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EMERGING TECHNOLOGIES COORDINATING COUNCIL

Development of an Advanced High Temperature Heat Pump

Efficient Recovery of Low-Grade Industrial Waste Heat

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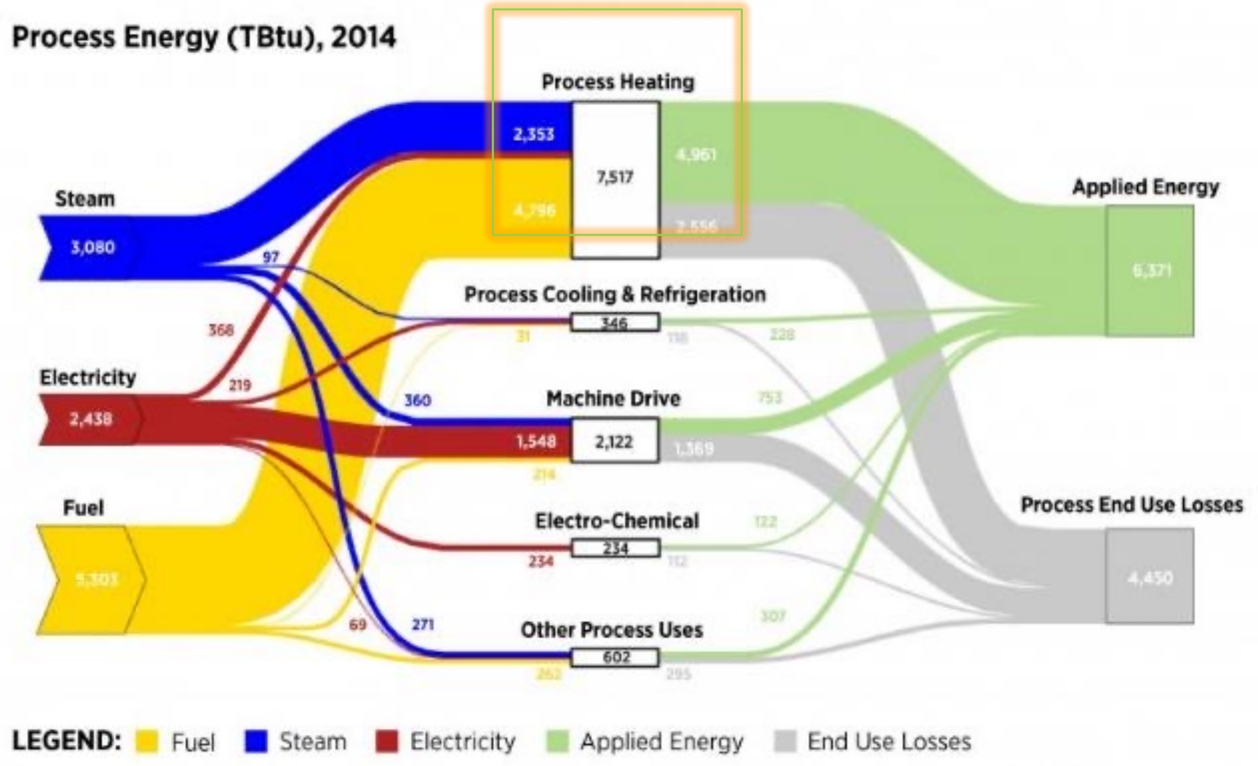
Agenda

- Problem Statement
- Solution
- Project Overview
- System Design
- System Development & Testing
- Expected Benefits
- Summary

Industrial Decarbonization – Problem Statement: Industrial Process Heating Uses Most Fossil Energy

- Total process heat (PH) energy use for U.S. manufacturing sector is 7,517 TBtu
  - Accounts for ~70% of the total process energy consumed in the manufacturing sector.
- Direct fossil fuel use for process heating is 4,796 TBtu/yr
- Direct and indirect (e.g., fuel used to generate steam) energy use for PH is 7,149 TBtu/yr
  - ~95% of all the process heating energy demand.
- About 35% of fossil energy is lost as waste heat



