2024 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Grid Interactive Micro-Distributed Refrigerated Display Case

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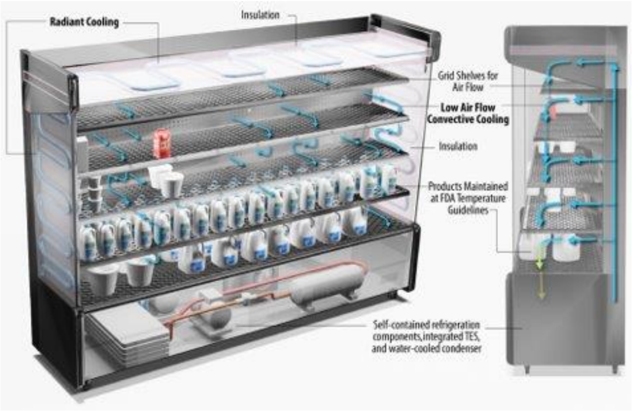
WBS # 3.2.2.127

Project Summary

OBJECTIVE, OUTCOME, & IMPACT

Develop a next-generation self-contained, refrigerated open vertical display case (OVDC) that leverages radiation and thermal energy storage (TES) to:

- Improve **energy efficiency**
- Provide **demand flexibility**
- Improve **human comfort**
- Improve **environmentally friendliness of refrigeration systems**



TEAM & PARTNERS

- The National Renewable Energy Lab
- Copeland Corporation
- Net Energy

Deployment and Commercialization Partners:

- Arneg USA
- Albertsons
- Commonwealth Edison Co

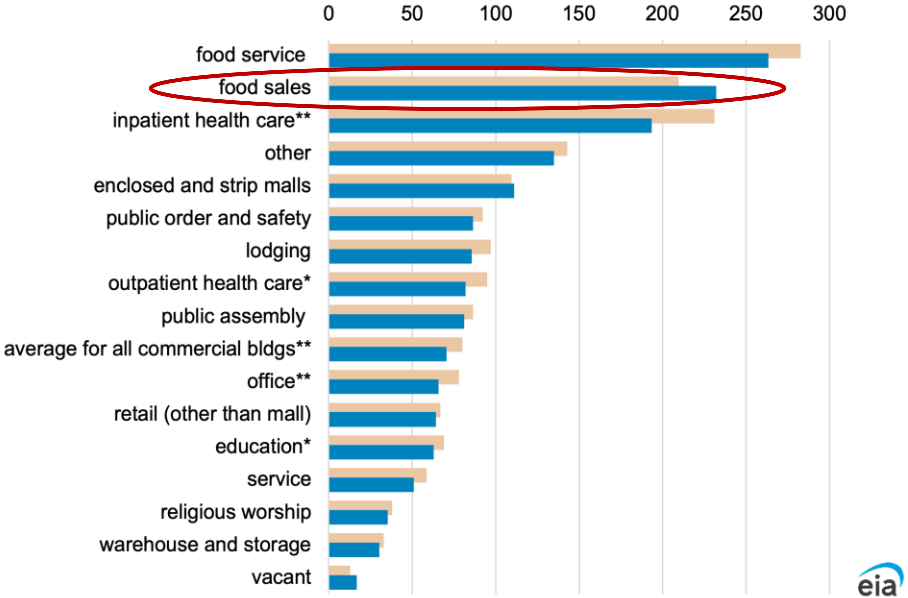
STATS

Performance Period: 10/1/2021 – 3/31/2025
DOE Budget: $2,527k **Cost Share:** $720k
Milestones:
Collect commercial refrigeration data
Hybrid radiative and convective cooling modeling
Model and design phase change material heat exchanger (PCM HX)
Characterize PCM material
Case performance and efficiency modeling (24 h)
Characterize PCM HX prototype
Optimize case design and TES controls for maximum efficiency
Characterize hybrid system heat extraction effectiveness
Characterize refrigerated case with hybrid cooling and TES (full-scale proof-of-concept)
Disseminate project information and findings

Problem Statement: Supermarkets

- **Supermarkets** have the **second highest EUIs** in the commercial buildings sector:
  - **Refrigeration** accounts for roughly **50%** of their **electric energy.**[1]
  - **OVDCs** comprise nearly **50% of total** case line-ups.

Major fuels intensity by principal building activity, 2012–2018
thousand British thermal units per square foot

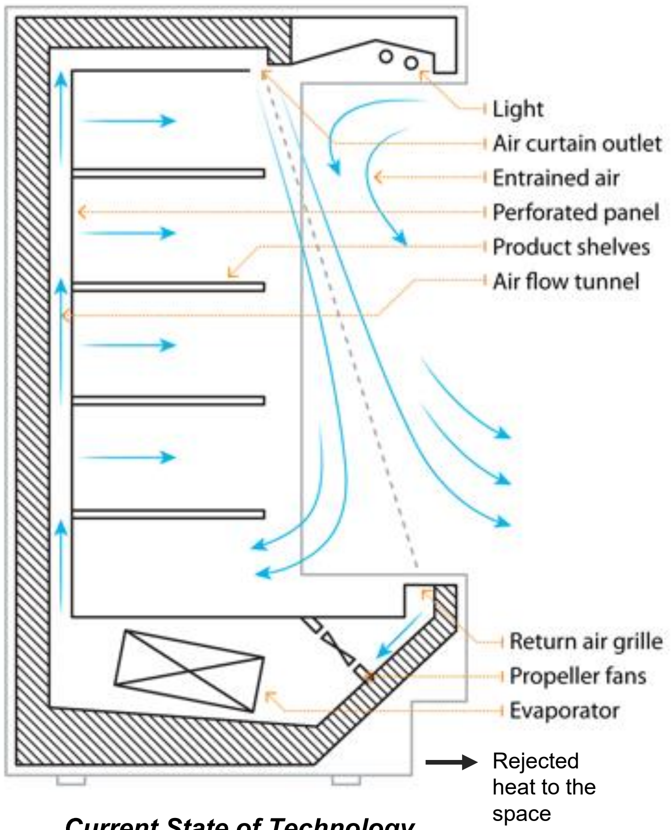


Data source: U.S. Energy Information Administration, *Commercial Buildings Energy Consumption Survey*
* Change is statistically significant at the 10% significance level.
** Change is statistically significant at the 5% significance level.
Note: Building Type Definitions on the CBECS web page provides more information about the principal building activities.

