Development of Sustainable Heat Pump Systems for Electrified Transitions in Winter Markets

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Project Summary

Objectives and Outcomes

❑ Design and introduce new novel ASHPS with reduced GWP refrigerant -namely TR-CO_2-for space heating/cooling and domestic hot water into Multi-Family Buildings in Cold-Climates.

❑ Lab and Field tests to demonstrate system performance of commercially available ASHPS, namely R410 systems and new low GWP systems exceeding DOE/BTO marks.

Motivation & Impact

❑ Cities' adoption of decarbonizing strategies with NYC as exemplar case with local Law 97 (80% reduction by 2050; effective in 2024).

❑ Buildings represent >70% of all NYC GHG Emissions.

Solution Idea Concept

❑ Novel Transcritical Cycle for Heating/Cooling/DHW

❑ Global Warming Potential (GWP) = 1

❑ Ozone Depletion Potential (ODP) = 0

Team and Partners

PI-Jorge E. Gonzalez-Cruz
CoI-Prathap Ramamurthy
Doctoral Students (2)
Master Students (2)
Undergraduate Students (1)
- _University at Albany & City College of New York_
- _City of New York_
- _Rheem_

Stats

Performance Period: 2021-2024

DOE budget: $740K, Cost Share: $N/A

Milestone 1: Design and Build Lab Testing Facility for R410 & R744

Milestone 2: Model development for unit

Milestone 3: Field testing of units in actual multi-family buildings in NYC.

Industry/Government Motivation

Motivation?

- ❏ NYC's roadmap to 80 by 50
- ❏ Compliance with NYC's Local Law 97

Why Buildings?

- ❏ 68% of all NYC GHG Emissions come from buildings
- ❏ 15,000 medium and large multifamily properties:
  - 35% of NYC real estate, ~1.35 billion square feet
  - ~82% are heated by old, inefficient steam systems, fueled by NG or fuel oil.

Why Transcritical CO2 Heat Pump Systems?

- ❏ Global Warming Potential (GWP) = 1
- ❏ Ozone Depletion Potential (ODP) = 0

GHG Emissions from Large Buildings by End Use (2014)

Image Source: New York City's Roadmap to 80 X 50 (2020). Accessed from nyc.gov/onenyc
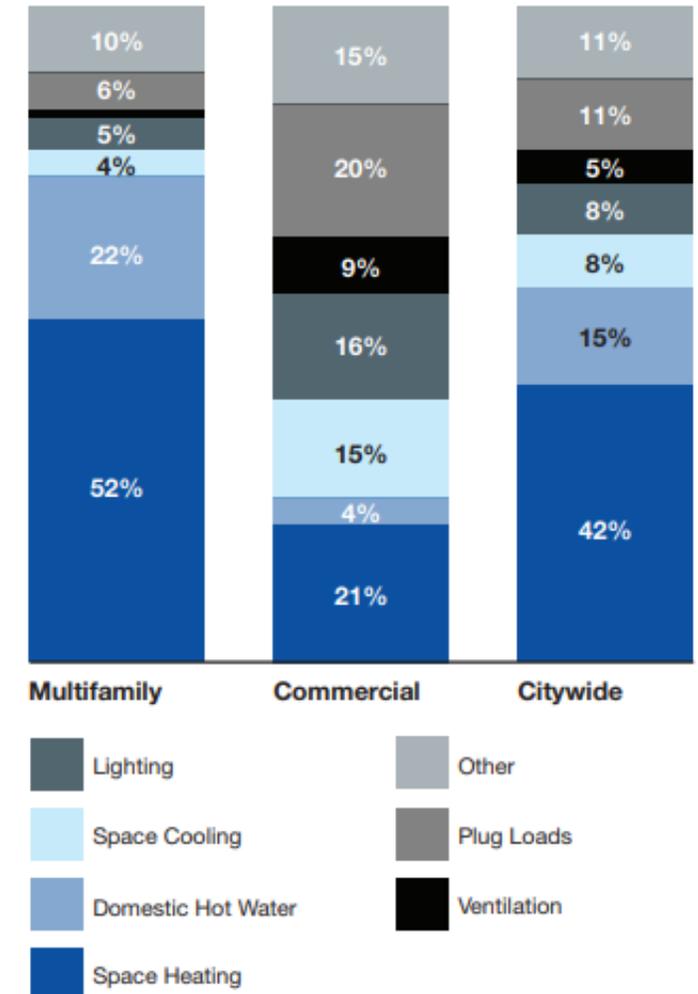
Main Objective & Approach:

- To design, develop, prototype and test electrical air-source heat pumps (ASHP) for hot water, space heating & cooling for multi-family buildings. Systems should specifically focus on the use of R410 & transcritical carbon dioxide (TR-CO$_2$) systems.

