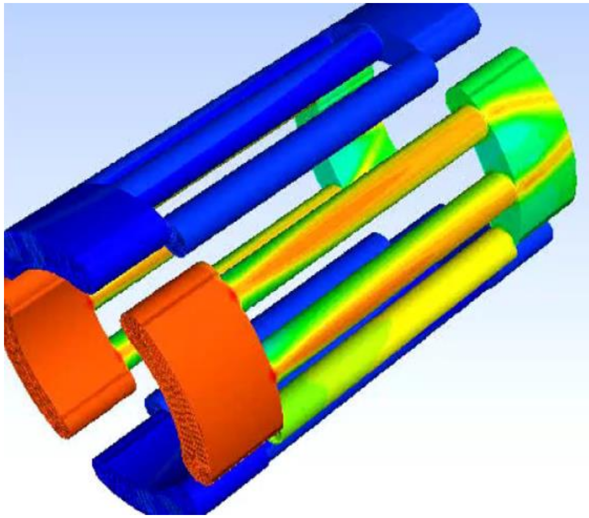
Commercial Refrigeration Expansion Loss Reduction Technique



Oak Ridge National Laboratory
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Project Summary

Timeline:

Start date: Oct 1, 2017

Planned end date: Sept 30, 2020

Key Milestones

1. Formalize collaboration with industry, Dec 31, 2018
2. Experimental evaluation of pressure exchanger performance, Dec 31, 2019

Key Partners:

energy recovery

Hillphoenix — A DOVER COMPANY

The University of Tennessee Knoxville

Budget:

Total Project $ to Date:

- DOE: $658K
- Cost Share: $0

Total Project $:985K

- DOE: $870
- Cost Share: $25K

Project Outcome:

ORNL will collaborate with industry and academia to develop a pressure exchanger for implementation in refrigeration systems that use carbon dioxide (R744). The outcome from this project will consist of a computer simulation tool for the pressure exchanger. In addition, a prototype pressure exchanger will be fabricated for use in a commercial refrigeration system using R744.

Team

- **Oak Ridge National Laboratory**
  - Brian Fricke (R&D staff)
  - Kashif Nawaz (R&D staff)
  - Ahmed Elatar (Postdoctoral associate)
  - Vishaldeep Sharma (R&D staff)
- **Energy Recovery, Inc.**
  - Azam Thatte (Director of Engineering)
- **Hillphoenix**
  - Michael May (Head of R&D, Innovation)
  - Jeff Newell (Director of R&D)
- **University of Tennessee**
  - William Miller (Lecturer)







Challenge

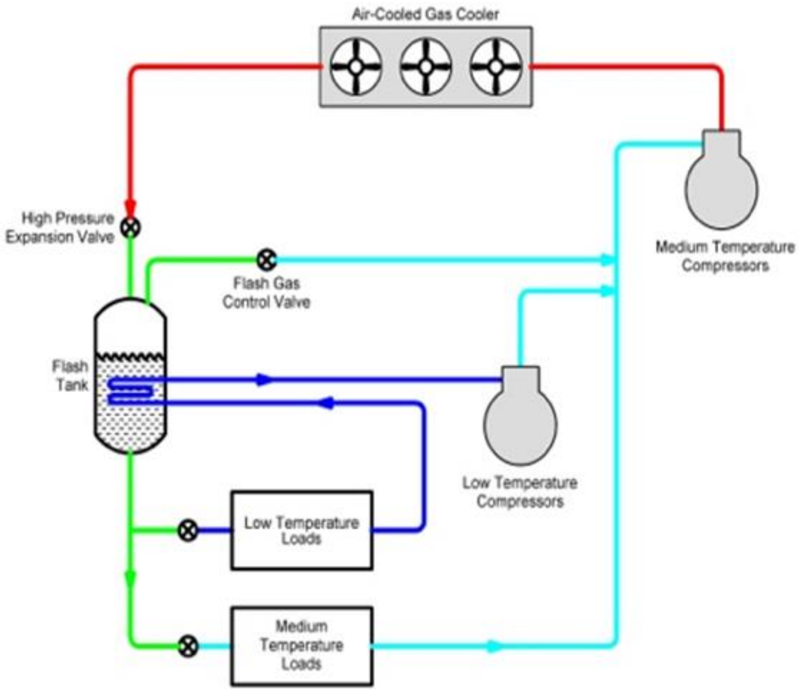
- **Pressure losses are unavoidable in HVAC&R systems**
  – Pressure drop in piping, heat exchangers, etc.
- **Pressure loss in certain components can be recovered, e.g., expansion processes**
  – Ejectors
  – Turbines/expanders
- **Existing techniques have limited implications due to operating constraints**
- **Transcritical CO_2 refrigeration systems**
  – Systems operate at high pressures
  – Expansion processes lead to significant "lost work"
  – Performance could be enhanced with work recovery