1 ASHRAE Handbook. Atlanta, Ga: American Society of Heating, Refrigerating and Air Conditioning Engineers

Problem Statement: OVDC

- **Forced convection** used to cool refrigerated products results in large mass exchange with the surrounded space:
  - Air infiltration accounts for ***80% of cooling load.***
  - The **spilled cold air** adversely **impacts human comfort.**
  - **Frost formation** on evaporator restricts air flow and **hampers heat transfer** → *degrades energy efficiency.*
  - Highly variable and **non-uniform product temperature** between shelves (up to 10°F).
- **Refrigeration heat** rejected into the sales floor **cannot be reclaimed** by heating systems.
- **Inability** to reliably **participate** in **demand response** (DR) events and load shaving/shifting strategies.



Current State of Technology

Alignment and Impact

- The successful completion of this project will:

- Accelerate the deployment of a cost-effective distributed energy resource technology.
- Improve energy efficiency and reduce site/source greenhouse gas emissions.
- Pave the path for decarbonizing retail food market segment and enhance resiliency.

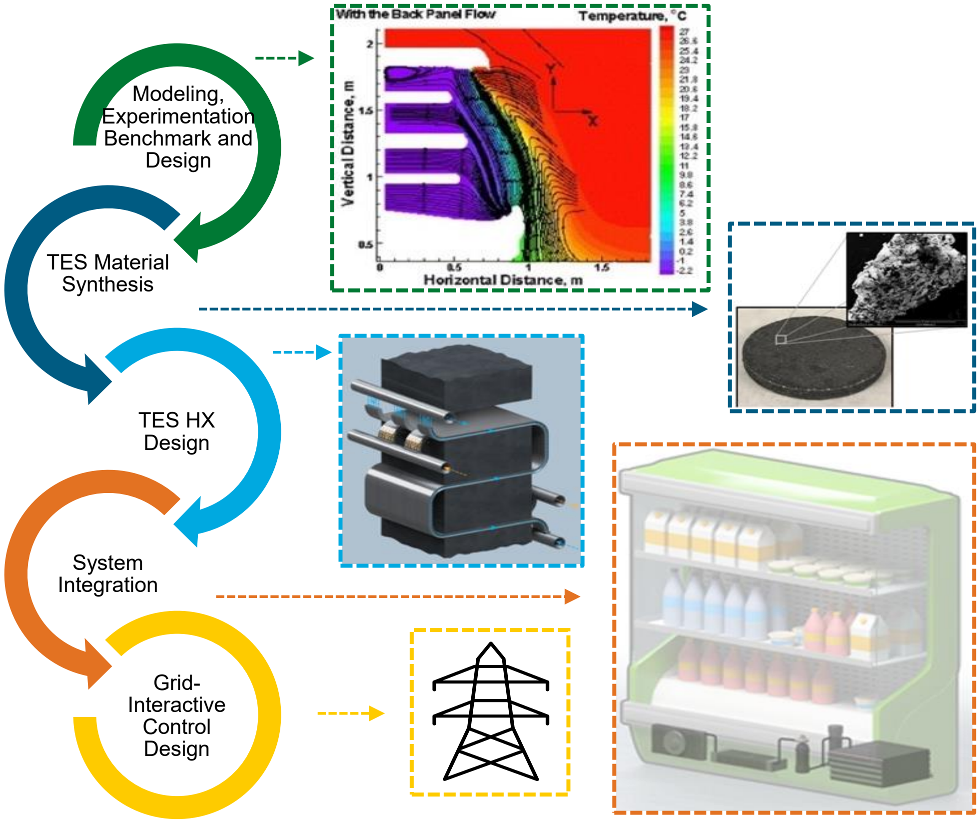
Potential *Decarbonization* Impacts (approximate estimates)

- **Annual electric energy of 9.72 TWh (25% of national refrigeration energy consumption) and natural gas savings of 320 million therms.**

Potential *Grid-Edge* Impacts (approximate estimates)

- **Permanent electric peak demand reduction of 1.54 GW**
- **DR and load shaving/shifting to enhance grid integrity (2 h, 1.9 GWh load curtailment).**