General Methodology
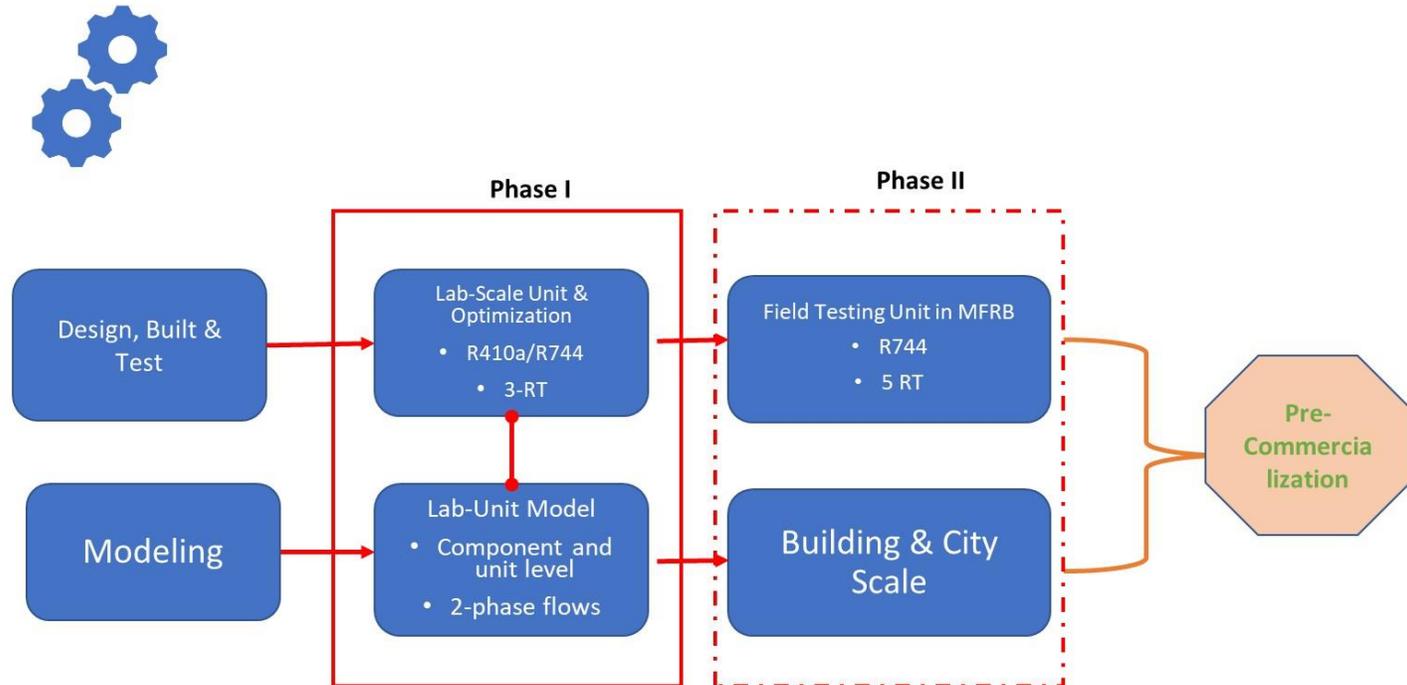
Approach

Transcritical Cycle Process

❑ Transcritical Cycle **=** when heat rejection takes place above the critical point of the refrigerant

Major Differences

❑ There is no condensing process as seen in conventional HP cycle

❑ Not a phase change process in the condenser

❑ Critical Point of R744 (CO_2): 31 °C (87.8 °F), 7.38 Mpa

❑ Critical Point of R410A: 71.4 °C (160.5 °F), 4.9 MPa, GWP = 208

Opportunities

❑ GWP=1.0

❑ ODP=0.0

❑ High temperature heat-rejection->Space Heatin+DHW

Challenges

❑ Transcritical instabilities

❑ Low COP
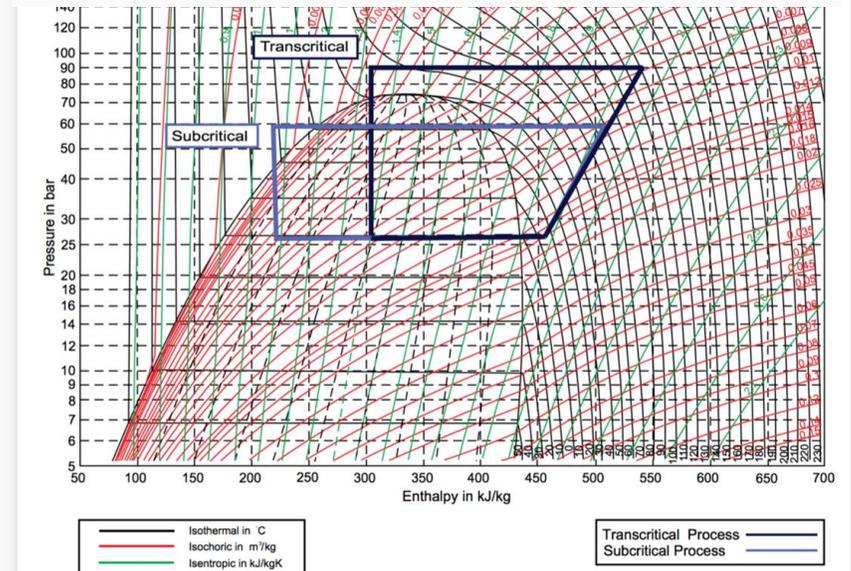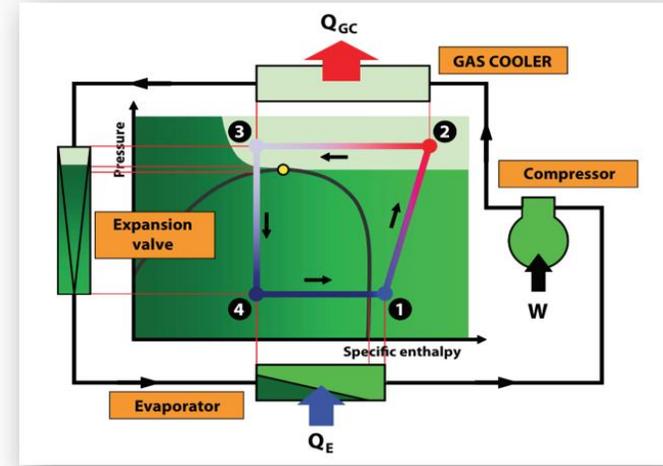

Image source: Commercial CO2 Refrigeration Systems Guide for Subcritical and Transcritical CO2 Applications.

Go/No-Go Approach:

| Task	Performance Parameter	Target Goal	Go/No-Go Point
1a	Functional operational testing facility	All system's components functional, safe, and enable continuous experimentation	Control experiments are possible for expected operational conditions; Outdoor 19-40⁰F
1b	Lab system performance	Seasonal COP > 2.0	COP >3.0
2a	All Lab-unit components Simulated	A unified model is functional with all components included	Validation with reported data
2b	Lab-unit model validation/R410/R744	Model validated with experiments, errors within 10%	Fully validated unit-level model
3	Building modeling for actual units for multi family buildings for NYC	Model configuration and validated with City Data for multi family buildings for R410 & R744	Model configuration for actual multi family buildings and validated with City Data for multi family buildings
4a	Building selection for field testing	Building retro-fitted design & cost analysis	Positive feedback of NYC Offices of Buildings
4B	Building unit commissioned & installed for selected building	Retro-fitting is completed, system commissioned and tested	Positive feedback of NYC Offices of Buildings & residents. System performance documented for scaling.
5	Expand for Dual/Triplet Functionality	New unit is designed and tested to include space cooling and hot water.	New unit meet performance standards for COP higher than 2.0 for heating, cooling, and DHW.

