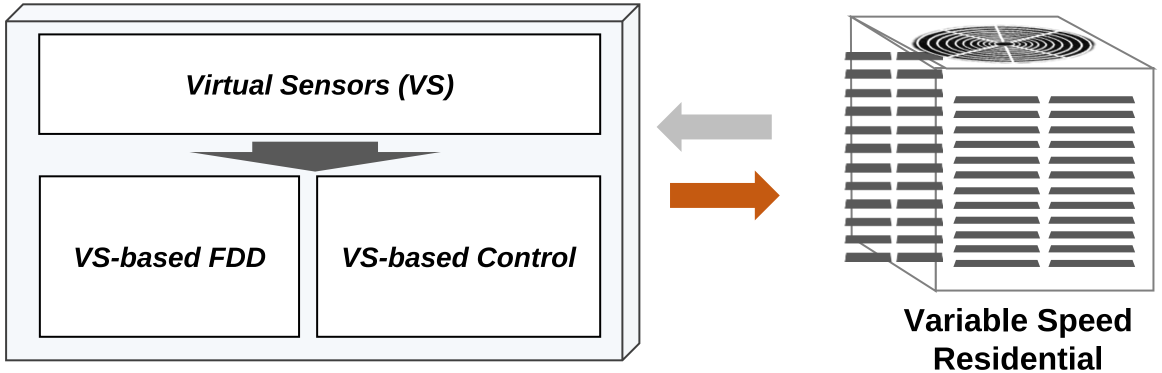
Objective

- Develop a technology to help disseminate **residential heat pumps that have built-in FDD**
- The technology is based on **virtual sensors** and aims to fully leverage the available sensor infrastructure, as well as the increased controllability of variable speed heat pump

Outcome

- Open-source Virtual sensor-based FDD & Control Suite
- A prototype of new heat pump system
- Laboratory performance test results

Target: (1) Increased FDD capabilities and reliability and (2) energy efficiency improvement, without adding additional sensors



Virtual Sensor-based FDD and Control Suite

Variable Speed Residential Heat Pump

Team and Partners

BERKELEY LAB · OAK RIDGE National Laboratory · PURDUE UNIVERSITY · The UNIVERSITY of OKLAHOMA · CBE CENTER FOR THE BUILT ENVIRONMENT · Johnson Controls

Stats

Performance Period (**new project**):

Oct/2022 – Sep/2025

DOE budget: $1,300k, Cost Share: $0 (Lab call)

Milestone 1: VS development

Milestone 2: VS-based FDD& Control Suite

Milestone 3: Performance test results for prototype

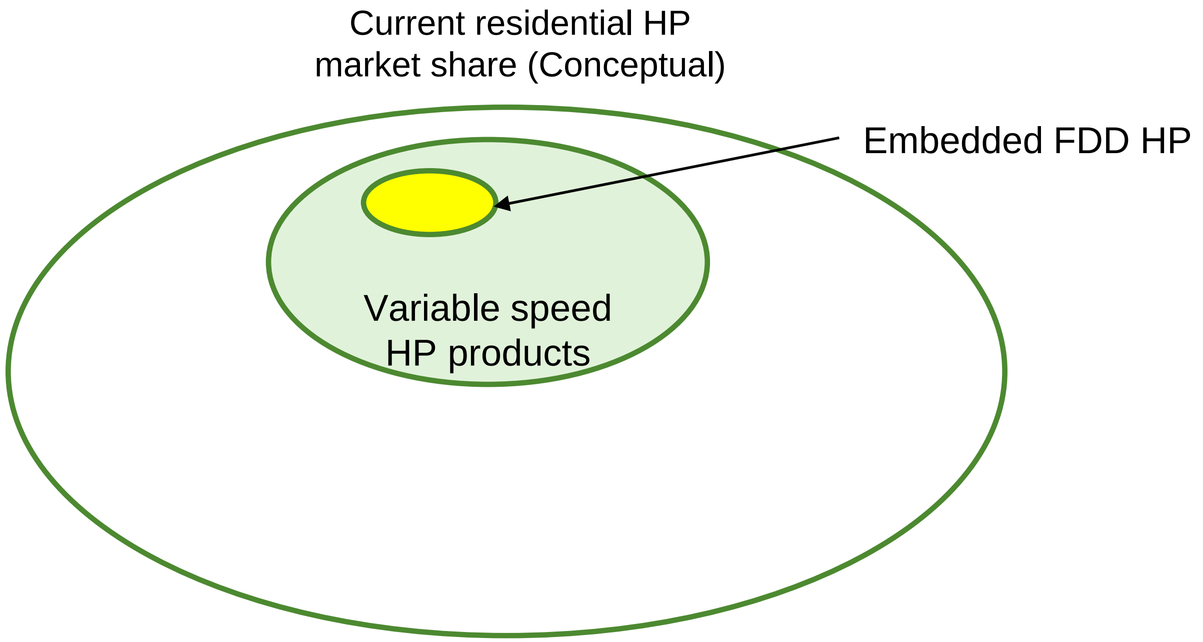
Problem Statement

All HP manufacturers have chosen to embed FDD

only in their premium variable speed HP models in the residential market [1]

This is because

- Incorporating FDD into low-tier products increases sensor/software/installation costs
- Homeowners are reluctant to bear the additional expenses for the FDD feature
- On the other hand, high-end products that feature variable speed compressors often come equipped with a built-in sensor network to monitor equipment reliability



[1] Butzbaugh, J., Tidwell, A., & Antonopoulos, C. (2020). Automatic Fault Detection & Diagnostics: Residential Market Analysis (PNNL-30077). Pacific Northwest National Laboratory. https://doi.org/10.2172/1670423

Alignment and Impact

– **Homeowners:** reduced maintenance cost (due to FDD) + reduced bills (due to better controls+ FDD)