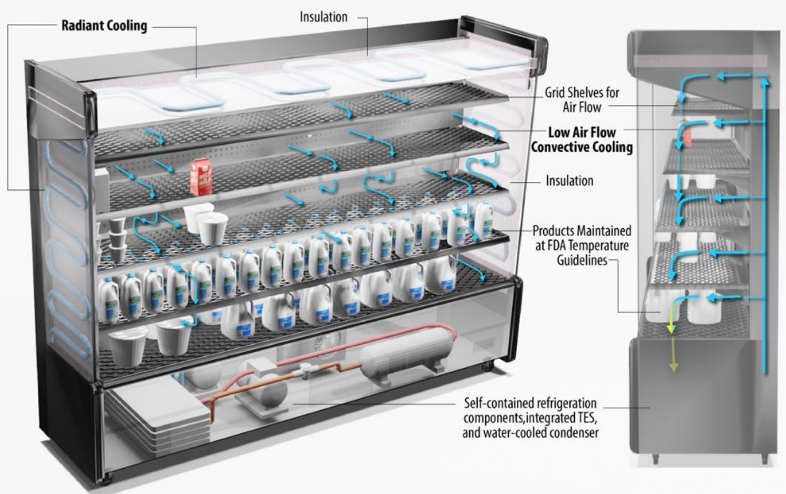
Integrated Research Approach



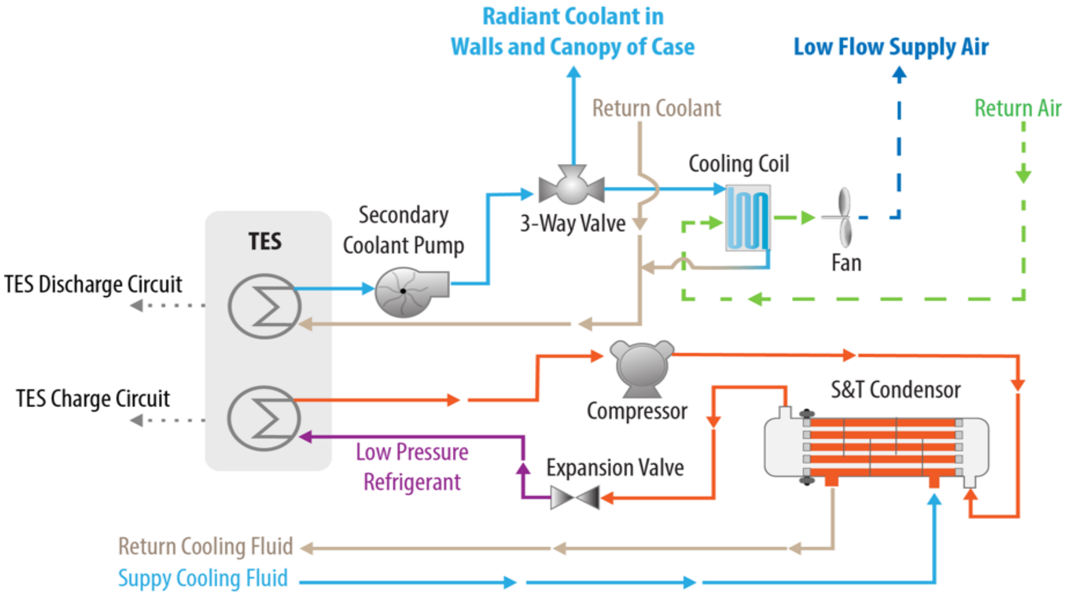
Proposed Innovation

Novel Features:

1. Complete removal of air curtain system replaced with hybrid radiant and convective cooling using R290.
2. Thermal energy storage (TES).
3. Water cooled integrated with building space and water heating.



Hybrid Cooled OVDC With an Integrated TES



R&D Targets

Energy Efficiency: *30% Improvement.*

- by **reducing infiltration** load, frost formation, defrost cycles, and post-defrost pull-down loads **with radiant cooling** and minimizing forced convection by air curtain removal.
- by **integrating water-cooled condenser** with the building's heating systems to reduce temperature lift and recover waste heat.

Transform Grid Edge through Demand Flexibility: *80% peak kW reduction of display case over 2 hours.*

- by adding **TES**

Affordability: *3-year payback period.*

- by **reducing operational costs** with energy savings and DR programs.

Occupant Comfort: *50% lower infiltration.*

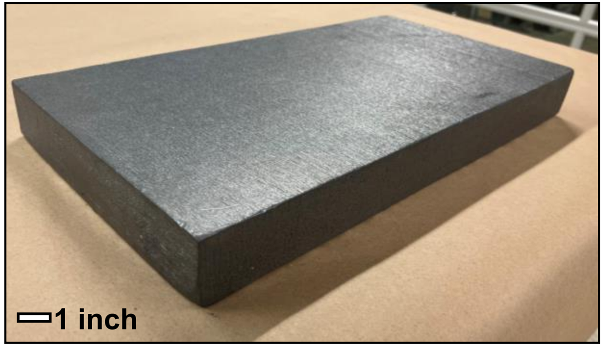
- by **reducing** cold **air spillage** in shopping aisles.

Thermal Energy Storage Component

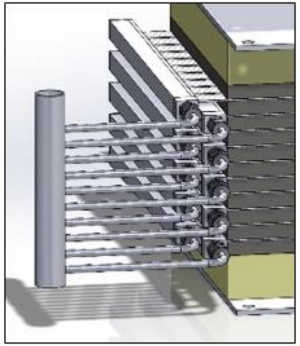
- The thermal energy storage consists of a **Phase Change Material (PCM) composite** of 10% graphite and 90% PCM.
- The PCM composite is integrated with aluminum microchannels to form a **PCM heat exchanger** with both refrigerant and glycol circuits.
- The PCM heat exchanger was designed using a finite difference model to achieve **2-hour 80% load shifting.**

Comparison of PCM to ice

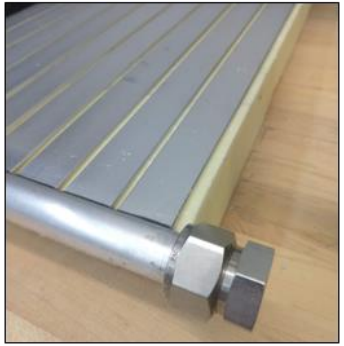
Property	Composite PCM	Ice/water	Units
Transition Temperature (T_t)	**-11**	**0**	**C**
Energy density	60	85	kWh/m^3
Conductivity	**8**	**0.6**	**W/m-K**
Form in liquid state	Shape-stable	Flows	-