Second Law Efficiency

- **Components of vapor compression refrigeration cycle**
  - Compressor, condenser, expansion device, evaporator
- **Irreversibility in these components**
  - Fluid friction
  - Heat transfer through a finite temperature difference
- **Consider the expansion device**
  - Isenthalpic process
  - First Law: $h_{in} = h_{out}$
  - Second Law: $\dot{S}_{gen} = \dot{m}(s_{out} - s_{in})$
  - Second Law Efficiency: $\varepsilon = \frac{h_{out} - h_o - T_o(s_{out} - s_o)}{h_{in} - h_o - T_o(s_{in} - s_o)}$

Second Law Efficiency

High-Pressure Expansion Valve	Temperature (°F)	Pressure (psia)	Enthalpy (Btu/lbm)	Entropy (Btu/lbm R)
Inlet	94.0	1310	127.2	0.3119
Outlet	33.5	517	127.2	0.3223
T_o, P_o	77.0	14.7	217.6	0.6541



Second Law Efficiency:

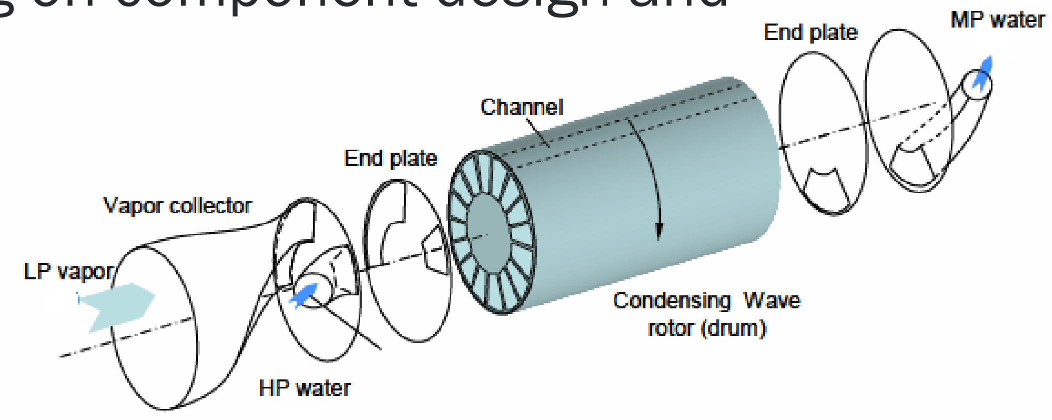
$$\varepsilon = \frac{h_{out} - h_o - T_o(s_{out} - s_o)}{h_{in} - h_o - T_o(s_{in} - s_o)}$$

$$\varepsilon = 0.875$$

Approach

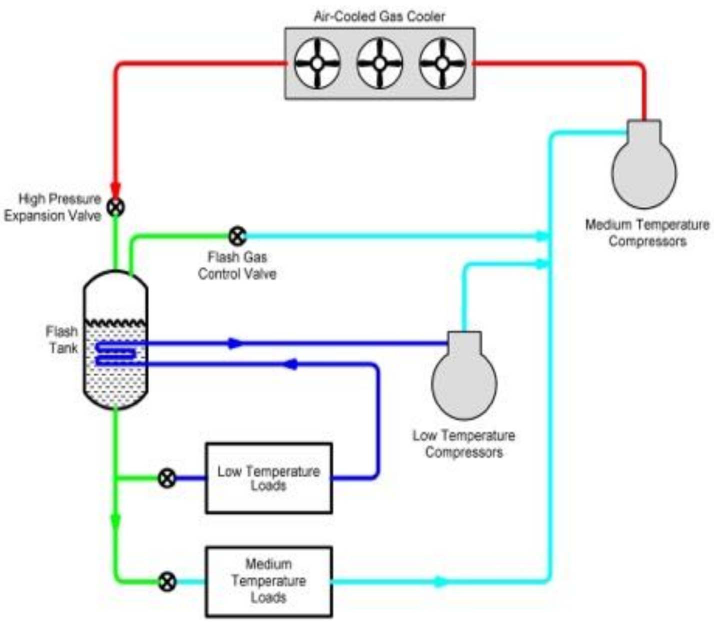
- **Design and implement "pressure exchanger" (PX) technology in refrigeration systems**