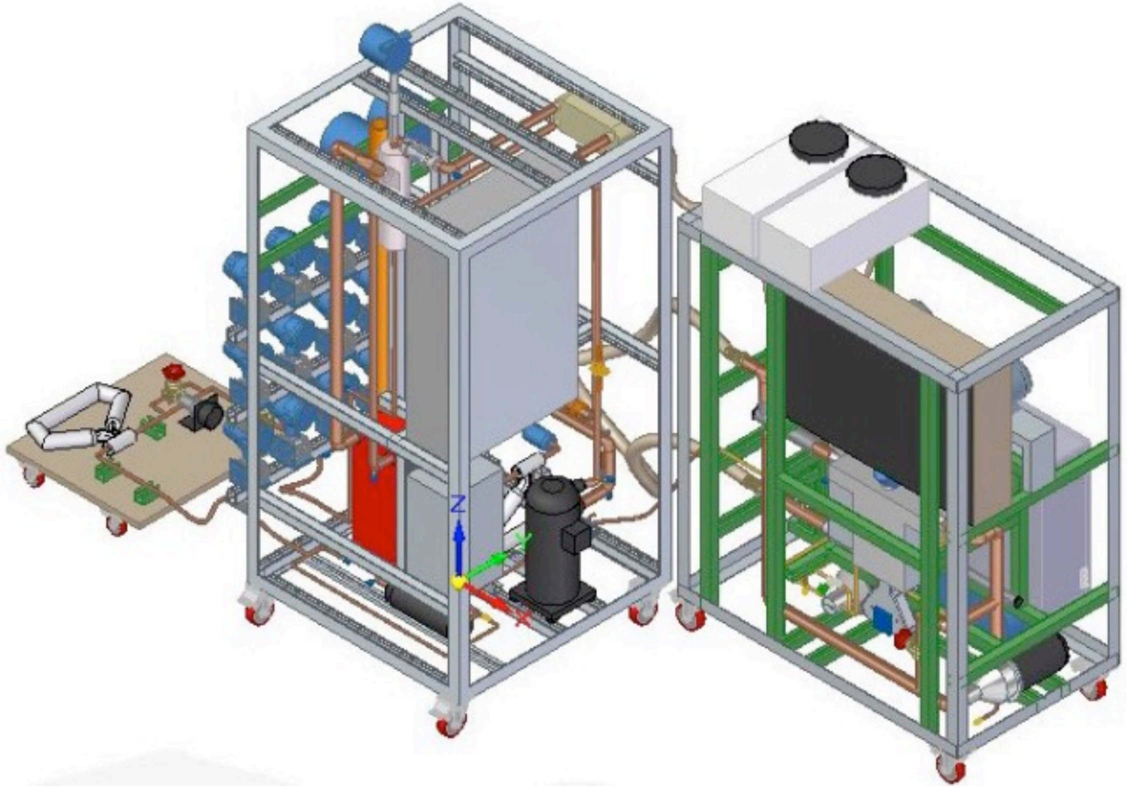
Source: https://www.energy.gov/eere/amo/static-sankey-diagram-process-energy-us-manufacturing-sector-2014-mecs

Problem Statement: How to use low temperature industrial waste heat?

- Low-temperature waste heat streams available abundantly in industries
- Typical waste heat are at temperatures in the 70-80 °C range
- Sources of waste heat: chillers, cooling processes, return steam condensate
- Many industries needs low-pressure steam in 120-125 °C range
- Industry applications: food manufacturing (e.g. bakeries, dairy etc.), paper, chemical, and textiles

Solution: High temperature heat pump that can produce steam at low pressure

- Key characteristics of the heat pumps:
  - Low ODP, GWP
  - Currently no high temperature heat pump that produces steam is available in US market
  - heat pumps offer an ideal solution for industrial decarbonization in California
  - New system produce steam at 120 °C from waste heat (80 °C) @ COP* of 3.4



*COP = Coefficient of Performance, which is a measure of system efficiency

Project Overview: Objectives, Goals & Benefits

Primary Objectives

- Develop and test an advanced high temperature heat pump (HTHP) for efficient recovery of industrial waste heat
- Produce low pressure steam.