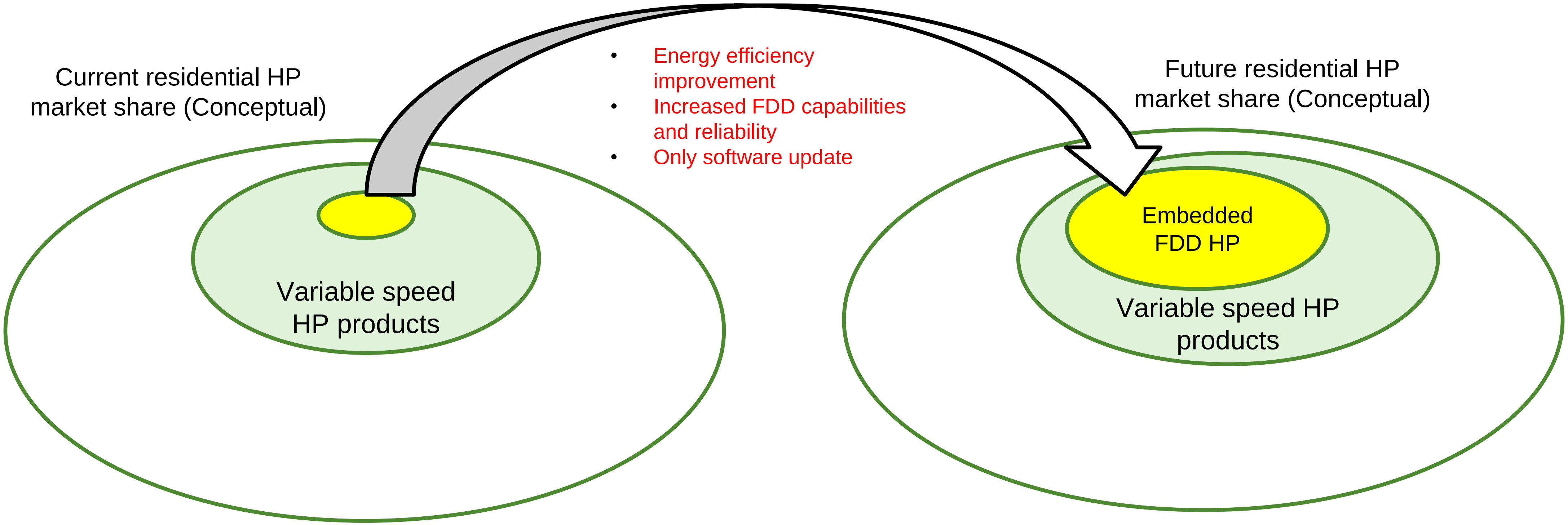
– **Manufacturers:** expanding the residential HP market (due to better efficiency)

– **Utilities:** reduced electrical load + monitoring capability to track energy efficiency

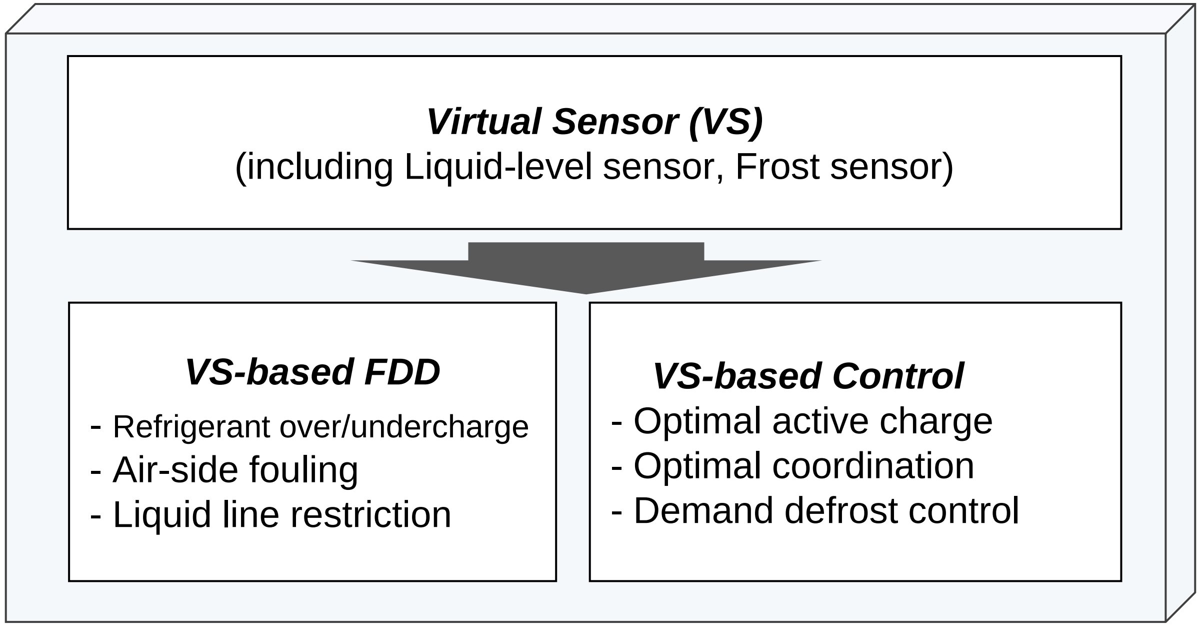
– **States and federal governments:** improved energy efficiency, facilitating electrification, and reduced carbon emission

Approach: we propose a solution that aligns with the industry's business decision

- Fully leverage the **available sensor infrastructure** and **increased controllability of variable speed HP** systems
  - To further improve energy efficiency and hence to **offset of the cost increment** for FDD
  - To increase FDD **capabilities and reliability**



Approach: we propose "Virtual Sensor based FDD and Control Suite" to achieve the goals based on previous research