Graphite/PCM composite

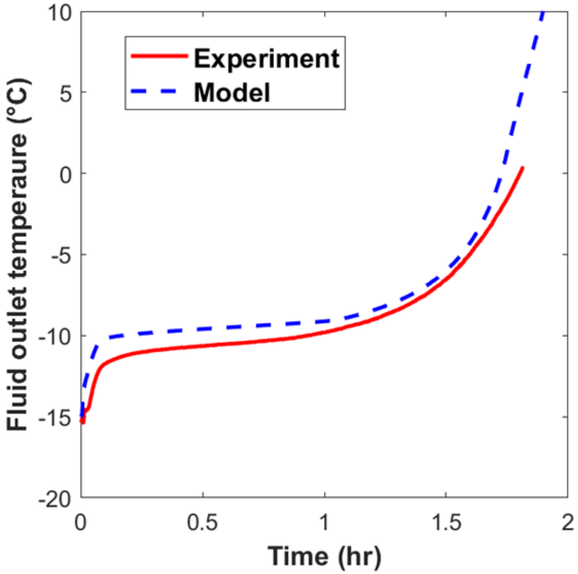


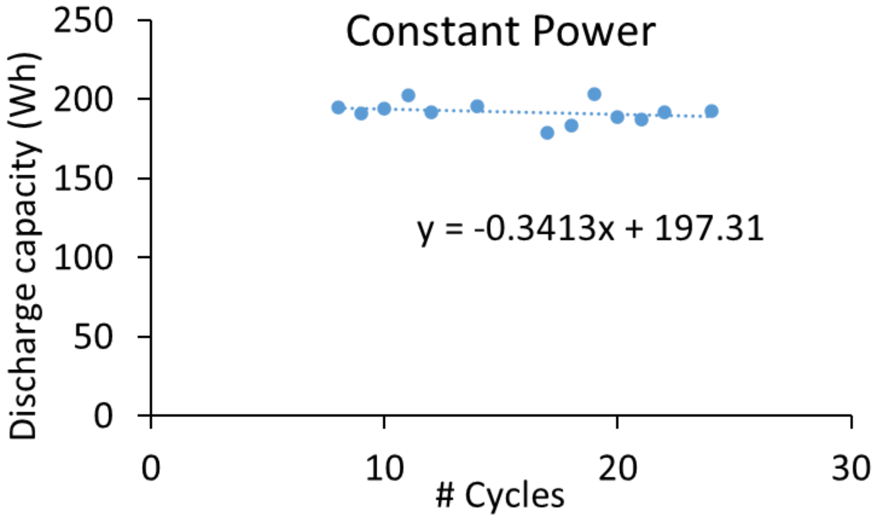
Composite PCM heat exchanger



Aluminum microchannels

Thermal Energy Storage – Bench-scale Prototype





Numerical model prediction matches experiments for bench-scale prototype (0.2 kWh). This model was used to design the full-scale prototype (~8 kWh_{th})

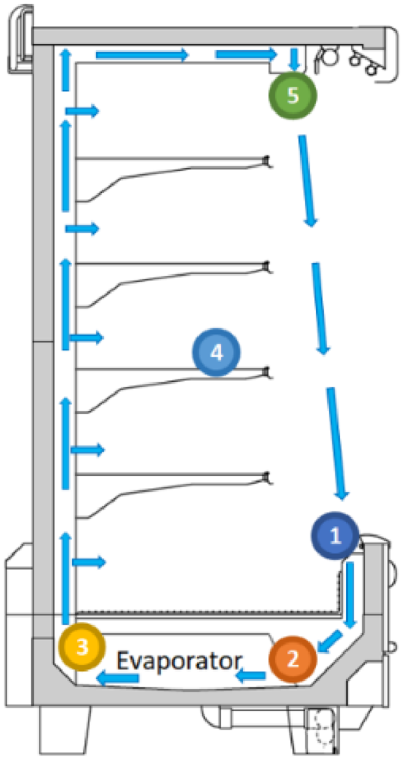
- 25 cycles of bench-scale prototype (0.2 kWh) show stable operation (above graph)

Baseline/Bench Scale Experimentation

- **Goal: Increase confidence in product temperature maintenance capability**

- Laboratory characterization of a typical 8-ft long, 5-deck, self-contained OVDC with a water-cooled condenser to calibrate the thermo-fluid model

- **117** channels of data collected every 1s over 24 hrs monitoring:
  - *Temperatures: Air, refrigerant, water, product*
  - *Pressure: Refrigerant Suction & Discharge, Condenser water*
  - *Power: Total case and components*
  - *Mass Flow: Condenser water*
  - *Condensate Mass measured to calculate latent load*



Baseline System

Baseline Display Case Cabinet:
8ft, 5-deck 13 ft^3 gross volume

Electronic Expansion Valve

Advanced Controls

Liquid-cooled Condensing Unit with Variable Speed Compressor

The Baseline refrigerated case is equipped with:

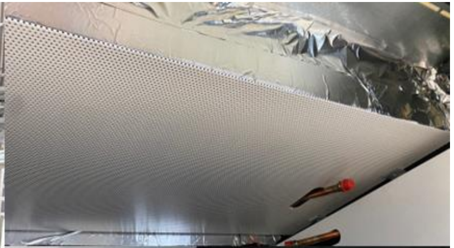
- water-cooled condensing unit
- advanced controls
- variable speed compressor
- electronic expansion valve

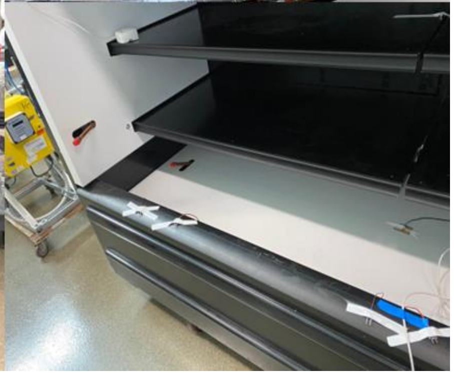
Experimentation Approach

- ASHRAE 72 and AHRI 1200 Standards were used to maintain consistent conditions between tests
- For the bench-scale validation, a chiller supplied the panels' coils with silicone coolant at controlled temperature and flow rate.