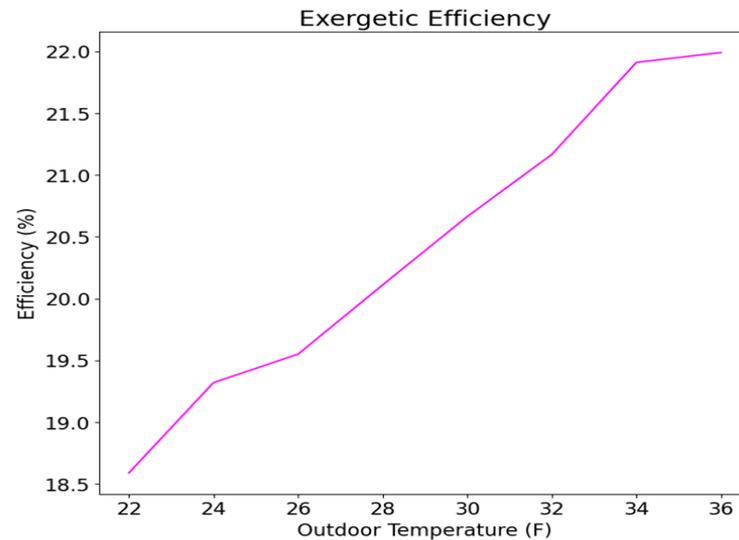# Task-1: Current Progress: Lab-Scale units design & construction for R410a & R744 Units
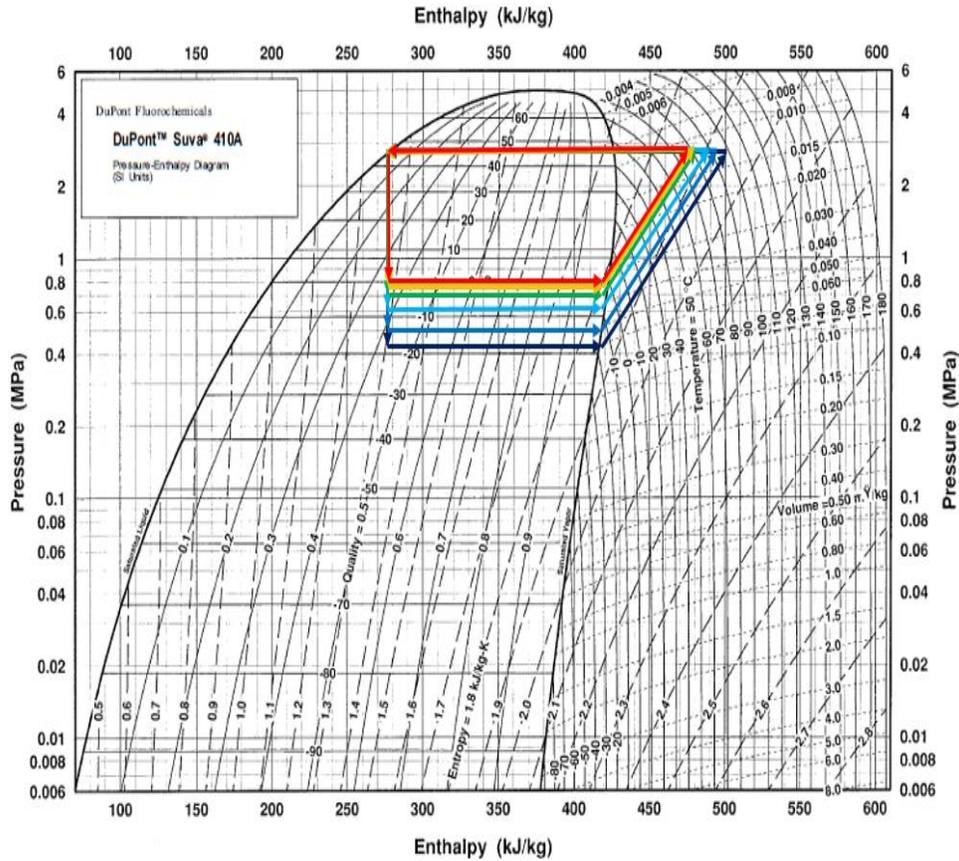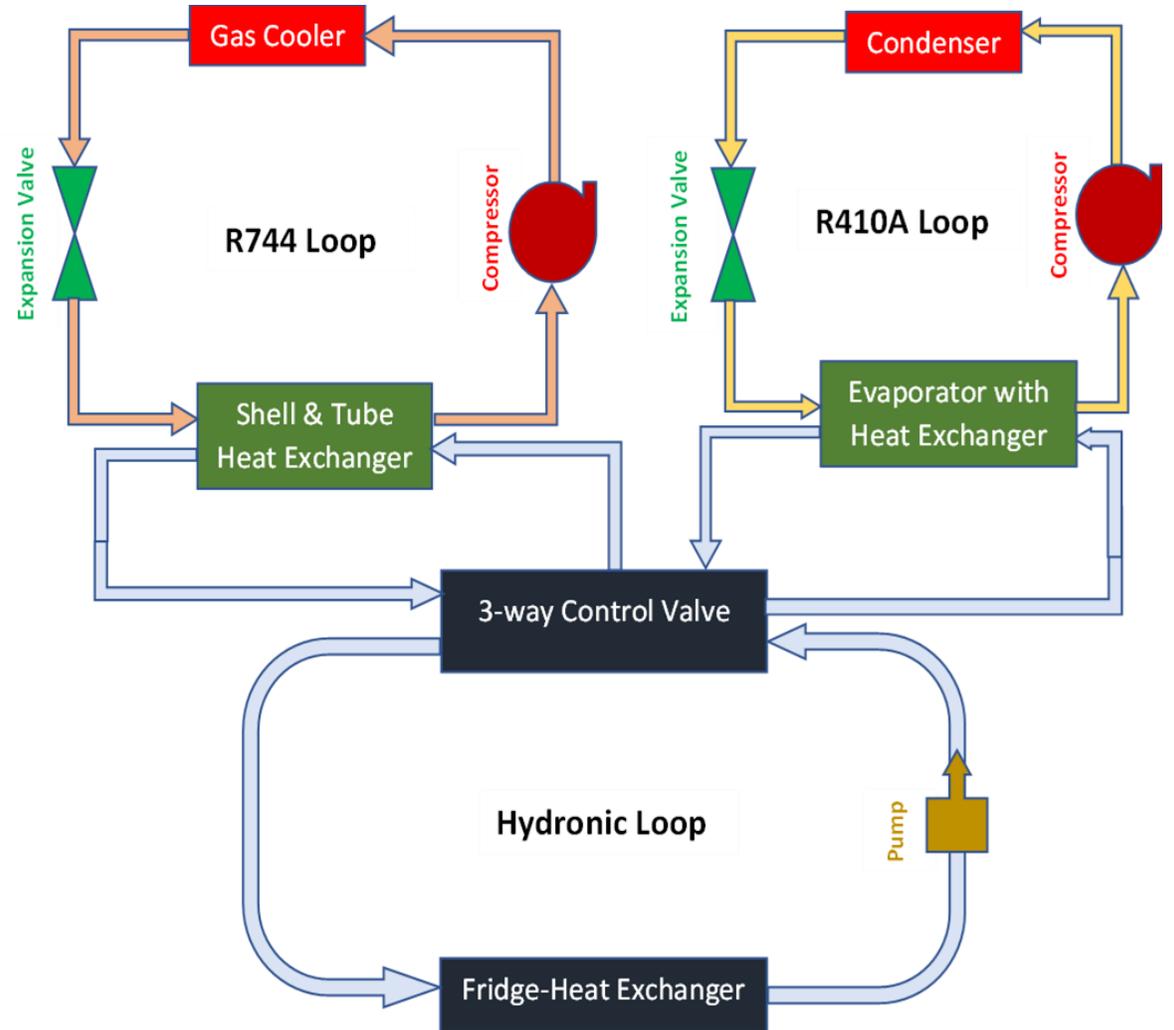