Goals

- Develop HTHP that uses near zero GWP refrigerant
- Recover waste heat at 80^0C; provide lift of 40^0C
- COP >3.4
- Move technology from TRL 3 to TRL 6.

Ratepayer Benefits

- Decarbonization solutions to California Industries
- Potential savings of 1.3 million metric tons CO_2/ year
- Potential energy savings of 280 million therms/year

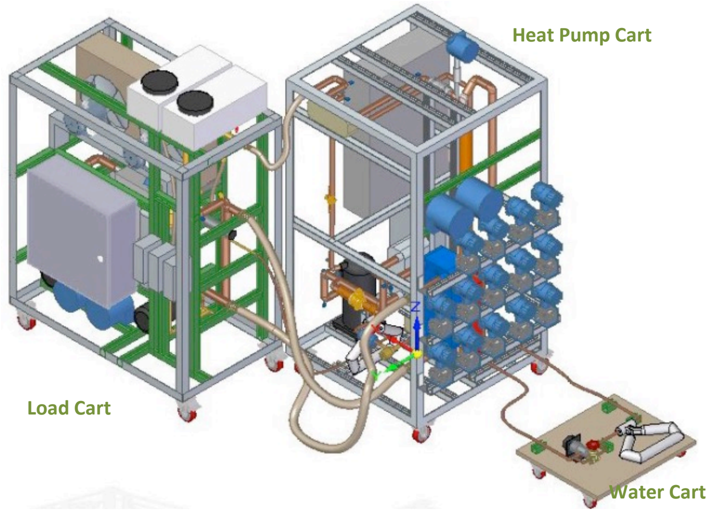
Link to CEC Agreement: https://www.energy.ca.gov/filebrowser/download/280

Performance Metrics

Performance Metric	Baseline Performance	Target Performance	Evaluation Method	End-of-Project Performance
Waste Heat Temperature Limits	70 - 80 °C	>120 °C	Laboratory Testing	125 °C
COP	0.8	3.4	Laboratory Testing	3.6
Estimated Equipment Capital and Installation Costs	$2540/unit or $85/kW	$2000/kW	Market Available Cost	$1500/kW
Estimated Operation and Maintenance Costs	$916	$215 (based on 3.4 COP)	Market Available Cost	$203 (based on 3.6 COP)
Other, specify	Size = 3bhp	Size = 30kW	Power Measurements in Lab	30kW

Breadboard Design

- Three important sub-systems:
  - Heat pump cart: hosts the heat pump design, namely, compressor, variable frequency drive, condenser and evaporator
  - Load cart: After the steam is generated, its conditions are measured in this cart then the condensate is recirculated back to the system
  - Water cart: a small cart with a system to recirculate and measure the flow rate in the steam-generating loop.
- Key features of the breadboard system design:
  - Simple single-stage vapor-compression cycle design
  - Closed loop refrigerant and closed loop steam system design
  - Hermetic sealed compressor to prevent refrigerant leakage



Refrigerant Selection

- Three refrigerants shortlisted: R245fa, R1233zd(E), R1336mzz(Z)
- R1233zd(E) and R1336mzz(Z):
  - Have lower GWP and ODP than R245fa
  - Higher COP than R245fa