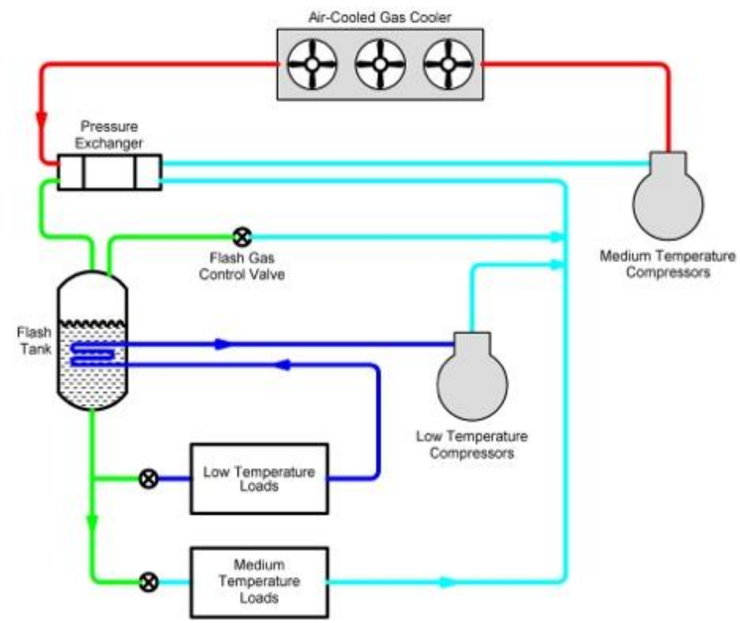
- **Challenges for integration**
  - Seals are critical path component for successful implementation
  - Laboratory data is sparse
  - Information is lacking on component design and implementation



Approach

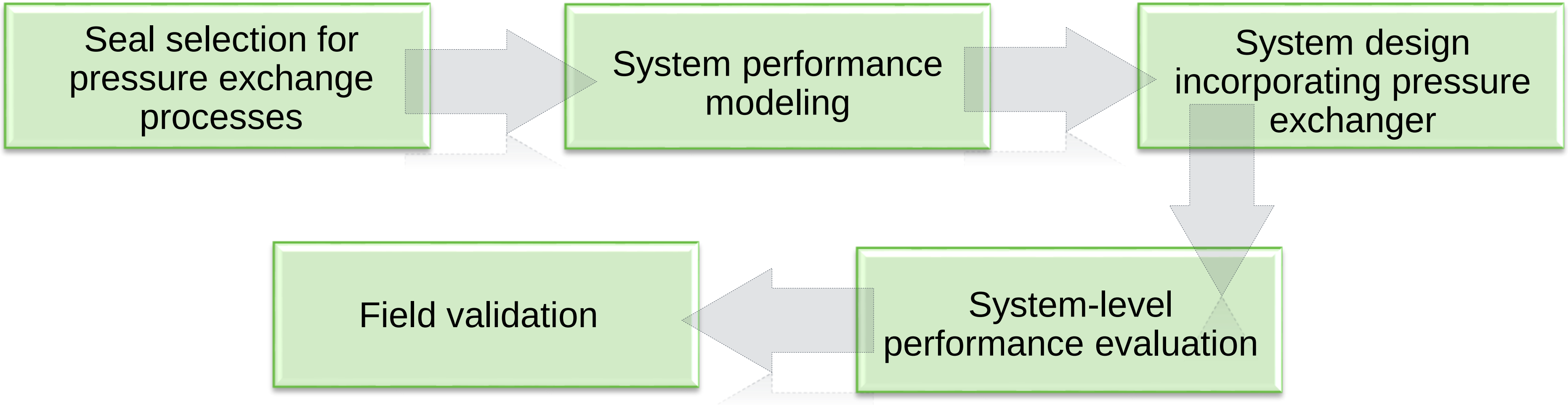
- **4-Port PX for CO_2 refrigeration**
  - PX is used to replace high-pressure expansion valve and increase pressure of the medium-temperature suction
  - Reduces power consumption of medium-temperature compressor
  - COP increases upwards of 15% if suction flow boosted by PX
  - Other configurations possible