Virtual Sensor-based FDD and Control Suite

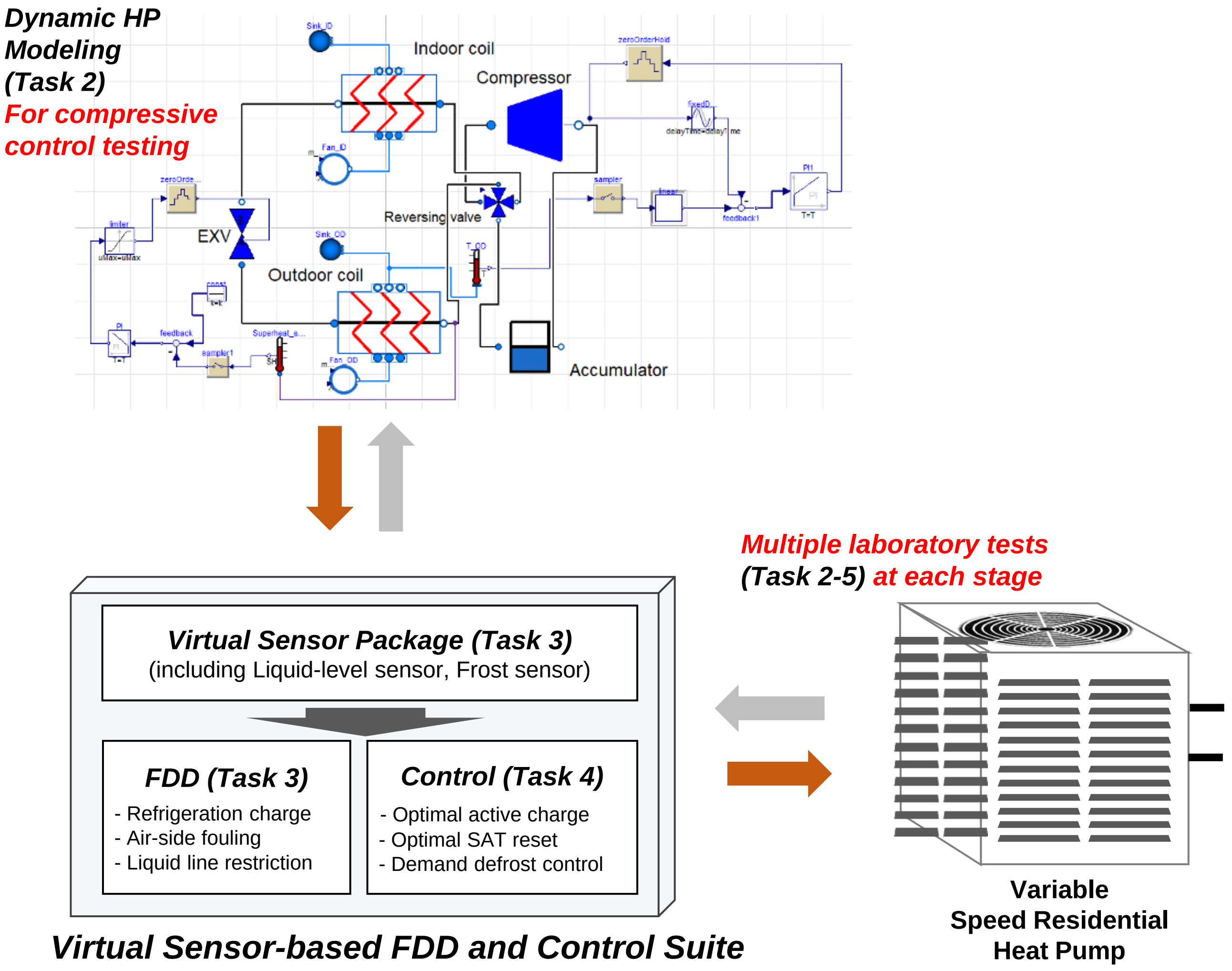
Sources of energy efficiency improvement

- By enabling **zero-superheating** while preventing refrigerant flood back, and **optimizing the active charge** by **observing the liquid volume** in the accumulator: around **10%** efficiency improvement in recent lab tests
- **Optimizing coordination** between compressor and fan speeds: **5%** improvement in a prior test
- **Demand defrost control** is also possible by combining with VS-based FDD providing an additional overall efficiency improvement

The reliability/capabilities of VS-based FDD has been demonstrated for a variety of different VCSs including chillers, split-systems, packaged systems, HPs/ACs with various component combinations.

Overall Task Breakdown

Task Name
Task 1: Planning, Reporting, and Management
Task 2: Development of **Dynamic HP Model**
Task 3: Development of VSs, and **VS-based FDD**
Task 4: VS & FDD-based **Control Design**
Task 5: Performance **Assessment**
Task 6: **Dissemination and Industry Engagement**



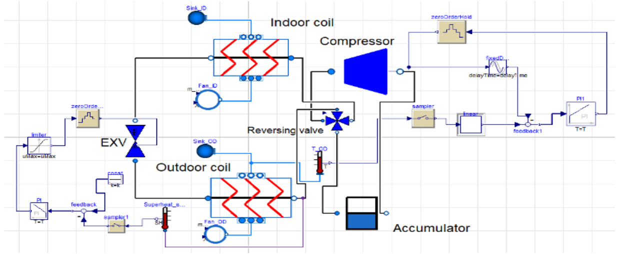
To effectively and timely carry out research tasks with reliability, this project engages

PURDUE UNIVERSITY

BERKELEY LAB

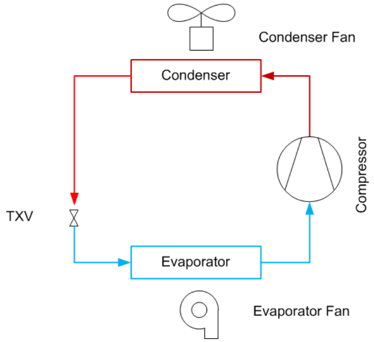
The UNIVERSITY of OKLAHOMA

OAK RIDGE National Laboratory



Dynamic HP model (Modelica)

Smart Building Lab



Heat Pump Design Model

Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
Program Management	Model Development	Virtual Sensor -based FDD	Control Development	Prototype Performance Test	Dissemination and Industry Engagement
LBNL, Purdue, OU, CBE, ORNL, JCI	LBNL, Purdue, ORNL, OU	LBNL, Purdue, OU	LBNL, OU	LBNL, CBE, OU	LBNL, Purdue, CBE

Johnson Controls

Dissimilation and Industry Engagement

CHPB CENTER FOR HIGH PERFORMANCE BUILDINGS AT PURDUE

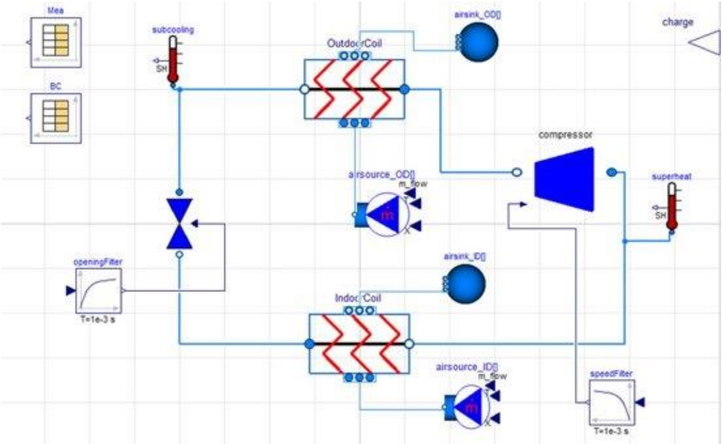
Carrier
DAIKIN
TRANE TECHNOLOGIES
Johnson Controls
LENNOX
Rheem
EMERSON Climate Technologies
LG