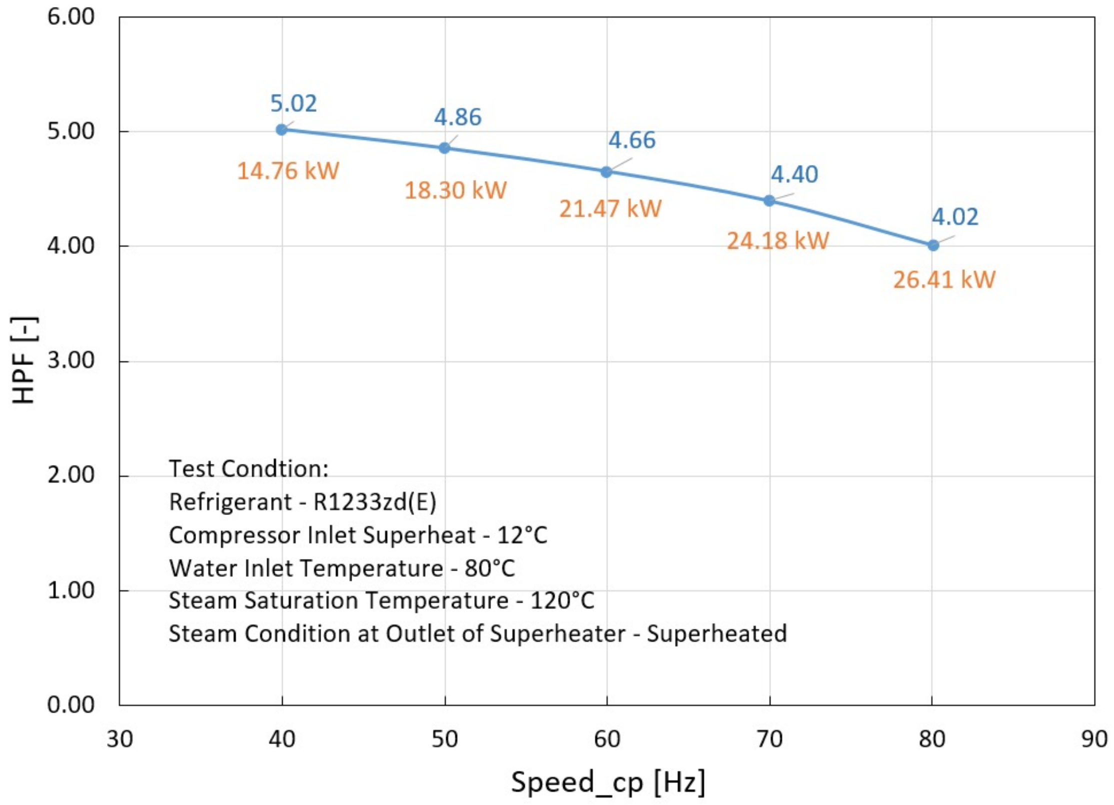
Refrigerants	MW [g/mol]	Tcrit [C]	Pcrti [MPa]	Vaporization Heat [kJ/kg] at 125 [C]	Saturated Vapor Density [kg/m³] at 75 [C]	ODP [-]	GWP [-]	ASHRAE Std 34 Satety Class [-]
R245fa	134.0	153.9	3.65	105.1	38.3	0	858	B1
R1233zd(E)	130.5	166.5	3.62	117.6	30.7	0.00034	1	A1
R1336mzz(Z)	164.1	171.4	2.90	107.1	24.4	0	2	A1

Refrigerants	q_tot [kJ/kg]	q_tot [kJ/m³]	w_th [kJ/kg]	w_elec [kJ/kg]	COP_th	COP
R245fa	128.11	4614.43	27.71	34.38	4.62	3.73
R1233zd(E)	138.83	4027.04	28.60	35.48	4.85	3.91
R1336mzz(Z)	116.92	2706.68	24.54	30.44	4.77	3.84
R245fa	1	1	1	1	1	1
R1233zd(E)	1.084	0.873	1.032	1.032	1.050	1.050
R1336mzz(Z)	0.913	0.587	0.886	0.886	1.031	1.031