<u>Baseline case was modified with:</u>

1. Complete elimination of the air curtain
2. Custom-fit radiant panels,
3. Variable-speed evaporator fan motors/controller
4. Back panel with modified perforations





Convergence of Resistive Model with CFD and Experimental Data

Average product temperatures from EES, CFD, and experimental measurements:

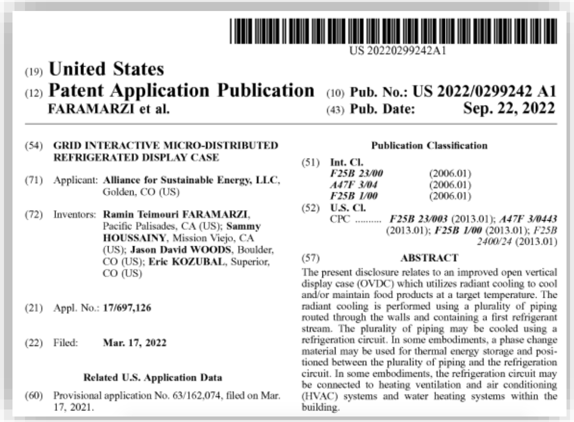
	EES (model approach 1)	CFD (model approach 2)	Experimental Measures
Baseline system	38.4°F	38.2°F	38.45°F
Hybrid system (bench-scale)	39.2°F	39.1°F	39.01°F

Conclusions / Accomplishments

- Convergence of resistive model with CFD and experimentation data increased confidence in modeling platform, which will be leveraged to design the POC

- The hybrid cooling system:
  - Complied with FDA product temp targets. *(39.0°F mean product temp at 900 RPM evaporator fan speed)*
  - Reduced infiltration load by 96% *(at 900 RPM evaporator fan speed) based on mass of condensate data)*

Published Patent Application



US 20220299242A1

(19) **United States**
(12) **Patent Application Publication**
FARAMARZI et al.

(10) **Pub. No.: US 2022/0299242 A1**
(43) **Pub. Date: Sep. 22, 2022**

(54) **GRID INTERACTIVE MICRO-DISTRIBUTED REFRIGERATED DISPLAY CASE**

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(21) Appl. No.: **17/697,126**

(22) Filed: **Mar. 17, 2022**

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F25B 23/00 (2006.01)
A47F 3/04 (2006.01)
F25B 1/00 (2006.01)

(52) **U.S. Cl.**
CPC ***F25B 23/003*** (2013.01); ***A47F 3/0443*** (2013.01); ***F25B 1/00*** (2013.01); *F25B 2400/24* (2013.01)

(57) **ABSTRACT**

The present disclosure relates to an improved open vertical display case (OVDC) which utilizes radiant cooling to cool and/or maintain food products at a target temperature. The radiant cooling is performed using a plurality of piping routed through the walls and containing a first refrigerant stream. The plurality of piping may be cooled using a refrigeration circuit. In some embodiments, a phase change material may be used for thermal energy storage and positioned between the plurality of piping and the refrigeration circuit. In some embodiments, the refrigeration circuit may be connected to heating ventilation and air conditioning (HVAC) systems and water heating systems within the building.

Future Work

- Use validated thermo-fluid model to identify further strategies for minimizing the cooling load of the case & developing specs - (in progress)
- Fabricate a hybrid proof-of-concept prototype fixture (including TES and advanced controls integration) - (in progress)
- Ascertain the energy efficiency benefits of the hybrid proof-of-concept in a laboratory setting
- Assess the impacts of load flexibility strategies by leveraging the TES system in a laboratory setting

*Beyond Current Scope:

- Field demo at Albertson's site
- Work with ComEd to include the technology in their incentive portfolio

Thank you

NREL, Copeland, Net Energy, Arneg, Albertsons, and ComEd

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Reference Slides

Project Execution

Task		Subtask	Lead	Q1 22	Q2 22	Q3 22	Q4 22	Q1 23	Q2 23	Q3 23	Q4 23	Q1 24	Q2 24	Q3 24	Q4 24	Q1 25	Q2 25
			Budget Period	BP1				BP2						BP3			
0.1 Project Management			Emerson/NREL														
1.2 Literature Survey and TAC Formation																	
	1.2.1	Collect data on commercial refrigeration	Emerson														
	1.2.2	TAC formation	Emerson/NREL														
1.3 Hybrid Display Case Thermal Analysis																	
	1.3.1	Model case heat removal strategies and product temperature maintenance															
		1.3.1.a Radiative cooling	NREL														
		1.3.1.b Low airflow convective cooling and CFD modeling	NREL														
		1.3.1.c Hybrid radiative and convective cooling	NREL														
		1.3.1.d Refrigeration cycle design	NREL														
		1.3.1.e Heat rejection modeling	NREL														
		1.3.1.f Total case performance and energy efficiency modeling over 24 hrs	NREL														
	1.3.2	Surface condensation risk mitigation research	NREL														
	1.3.3	Customer discovery and market analysis	NETenergy														
	1.3.4	Technology assessment with building-level analysis	NREL														
1.4 TES Design and System Characterization																	
	1.4.1	Model TES															
		1.4.1a Model and design PCM HXs	NREL														
	1.4.2	PCM creation and characterization															
		1.4.2.a Synthesize PCM material	NETenergy														
		1.4.2.b Characterize PCM material	NETenergy/NREL														
	1.4.3	PCM HX creation and characterization															
		1.4.3.a Construct PCM HX prototype (bench-scale)	NETenergy														
		1.4.3.b Characterize PCM HX prototype (bench-scale)	NREL/Copeland														
		1.4.3.c Construct PCM HX prototype (full-scale)	NETenergy														
		1.4.3.d Characterize PCM HX prototype (full-scale)	NREL														
1.5 Display Case Design and Specifications																	
	1.5.1	Model and optimize the hybrid refrigerated case with TES															
		1.5.1.a Develop a model of integrated system	NREL														
		1.5.1.b Optimize case design and TES controls for maximum efficiency	NREL														
		1.5.1.c Develop cost estimate for solution based on optimized Design	Copeland														
	1.5.2	Determine mechanical component sizing and specifications	NREL														
1.6 Display Case Proof of Concept (POC) Characterization and Fabrication																	
	1.6.1	Construct hybrid case prototype (bench-scale)	NREL														
	1.6.2	Mechanical components integration (bench-scale)	NREL														
	1.6.3	Heat rejection component integration (bench-scale)	NREL														
	1.6.4	Characterize hybrid system heat extraction effectiveness (bench-scale)	NREL														
	1.6.5	Construct hybrid case prototype (full-scale)	Copeland														
	1.6.6	Mechanical components integration (full-scale)	Copeland														
	1.6.7	Heat rejection component integration (full-scale)	Copeland														
	1.6.8	Characterize hybrid system heat extraction effectiveness (full-scale)	NREL/Copeland														
1.7 Display Case System Integration																	
	1.7.1	TES Integration	Copeland														
	1.7.2	Controls Integration	Copeland														
1.8 Display Case POC Performance Assessment			Arneg														
	1.8.1	Characterize refrigerated case with hybrid cooling and PCM HX	Arneg														
1.9 Information Dissemination			NREL/Copeland														