ASHRAE

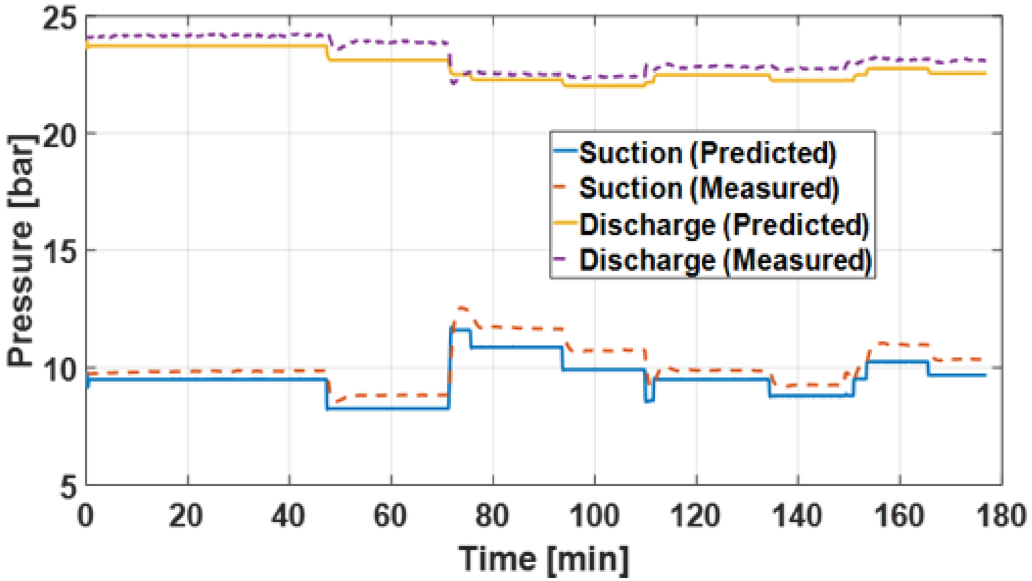
Barriers, Technical Challenges, Project Risks & Mitigation

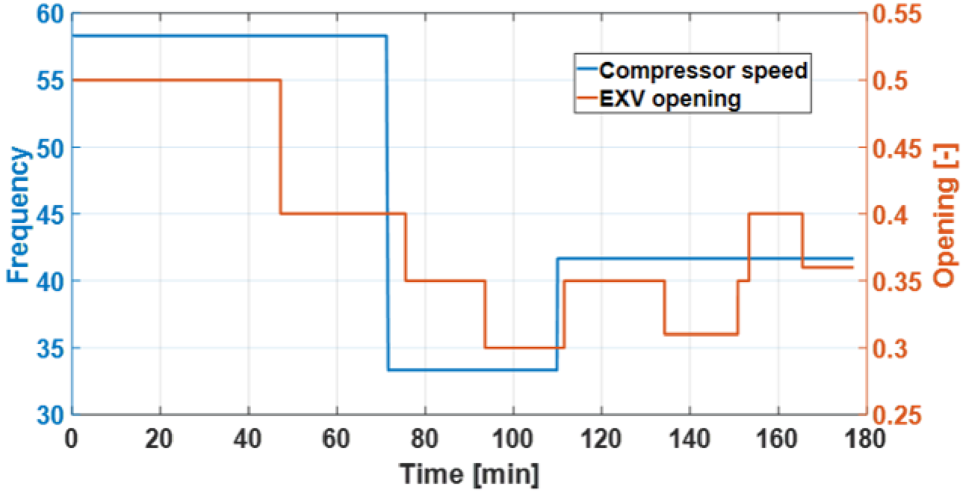
Technical challenges, Risk Descriptions	Response Plan
Unforeseen **cost overruns** in the deployment budget occur.	Leverage existing installation and facilities of our diverse team member and pursue to **create synergistic projects within the CHPB and ASHRAE** (Task 6)
A certain development step (e.g., virtual sensor development) **does not perform** well.	Immediately share and discuss the issue(s) in our team meetings and to resolve. If it is identified as unresolvable, **find an alternative strategy through brainstorming**: each team member has **extensive experience** in thermal systems
The test procedure development (Task 5.1) is not straightforward due to lack of **standard procedures for evaluating controls** (Task 5).	If the test procedure is not well established, switch to an alternative laboratory facility of our teams (ether FLEXLAB or Purdue Chamber) which can compare two systems under the same load conditions: **load-based performance rating**

A complete dynamic cycle model for cooling mode was developed and validated with measurements