Current Progress- Hydronic Loop & R410a Unit
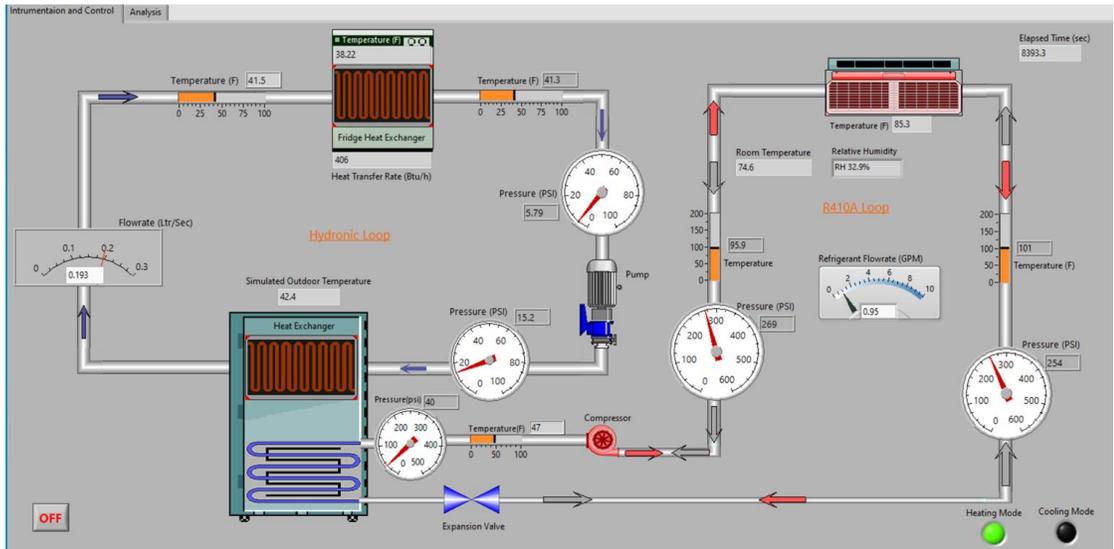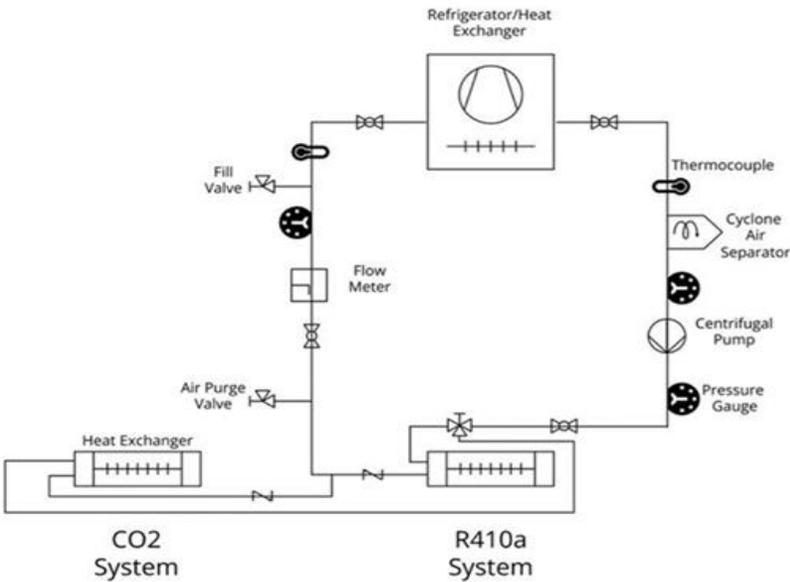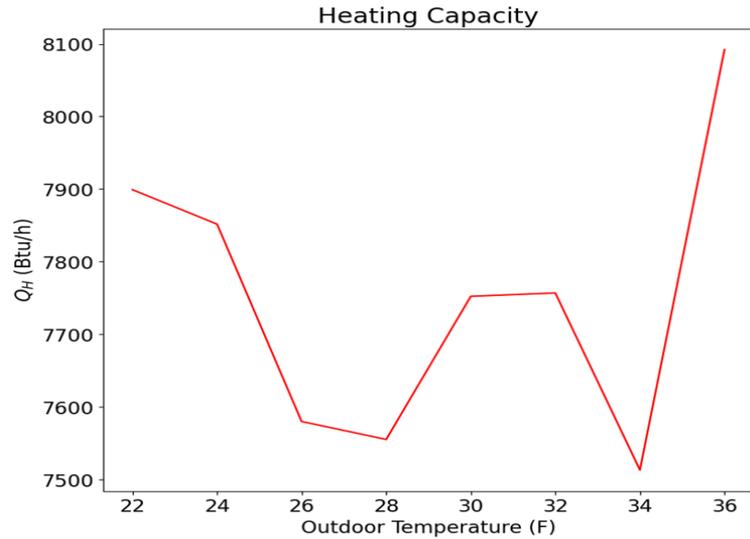
Task-2: Preliminary Testing and performance Analysis-R410a