◆ Go/No-Go Decision Point
▲ Milestone

Team

COPELAND

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Suresh Shivashankar
Director – Solutions and Systems Engineering

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Emily Sherburne
Project Controller

Khanh Nguyen Cu
Research Engineer

NETenergy

Dr. Said Al-Hallaj
Founder and CEO

Dr. Yana Galazutdinova
Postdoctoral Researcher

Dr. Monica Cook
VP business technology

Modeling Approach

24-h Period Experiment of Baseline Display Case

Experimental performance evaluation *of baseline technology in NREL's environment-controlled thermal testing chambers*

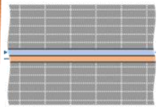
*→ **To validate baseline and hybrid** system-level and component-level **models***

Baseline and Hybrid System Model Development

Separate Models of Major Components

Refrigeration Cycle | TES | Display Case Heat Extraction

Detailed TES & Refrigeration Cycle Model



Independent modeling approaches *to build confidence in predictions*

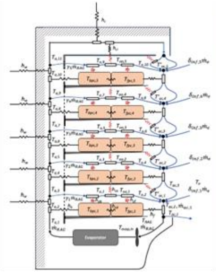
Component-Based Framework | Finite Difference Model | 3D, Steady State, CFD | 2D, Transient, Resistive Network

Surrogate model for ease of integration

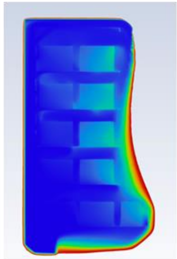
Validated Neural-Network Surrogate Models | Validated Transient Resistive Network Model

Validated models to predict performance

Integrated, Transient, and Validated Baseline and Hybrid System Model



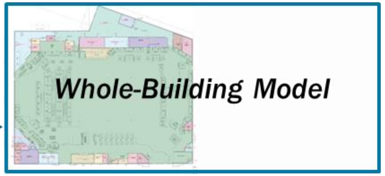
Resistive Network



CFD

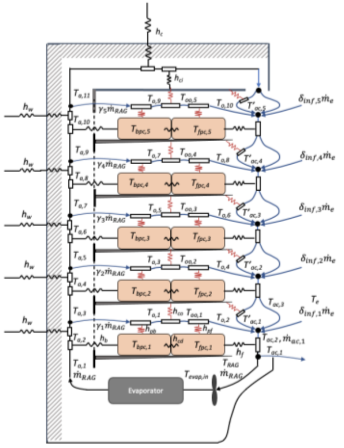
*Modified E+ DOE prototype to reflect **typical Albertsons store** specifications*

*→ **Assess** 8,760 h **whole-building performance***

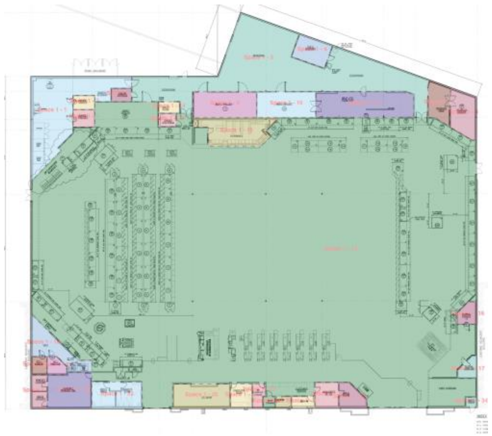


Modeling Approach Based on Experimental Data

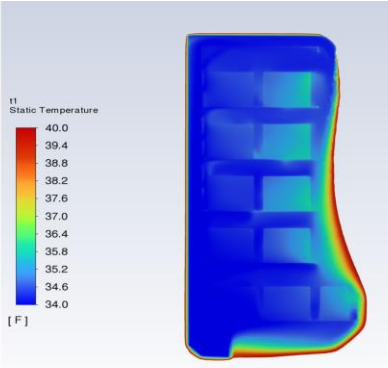
1. Thermo-fluid heat extraction Resistive Network modeling of the OVDC
   - Validation using 3-D CFD modeling
   - Experimentation Data
2. Refrigeration system modeling
3. Thermal energy storage system modeling
4. Integrated system model
5. Whole-building EnergyPlus® hourly simulation based on an actual Albertsons store