Approach

- Model the pressure exchanger, develop designs, and test the designs in benchtop test stands
- Validate the technology to evaluate the potential improvement in performance
- Develop practical performance correlations for commercial systems

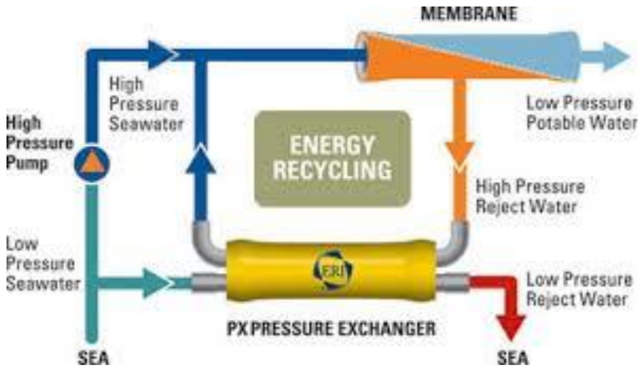


Impact

- **Commercial refrigeration in food retail:**
  - 550 TBtu of primary energy per year
  - 25 Mt CO_2 emissions per year
- **Estimated to increase efficiency of CO_2 (R744) refrigeration systems by up to 15%**
  - Annual energy savings: 66 TBtu
  - ~$600M savings in electric bills for commercial refrigeration customers
- **Increased deployment of the low-GWP refrigerant CO_2 (R744) in commercial refrigeration:**
  - R404: GWP = 3900
  - R744: GWP = 1
- **Extended use of CO_2 refrigeration systems into warmer climates**
- **Direct support of BTO Emerging Technologies 2016-2020 MYPP**
  - By 2030, develop cost-effective technologies capable of reducing a building's energy use per square foot by 45%, relative to 2010

Progress — Industrial Engagement

- **Energy Recovery, Inc., has been engaged**
  - Global leader in pressure energy technology
  - Primary market: Water desalination
    - Great potential for work recovery
- **There are some major differences compared with proposed implementation**



Desalination	Refrigeration
High operating pressure	Moderate operating pressure
Moderate operating temperatures	Moderate operating temperature
Working fluid: liquid	Working fluid: liquid and vapor
Mixing is not desired	Mixing is acceptable

Progress — Characterization

- PX: Analogy to Heat Exchangers

Heat Exchanger	Pressure Exchanger
Transfer heat energy	Transfer work energy
Involves heat losses	Involves pressure losses
Fluids can be in liquid/gas or 2-phase state	Fluids can be in liquid/gas or 2-phase state
Phase change process can occur during the transport process	Phase change process can occur during the transport process
Geometry establishes the effectiveness	Geometry establishes the effectiveness

Progress — Characterization

- PX: Analogy to Heat Exchangers

Heat Exchanger

$$q_{max} = C_{min}\left(T_{h,i} - T_{c,i}\right)$$

$$\varepsilon = \frac{q}{q_{max}}$$

$$\varepsilon = \frac{C_c\left(T_{c,o} - T_{c,i}\right)}{C_{min}\left(T_{h,i} - T_{c,i}\right)}$$

$$q = \varepsilon C_{min}\left(T_{h,i} - T_{c,i}\right)$$

$$\varepsilon = f\left(NTU, \frac{C_{min}}{C_{max}}\right)$$

$$NTU \equiv \frac{UA}{C_{min}}$$

Pressure Exchanger

$$W_{max} = v_{min}\left(P_{h,i} - P_{l,i}\right)$$

$$\varepsilon = \frac{W}{W_{max}}$$

$$\varepsilon = \frac{v_l\left(P_{l,o} - P_{l,i}\right)}{v_{min}\left(P_{h,i} - P_{l,i}\right)}$$

$$W = \varepsilon v_{min}\left(\mathrm{P}_{h,i} - P_{l,i}\right)$$

$$\varepsilon = f\left(NTU, \frac{v_{min}}{v_{max}}\right)$$

$$NTU \equiv \frac{\Delta P_{max} - \Delta P_{loss}(f, mixing)}{\Delta P_{max}}$$