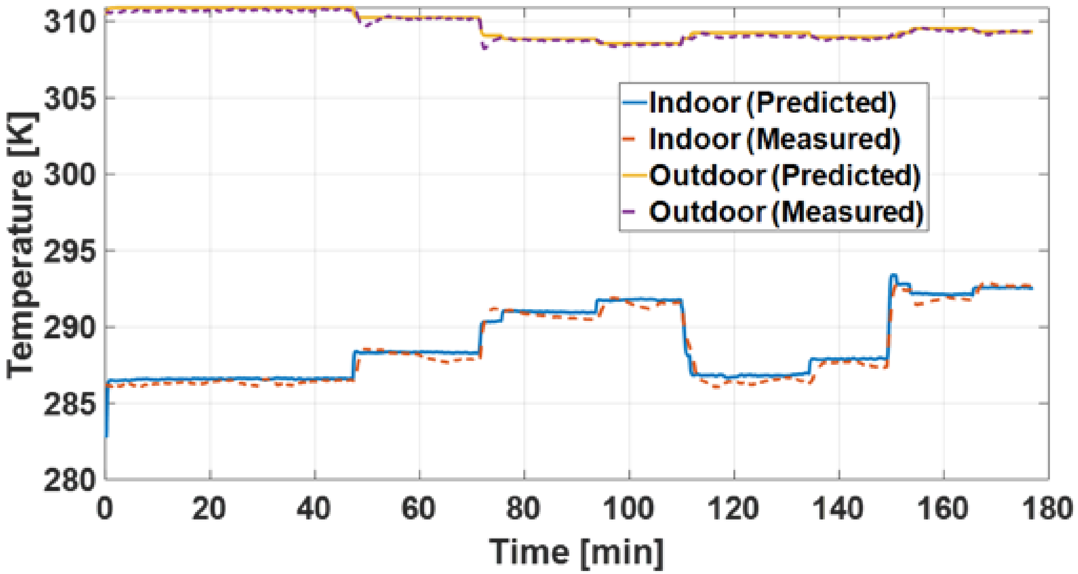


Modelica model for the JCI unit



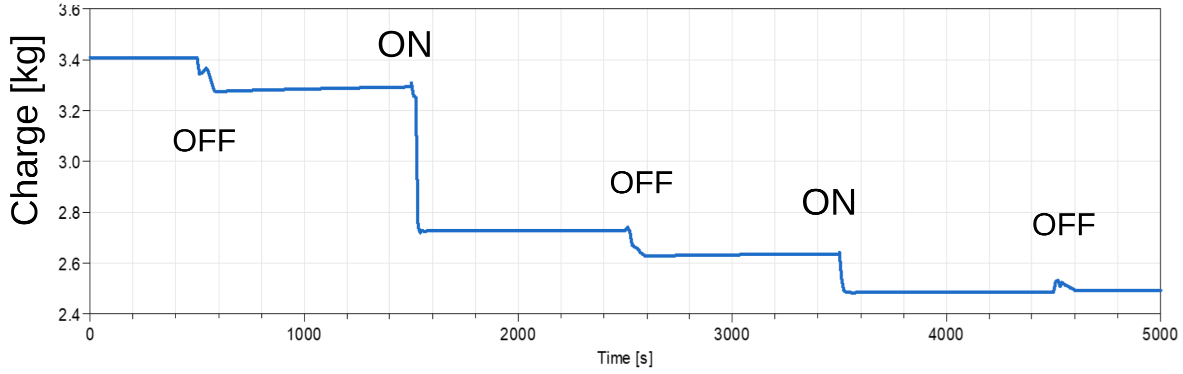


Test signals to the dynamic model

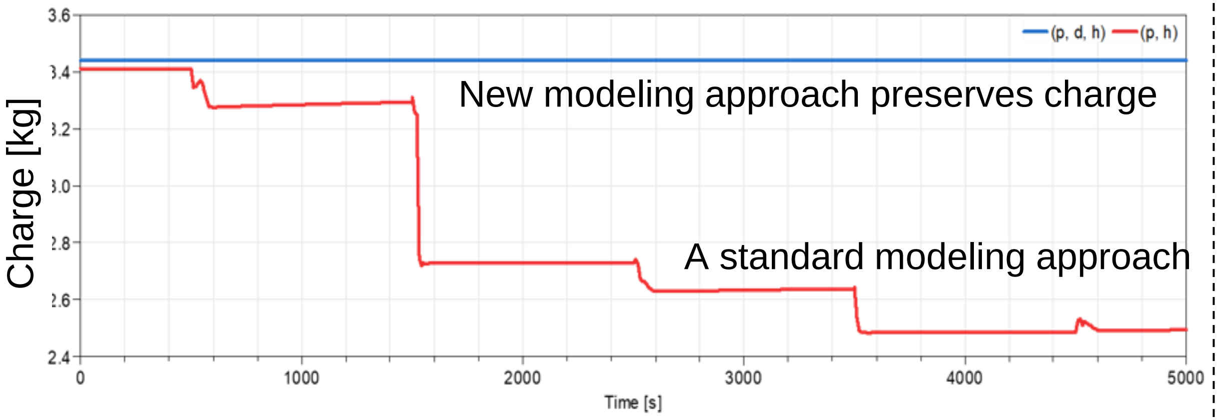


We resolved numerical issues for compressor ON/OFF cycling & mode switching

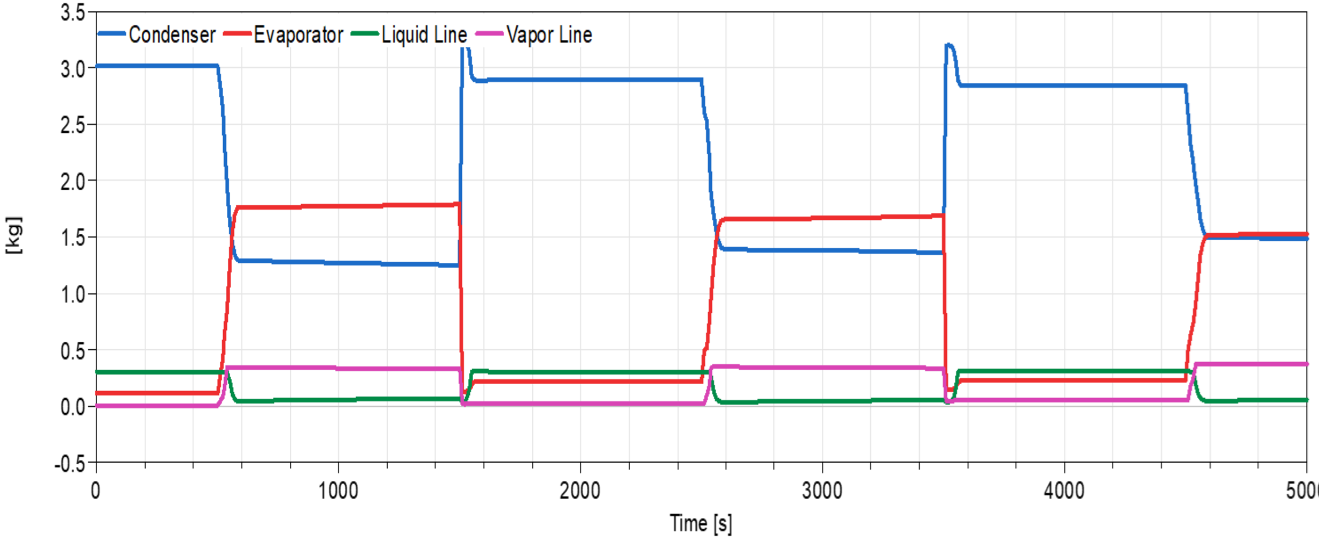
Problem: A standard dynamic modeling approach does not preserve refrigerant charge