Heating Capacity

Power Consumption

1st Law Efficiency

Exergetic Efficiency
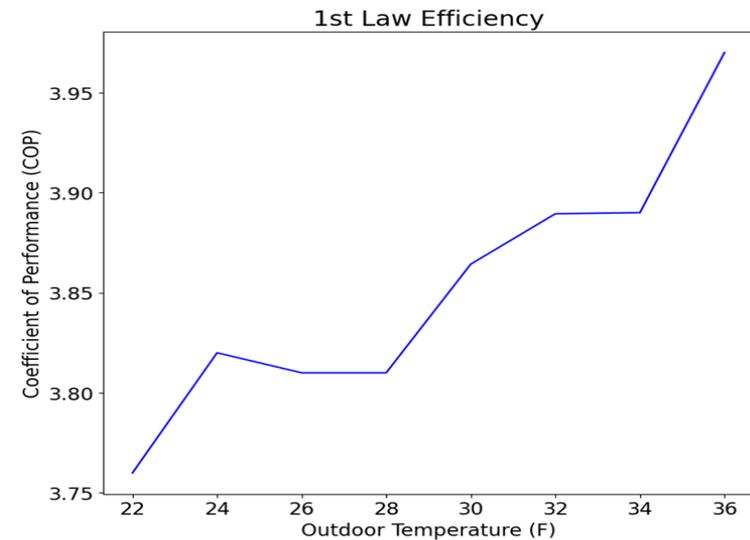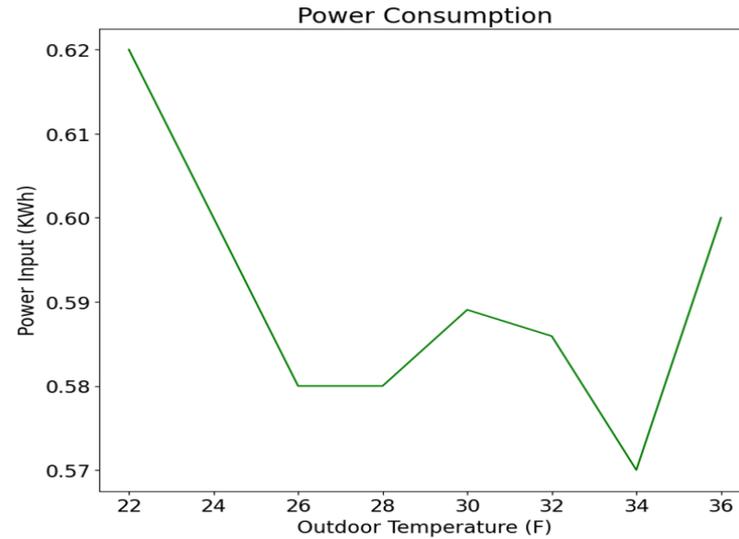
1st Law Analysis

$$Effectiveness = \dot{m}_{refrigerant} \times \frac{h_2 - h_3}{\dot{m}_{air} \times c_{p,air} \times (T_2 - T_{room})}$$

$$Q_{cond} = Effectiveness \times \dot{m}_{air} \times c_{p,air} \times (T_2 - T_{room})$$

$$Heating\ Capacity\ \ Q_H = Q_{cond} \times 3.41\ (Btu/h)$$

$$Power\ Input = W_c$$

$$Coefficient\ of\ Performance = COP = \frac{Q_{cond}}{W_c}$$

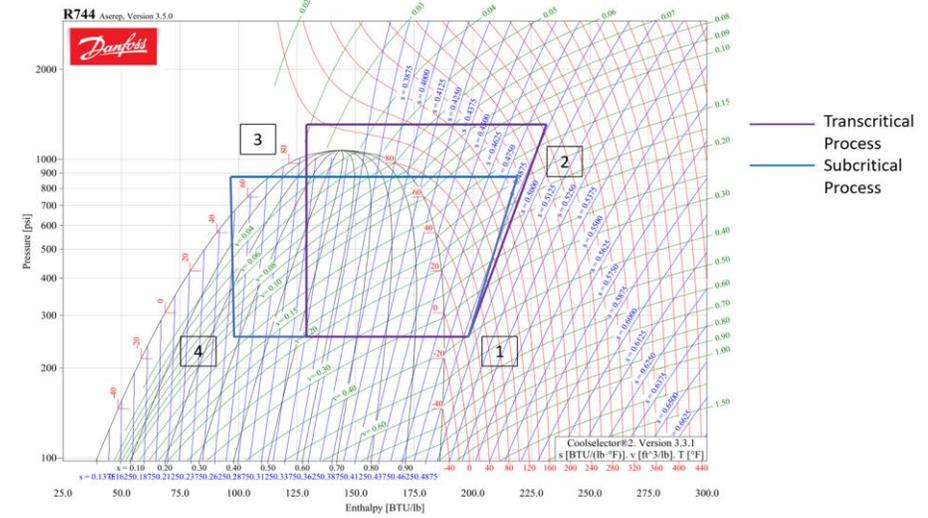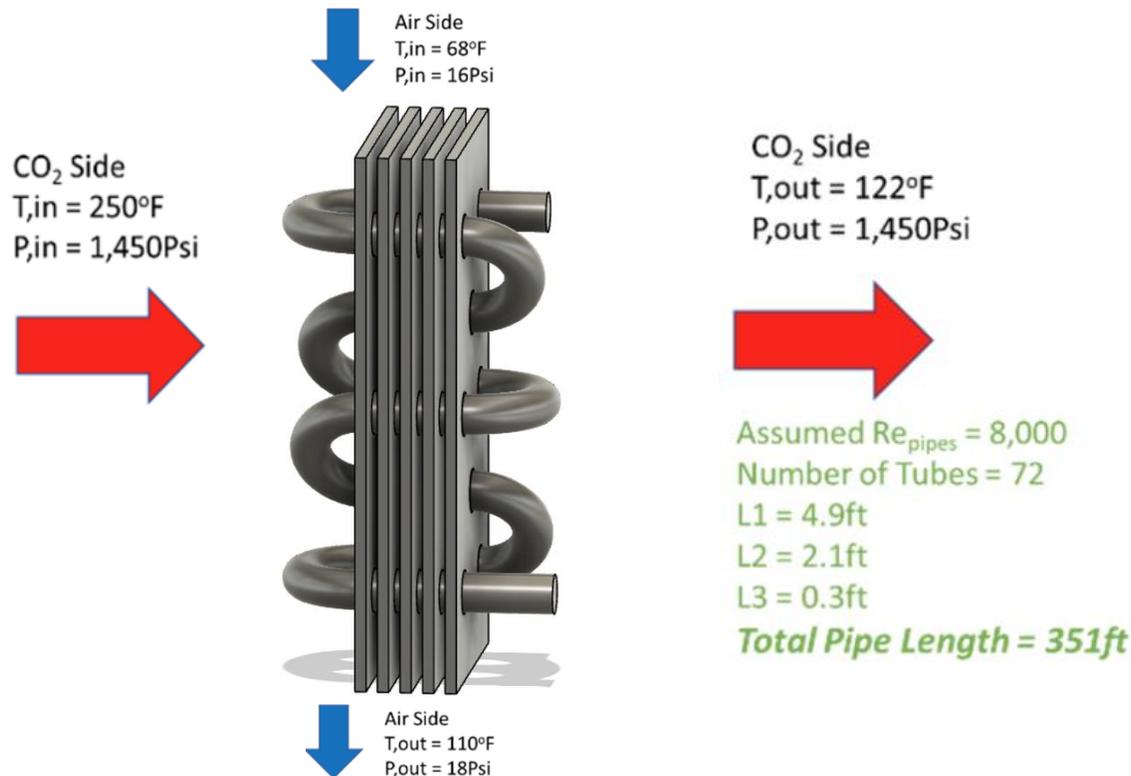$$Energy\ Efficiency\ Ratio = EER = COP \times 3.412$$