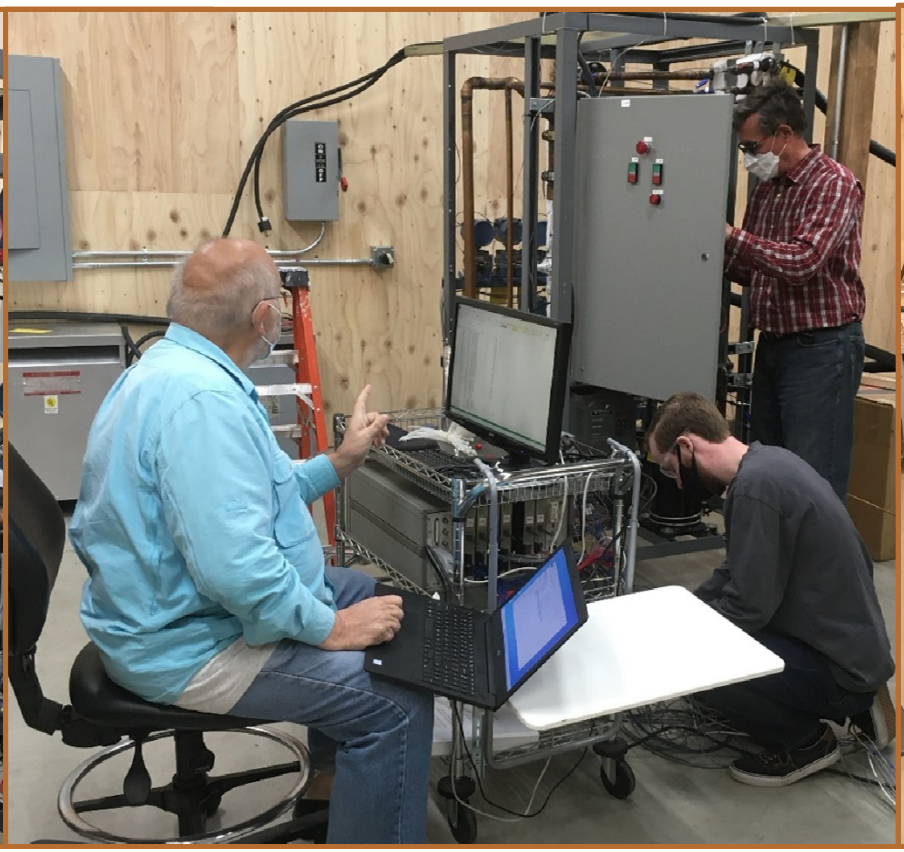
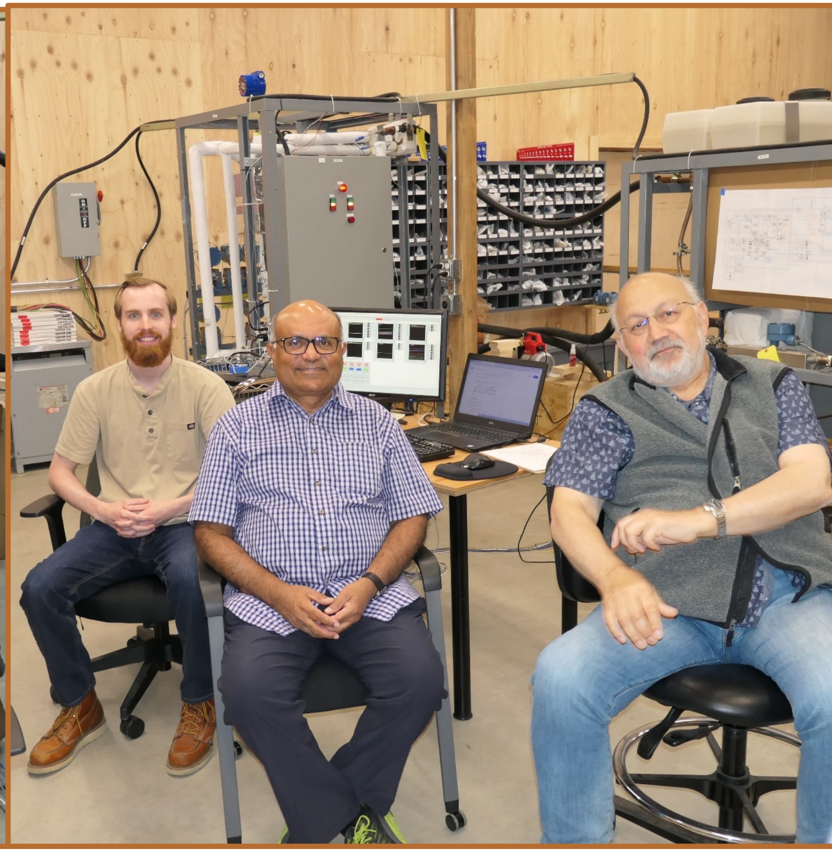
Preliminary Lab Testing