Result comparison

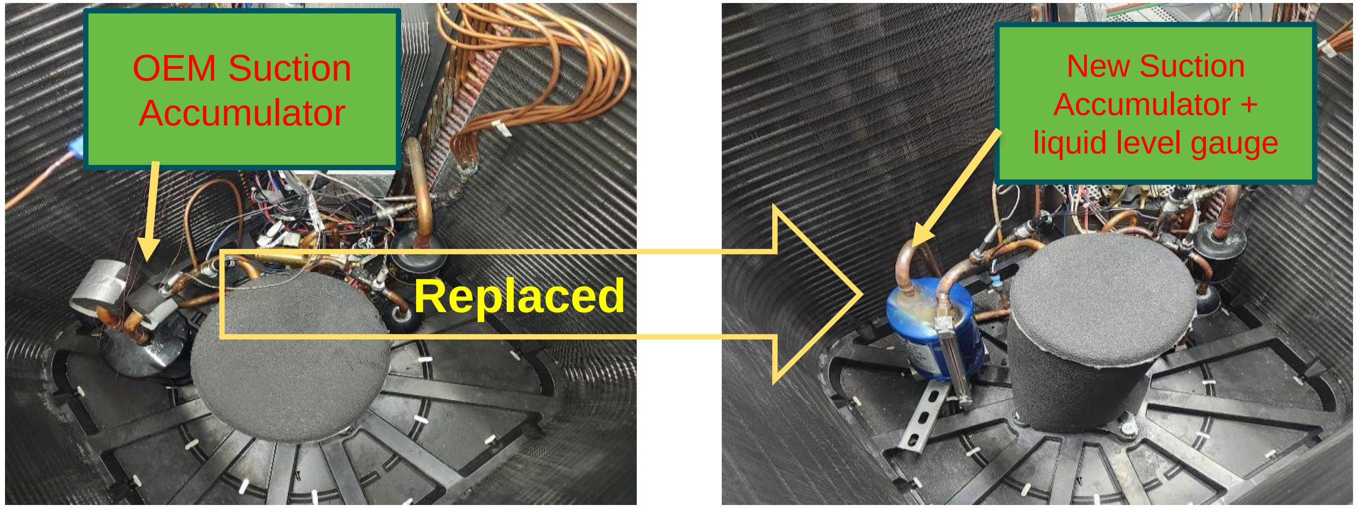


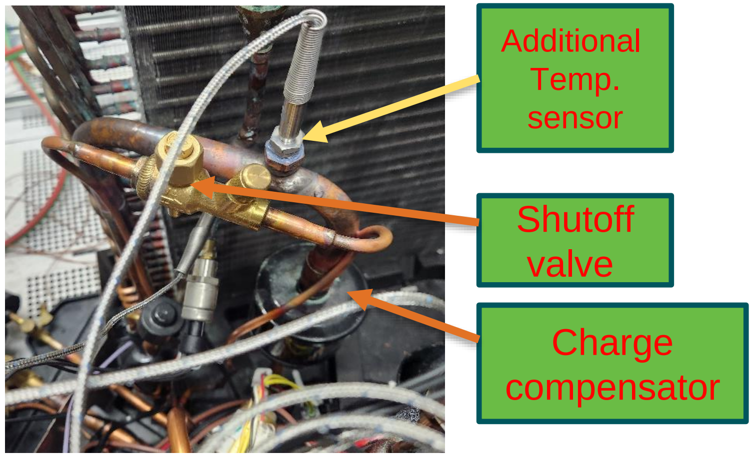
The new modeling approach also allows investigating charge migration during compressor cycling



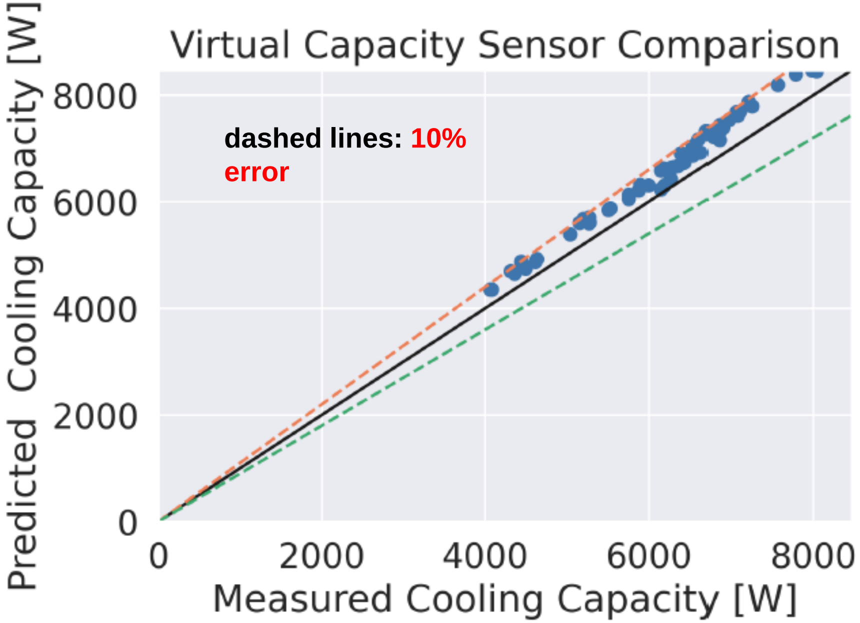
We are upgrading and incorporating additional devices into the baseline HP