2nd Law Analysis

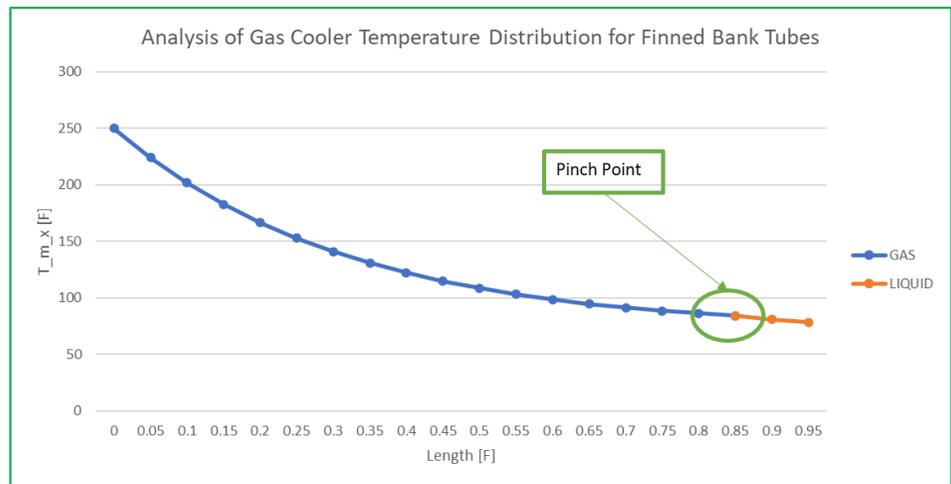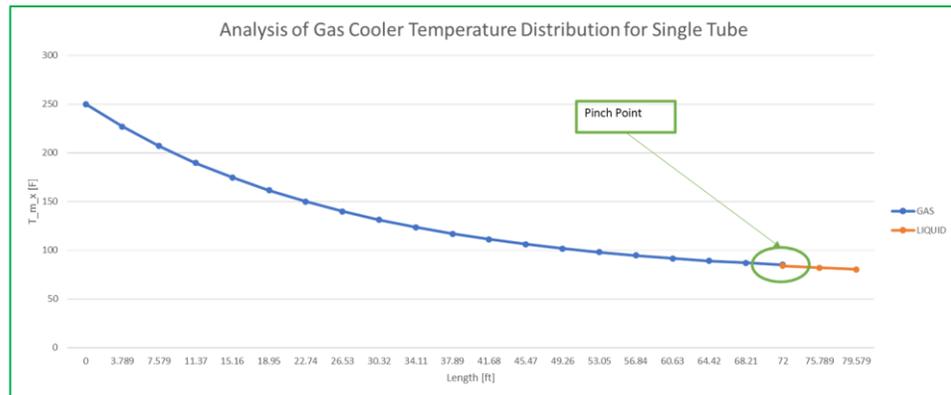$$Q_{H,max} = \left(1 - \frac{T_{room}}{T_{condenser\ surface}}\right) \times Q_{cond}$$

$$Exergetic\ Efficiency = COP_{rev} = \frac{Q_{H,max}}{W_c} \times 100$$

Task-3: Gas-Cooler Design

- After careful consideration and research, 2 initial design models appear as feasible options.

- *Option-1:* Currently an air-cooled gas cooler is being designed.

- *Option-2:* Intercooler design for multi-stage compressor subject to cost-constraints.

- A suitable configuration for the gas cooler has been established, via hybrid-black box modeling (1D/Transient).

- An assumed total equivalent pipe length of 351ft is required, with a total of 70 tubes of about 5ft each.

- Our challenge moving forward is to make the gas cooler more compact for multi-family use, location of pinch-point is crucial for this.

Air Side
T,in = 68°F
P,in = 16Psi

CO₂ Side
T,in = 250°F
P,in = 1,450Psi

CO₂ Side
T,out = 122°F
P,out = 1,450Psi

Assumed Re$_{pipes}$ = 8,000
Number of Tubes = 72
L1 = 4.9ft
L2 = 2.1ft
L3 = 0.3ft
Total Pipe Length = 351ft