Key findings from the laboratory tests:

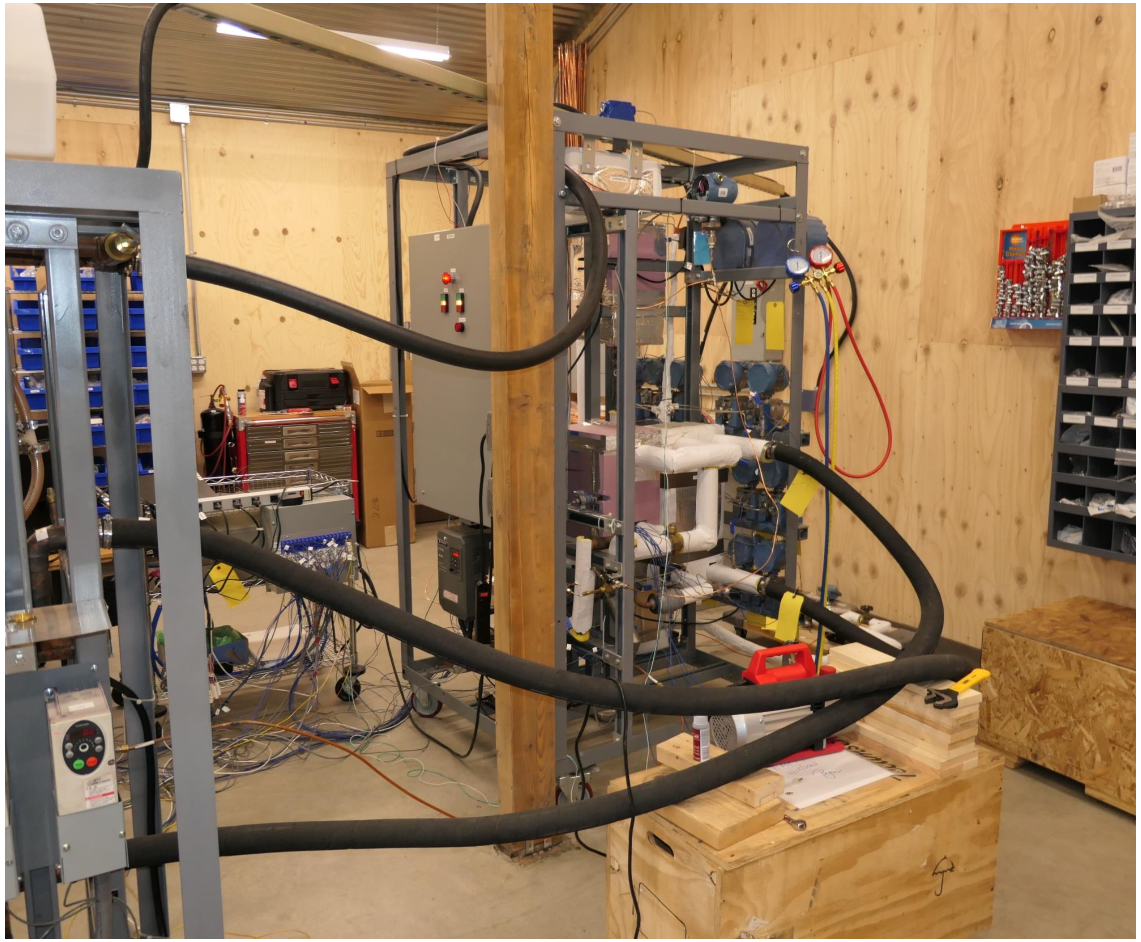
- Heating Performance Factor (HPF) (equivalent to COP) has an inverse relation with system speed, a direct indicator of system load
- Higher load (capacity) or compressor speed results in lower HPF values
- The target capacity of 30 kW could likely be achieved at speeds around 90 Hz
- Repeatability: Breadboard system runs reliably and has shown that repeated test conditions produce similar results
- System optimization needs to be completed to get COP>3.4 at 30kW (90Hz compressor speed)
- More iterations are in progress to test all the refrigerants