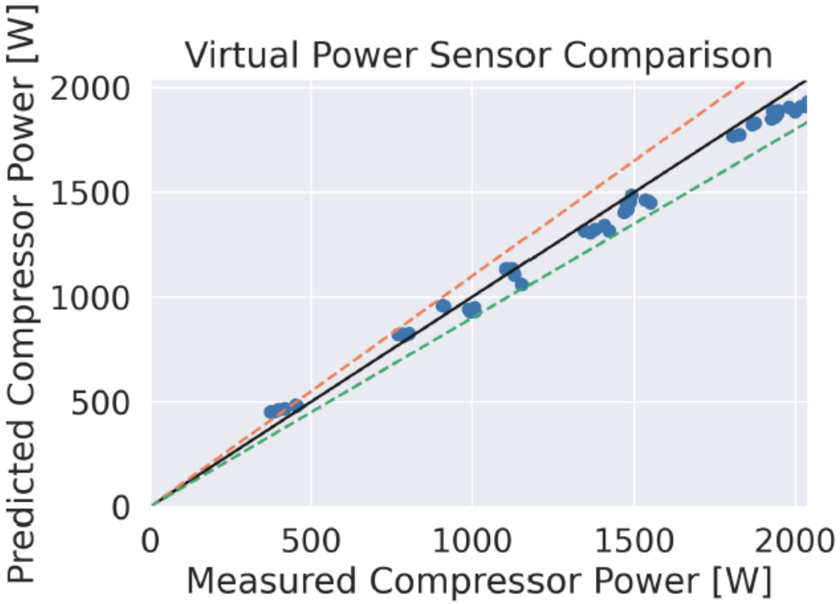
- Installed the suction accumulator **liquid level gauge**
- Installed additional pressure and temperature transducers **needed for analysis**
- Installed manual **shutoff valve** to isolate/re-connect charge compensator
- Completed pressure tests and two nitrogen-vacuum cycles to remove any moist air in the refrigerant circuit
- Reconfigured refrigerant mass flow meter to measure bidirectional flow





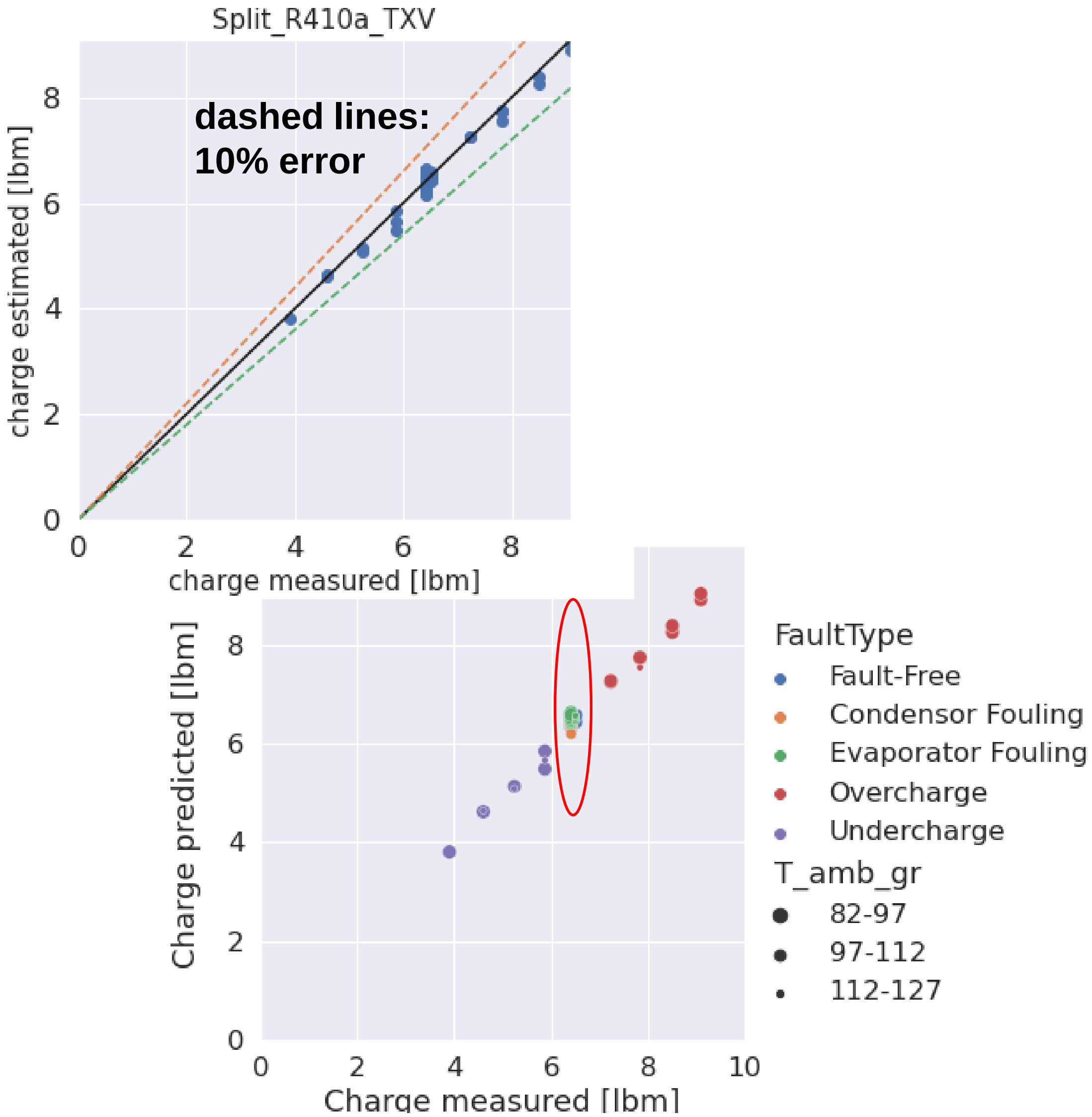
Implemented virtual power and capacity sensors, and compared with the OU's experimental data for the baseline HP unit (57 operating data points)