Resistive Network



Actual Albertsons Store

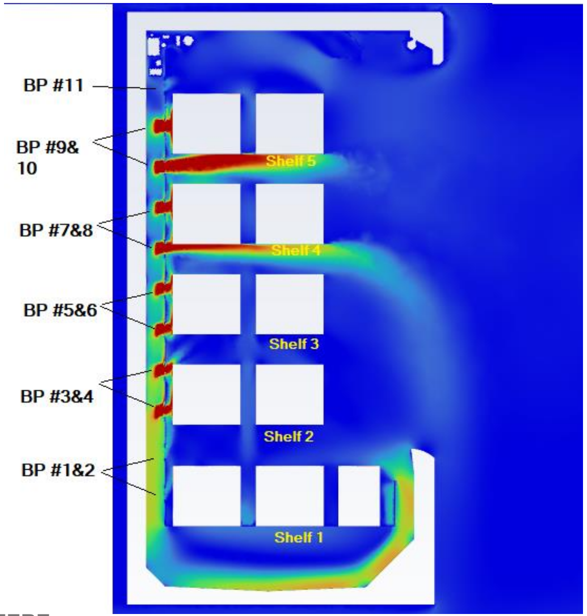


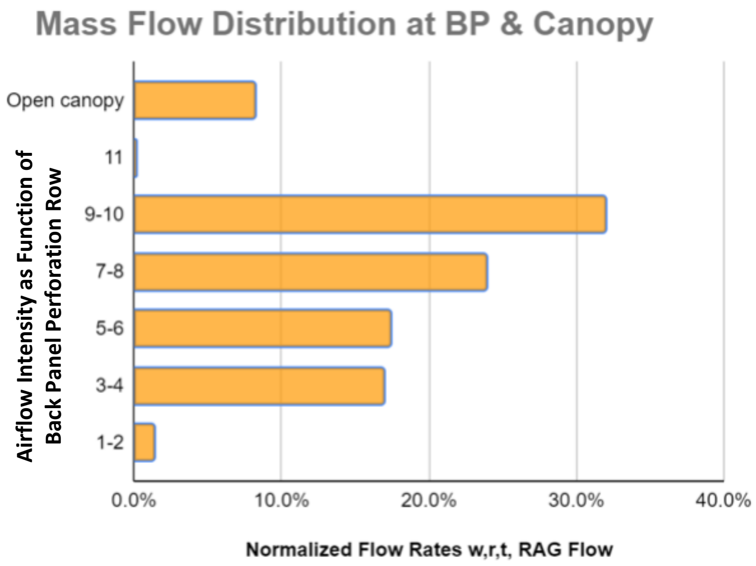
CFD

EnergyPlus Building Model

Modeling Results Informing Hybrid Case Design

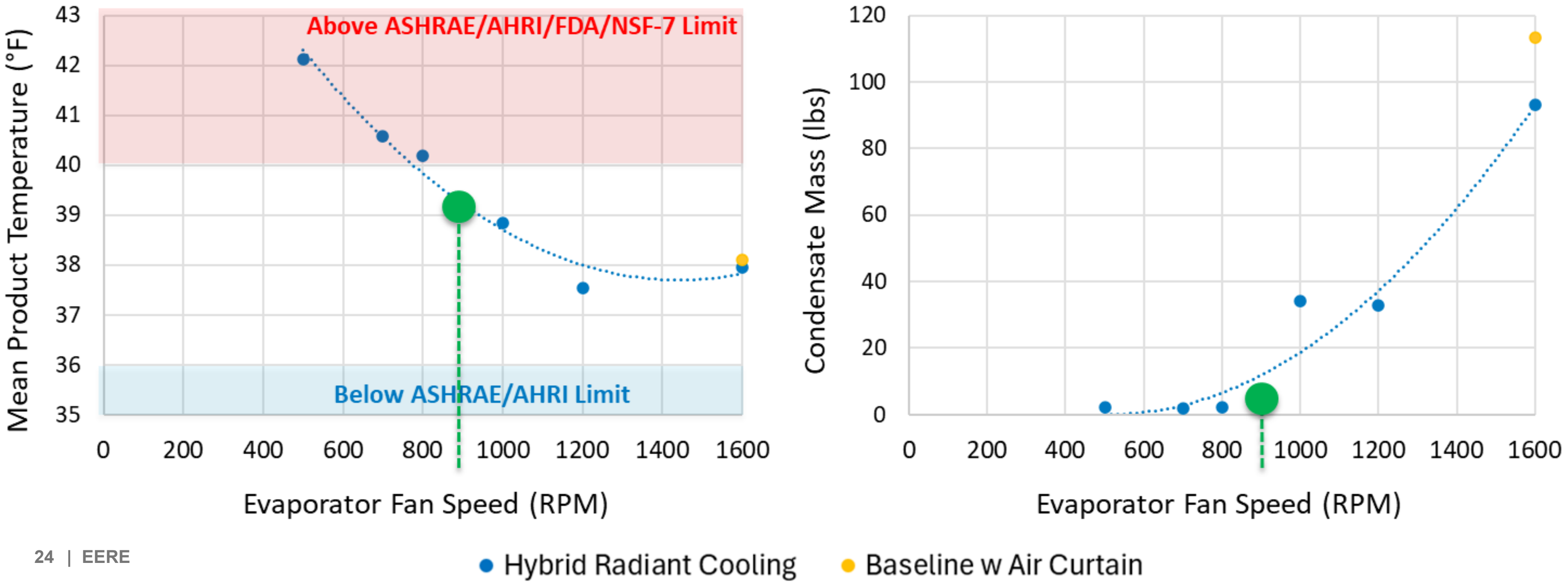
- Both CFD and EES models closely aligned with measured data:
  - Informed back panel air flow at 900 RPM and custom perforation for optimally-distributed air flow
  - Informed mean panel surface temperature of 32°F