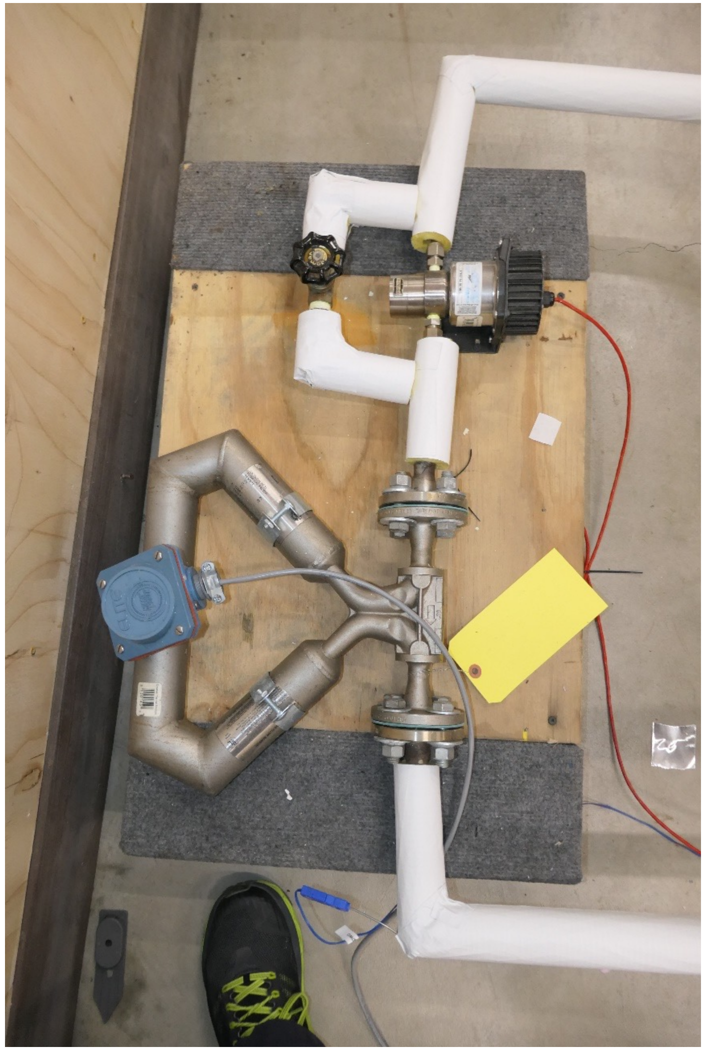
Breadboard System Assembly

Instrumentation and Monitoring



Final Design Layout



Expected System Benefits

- Lower Costs
- Greater Flexibility
- Environmental Benefits
- Increased Safety
- Energy Security
- Economic Development

Summary

- Initial test results are promising
- Technology has potential to recover abundantly available waste heat
- Steam can be used readily in many processes
- Can easily integrate with existing boilers and reduce fossil-fuel use
- A variety of industrial applications (Food, Chemical, Pulp and Paper etc.)

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For more information, contact the CEC CAM Mr. Rajesh Kapoor at
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The project is currently ongoing

Resources/ References:

1. Arpagaus, C., Bless, F., Schiffmann, J., Bertsch, S.S., 2016. Multi-temperature heat pumps: A literature review. Int. J. Refrig. 69, 437–465.

2. Viking Heat Engines, 2018. HeatBooster HBS4: Industrial heat pump for clean energy production up to 160 °C.

3. Kondou, C., Koyama, S., 2015. Thermodynamic assessment of high-temperature heat pumps using low-GWP HFO refrigerants for heat recovery. Int. J. Refrig. 53, 126–141.

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