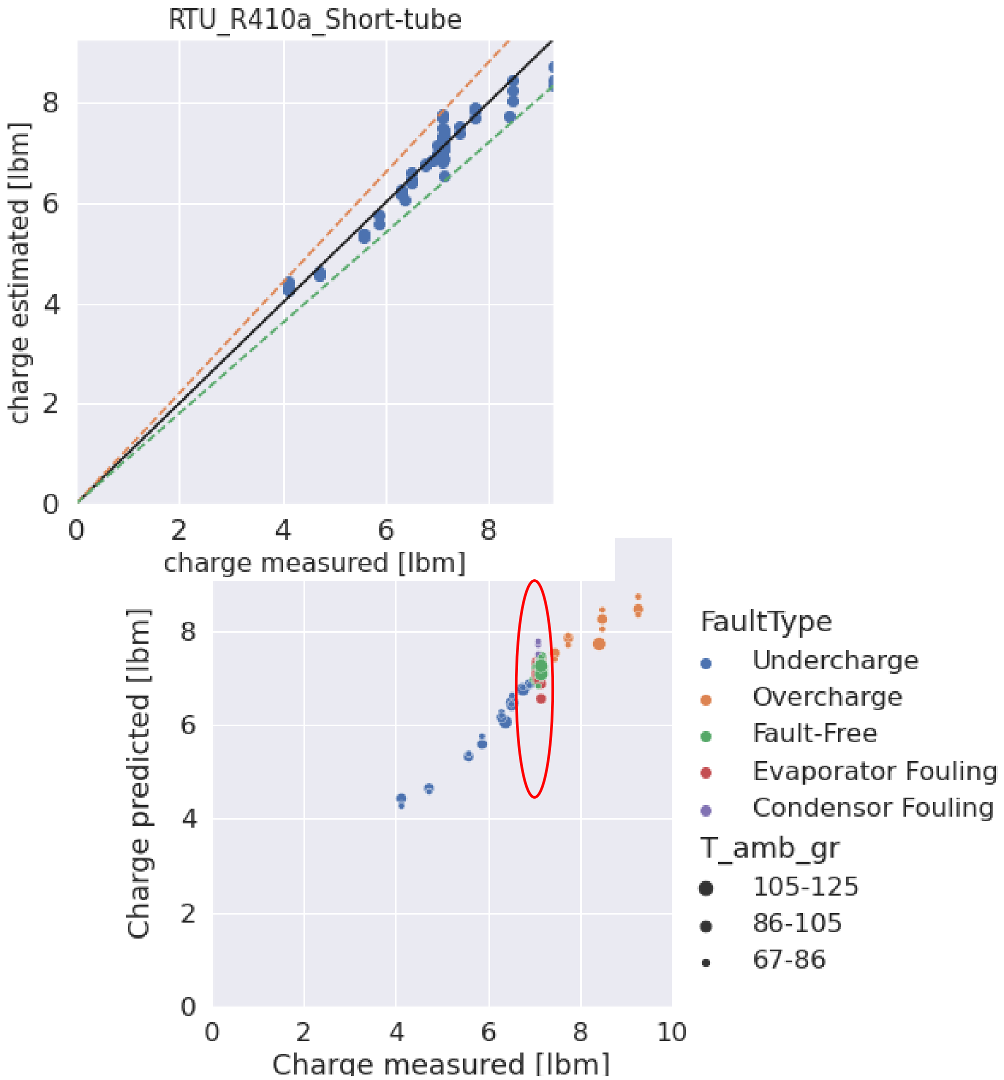




Confirmed that the information is available for the baseline HP unit

Compared the virtual refrigerant charge sensor with fault-free and faulty data for other units: VRC is insensitive to other faults and operating conditions





Future Work (FY23 - FY24)

LBNL	Complete validating VSs, VS-based FDD/Control using the simulation model and experiments
	Perform final experiments
ORNL	HPDM modeling for the JCI HP unit and comparison with experimental data
Purdue	Cross validate the dynamic model with HPDM and experiments
	Build a dynamic model for the JCI unit under frosting and defrosting conditions
OU	Finalize experimental setup and perform lab tests
	Develop and validate the virtual liquid-level sensor
	Develop and test control using both simulation and lab tests
JCI	Provide feedback on the project progress
	Donnate the baseline HP product

Thank you

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Project Execution

Task Name	FY23				FY24				FY25			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1: Planning, Reporting, and Management												Final Report
Task 2: Development of Dynamic HP Model	M2.1		M2.3	G/NG1								
Task 3: Development of Virtual Sensors, and Virtual Sensor-based FDD		M3.2			M3.4							
Task 4: Virtual Sensor & FDD-based Control Design						M4.2	M4.3	G/NG2				
Task 5: Performance Assessment									M4.5	M5.2	M5.3	
Task 6: Dissemination and Industry Engagement					M6.3			M6.2				M6.4

Key Team Members

- **LBNL:** Donghun Kim (PI), Sang Woo Ham
- **Purdue University :** James Braun, Jiacheng Ma
- **University of Oklahoma:** Jie Cai,
- **ORNL:** Bo Shen
- **Johnson Controls Inc**: Roy Crawford
- **UC-Berkeley, Center for the Built Environment:** Hui Zhang

Competitive Advantages

	Commercially existing embedded- FDD HP products	Academic state-of-the-art FDD or state-of-the-art controls	Proposed technology
FDD capabilities	Vary depending on products	Refrigerant over/undercharge, leakage, refrigerant liquid-line restriction, air-side fouling	Isolated frost-level detection (from fouling) in addition to the state-of-the-art FDD
Sensor costs for FDD	Proprietary, expected to be high	Low (only temperature sensors, cf. compressor speed info. is available for variable speed units)	Low (the same as the state-of-the art FDD)
Real-time monitoring of energy efficiency	No (no products provide this, Butzbaugh et. al. 2020)	Yes	Yes
Dynamic active charge control	No	Yes (Koeln & Alleyne, 2014) with a special liquid level detector	Yes, but with sensors for FFD (through the low-cost virtual liquid-level sensor).
Energy efficiency	High because of the premium variable-speed unit	Higher (8~10% efficiency improvement for variable speed AC unit, Koeln & Alleyne, 2014, Liu & Cai, 2022)	Highest (target overall efficiency improvement of 15%)
Defrost control	Either schedule-based or thermistor-based initiation, Mostly clock-based termination	Demand defrost mostly for initiation (Song et. al. 2017). Need additional sensor(s) such as evaporator temp. or temp. difference, pressure difference, infrared thermometer or photo-optical	Demand defrost for both initiation and termination. Use sensors for FFD
Defrost energy	High	Low	Low (the same as the state-of-the-art control)
Integrated FDD and advanced controls	No	No	Yes
Product price for FDD	High	- Medium without advanced controls (due to reduced sensor cost) - Very high with advanced controls	Medium (the same as the state-of-the-art FDD)
FDD scale-up potential for the residential market	Low (limited market: the current issue)	Low	Medium