Air Side
T,out = 110°F
P,out = 18Psi

Task-3: Heat Transfer Across Pipe, Pinch-Point Location

Analysis of Gas Cooler Temperature Distribution for Single Tube

Analysis of Gas Cooler Temperature Distribution for Finned Bank Tubes

REFRIGERANT FLOW IN

Pinch Point

REFRIGERANT FLOW OUT

- The gas cooler typically operates with the R744 in a gaseous state but it is possible for a phase change to occur here also.
- If this is the case, it is important for the pinch point to occur away from the center of the gas cooler which also takes advantage of the increasing thermal capacitance and heat transfer coefficient up to that point.
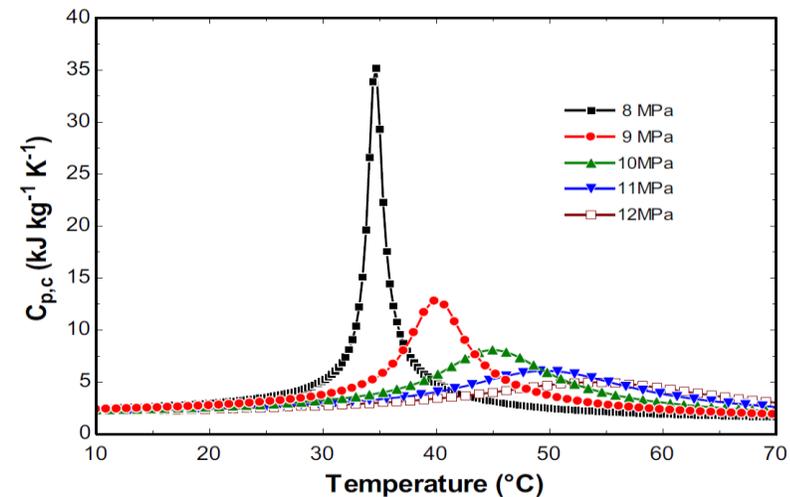
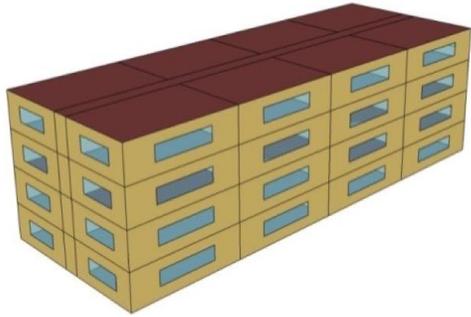Specific Heat Capacity vs Temperature for different pressures
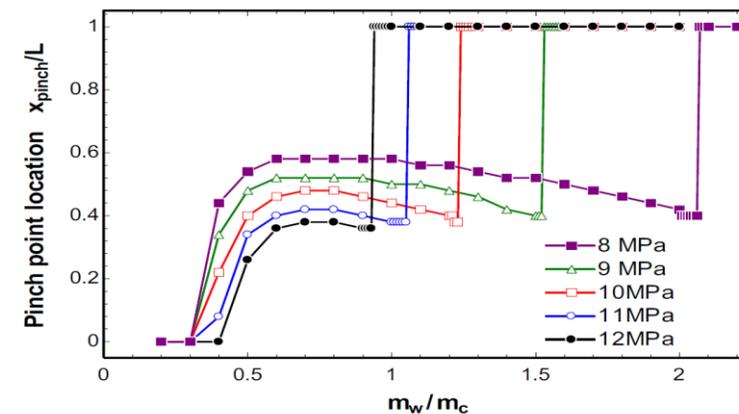
The effect of mass flow ratio and refrigerant pressure on pinch point location
Source: Pinch point analysis and design

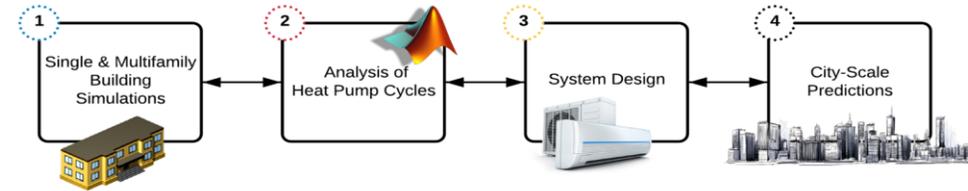# Task-4: Multifamily Building Modeling & Selection

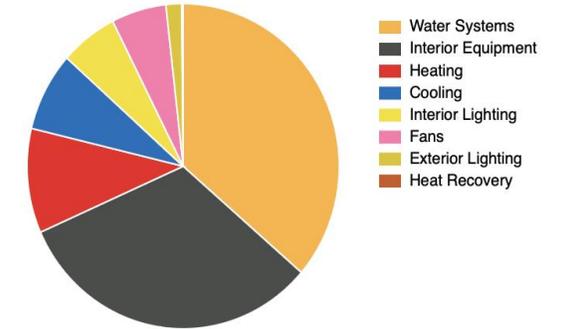**DOE Midrise Multifamily Prototype**

Typical NYC Multifamily

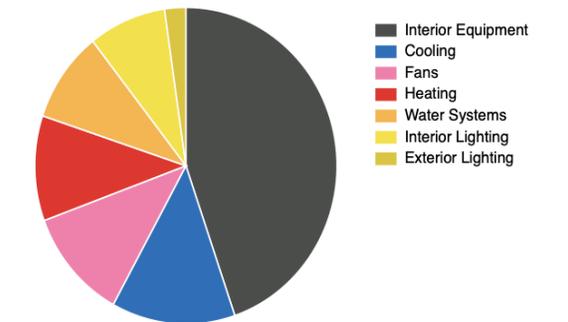| Modeling/Selection Steps	Status/Expected Completion
Model DOE Midrise Prototype, Unchanged	Complete
Model Prototype With Typical NYC Characteristics (NG DHW, NG Central Steam Boiler, Window AC Units, etc.)	Complete
Model Prototype With R410a Heat Pumps, Various Condenser Configurations	Complete
Alter R410a Models To Reflect CO_2 Characteristics	In Process, Spring 2023

Current Progress : Multifamily Building Modeling Results

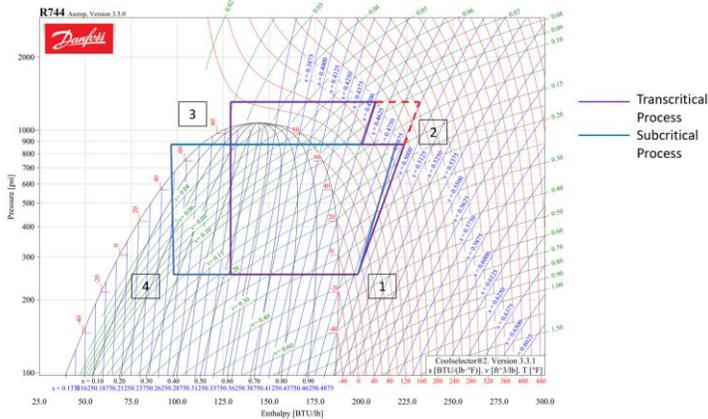| Configuration	Water Heating Equipment	Heating Equipment	Cooling Equipment	Cooling Peak Load (kW)	Total Annual Energy Use - Heating (kWh/Therms)	Total Annual Energy Use - Cooling (kWh)	Total Water Heating Load (kWh/Therms)
DOE Prototype Model, Unchanged*	Electric Resistance (100% TE)	Gas Furnace (80% TE)	Heat Pump (14 SEER)	21.4 (July)	1,573 (Therms)	34,844	132,239 (kWh)
DOE Prototype Model, Gas Water Heating*	Gas WH (80% TE)	Gas Furnace (80% TE)	Heat Pump (14 SEER)	20.5 (July)	1,573 (Therms)	34,844	4,934 (Therms)
DOE Prototype Model, HPWH, VRF 1:1 Condenser to apt	HPWH (3.2 COP)	VRF (3.5 COP)	VRF (14 SEER)	34.4 (July)	34,069 (kWh)	40,739	29,547 (kWh)
DOE Prototype Model, HPWH, VRF 1 Condenser/Floor	HPWH (3.4 COP)	VRF (3.5 COP)	VRF (14 SEER)	31.7 (July)	34,733 (kWh)	40,433	29,547 (kWh)