Hybrid Radiant + Convective Cooling Experimental Results

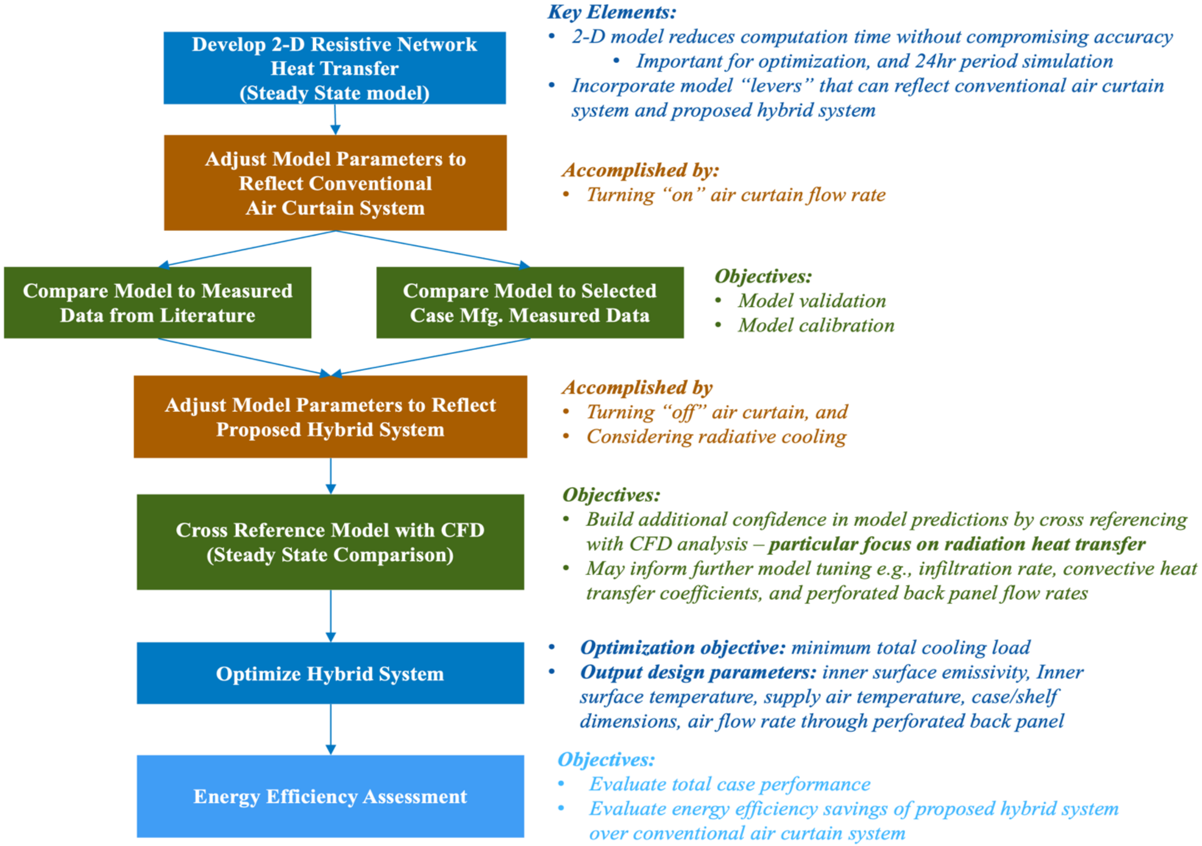
- *Varied fan speeds from 500 RPM (fan motor minimum) to 1600 RPM (baseline airflow)*
- *900 RPM provided optimum BP airflow while maintaining mean product temp & minimizing*



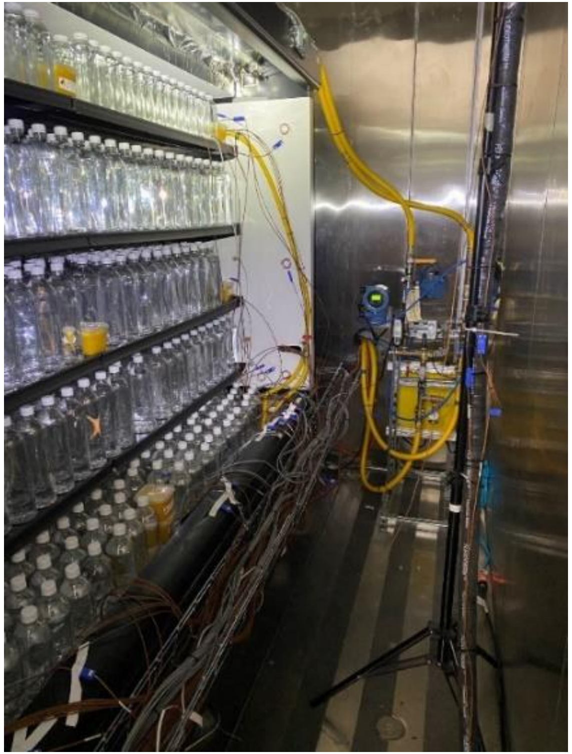
Thermo-Fluid Modeling

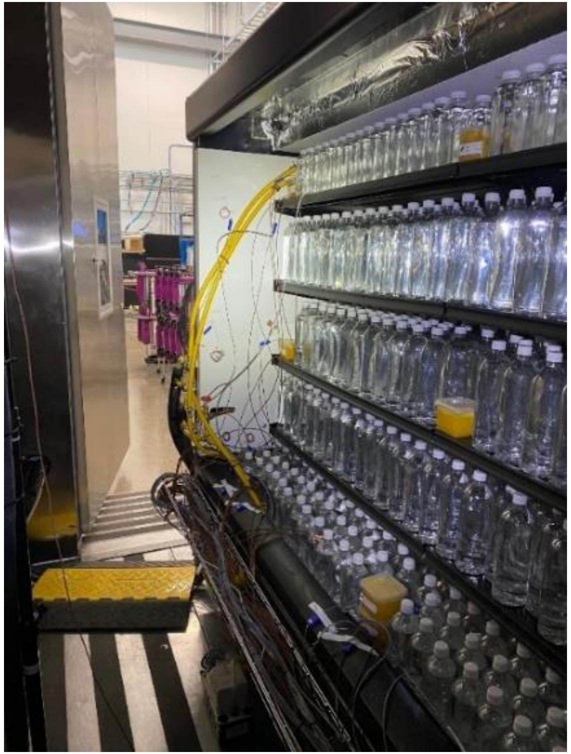
- **1st approach (thermal resistive network model) used Engineering Equation Solver (EES): considers conduction, convection, and radiation heat transfer modes and predicts temperatures**
- **2nd independent approach leveraged 3D CFD modeling.**

*models reflect the geometry of an actual OVDC.



Experimentation Setup: Bench-Scale





Case Inside Environmental Chamber

Radiant Cooling Loop

A: port into/out of chamber

B: condensate drum and scale

C: flowmeters, pressure gauges, and thermocouples

D: chiller – serving radiant panels

E: control box for the chiller, valves, and flood switches to detect leaks.