*Modeled with ERV

DOE Prototype Unchanged, Gas WH

Legend: Water Systems, Interior Equipment, Heating, Cooling, Interior Lighting, Fans, Exterior Lighting, Heat Recovery

VRF, 1:1 Compressor to Apt, w/HPWH

Legend: Interior Equipment, Cooling, Fans, Heating, Water Systems, Interior Lighting, Exterior Lighting

Current Progress: Scaling to City-Wide Building Energy Modeling: CCNY/UAlbany uWRF

Next Steps
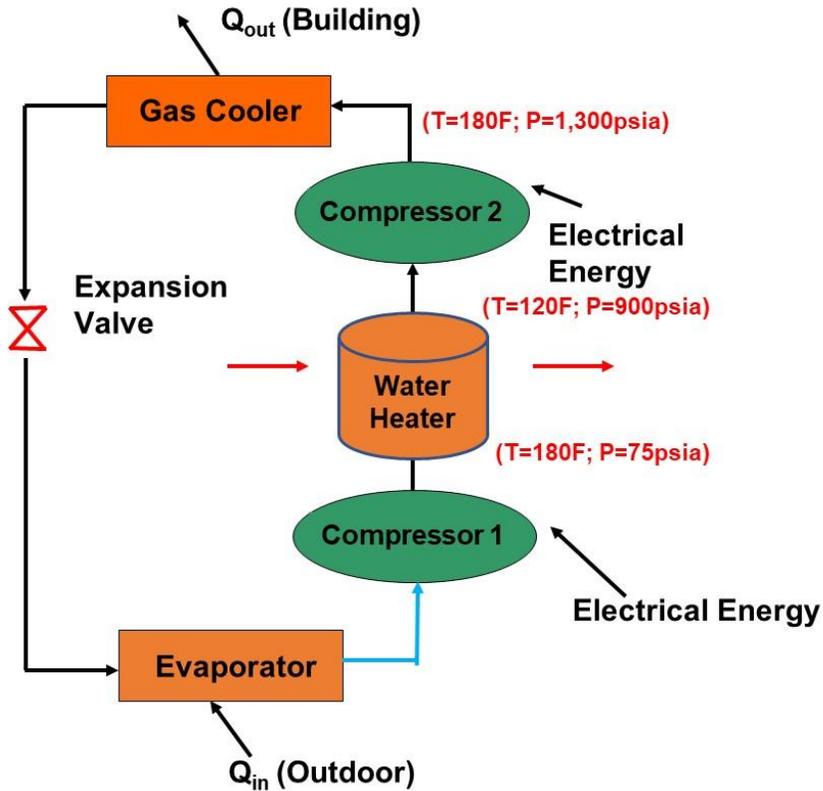
- **Capture real-time lab data to compare with the BlackBox Model.**

- **Complete the Design, build and test small scale R744 unit (3RT) and gas cooler.**

- **Select building for field testing.**

- **Field Testing of Commercial Scale Unit for Multi-family Buildings (R410 & R744).**

- **Expand to dual & Triplet functionality space cooling/heating + heat water.**

- **System optimization.**

- **Scale for citywide implementation.**

Thank you!

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Prof. Jorge E. Gonzalez

SUNY Empire Professor of U. Albany
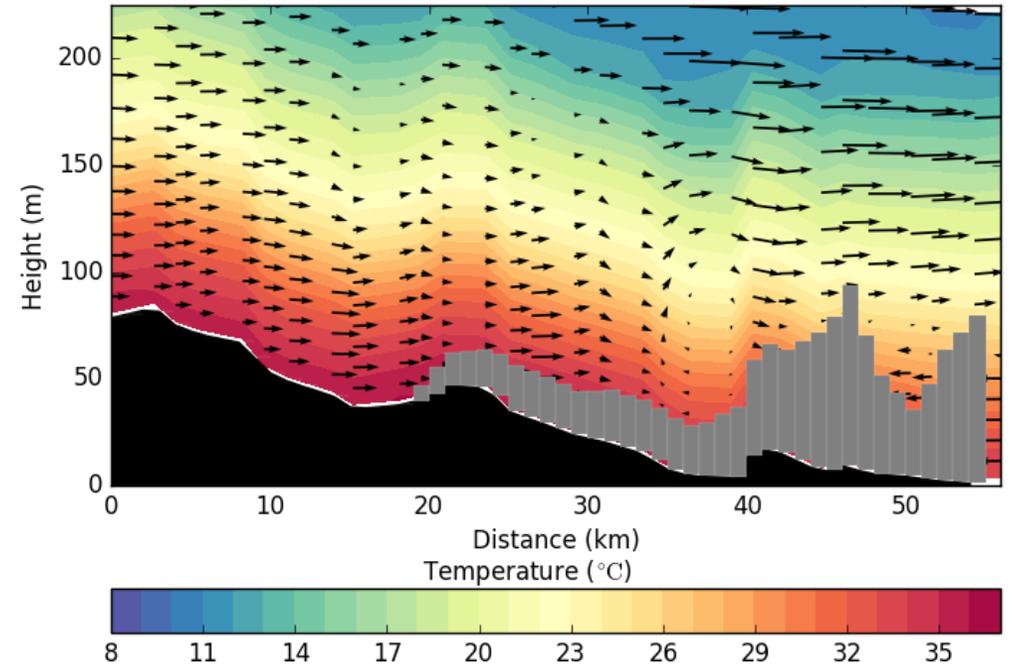
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