Progress — Characterization

- PX: Analogy to Heat Exchangers

Heat Exchanger

$$\boldsymbol{q_{max} = C_{min}(T_{h,i} - T_{c,i})}$$

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Progress — Characterization

- PX: Analogy to Heat Exchangers

Heat Exchanger

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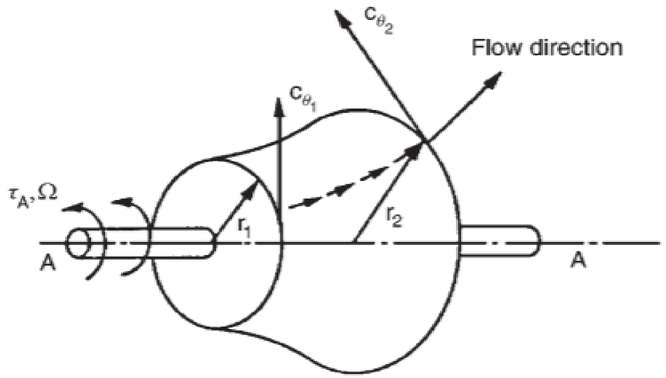
Progress — Performance Characterization

Euler's equation (angular momentum):

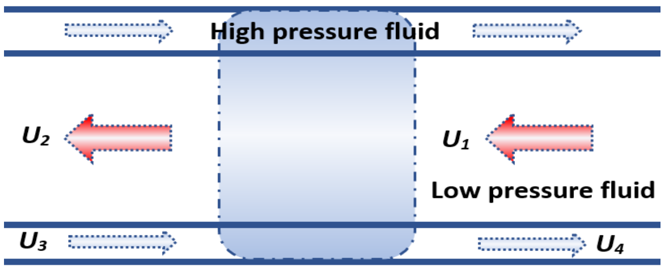
$$\tau_A \Omega = \dot{m}(U_2 c_{\theta_2} - U_1 c_{\theta_1})$$



Work imparted on fluid streams:

$$\Delta W_{LP} = \frac{\dot{W}_{LP}}{\dot{m}_{LP}} = \frac{\tau_A \Omega}{\dot{m}_{LP}} = \left(U_2 c_{\theta_2} - U_1 c_{\theta_1}\right) > 0$$

$$\Delta W_{HP} = \frac{\dot{W}_{HP}}{\dot{m}_{HP}} = \frac{\tau_A \Omega}{\dot{m}_{HP}} = \left(U_4 c_{\theta_4} - U_3 c_{\theta_3}\right) < 0$$



Efficiency of PX:

$$\eta_{PX} = \frac{\Delta W_{LP}}{\Delta W_{HP}}$$

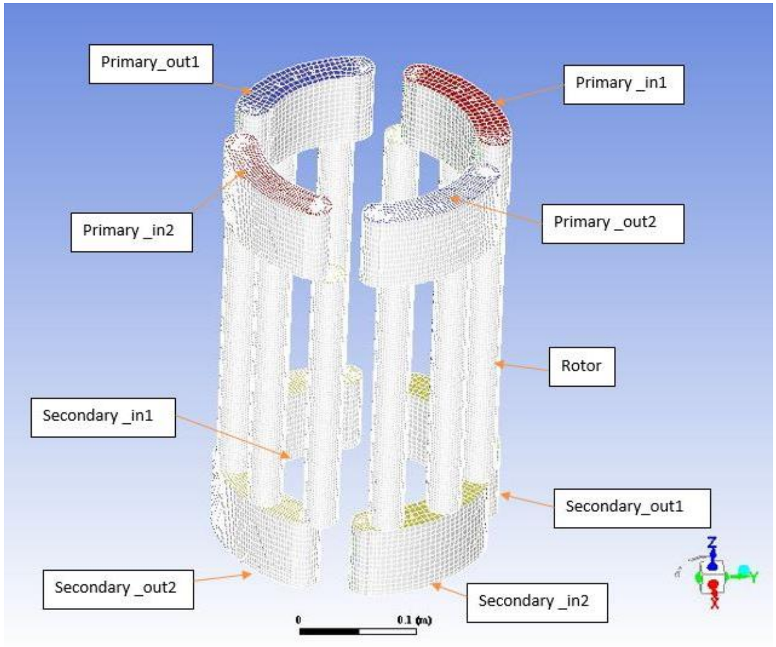
Rothalpy and Lost Work:

$$R = h + \frac{1}{2} c^2 - U c_\theta$$

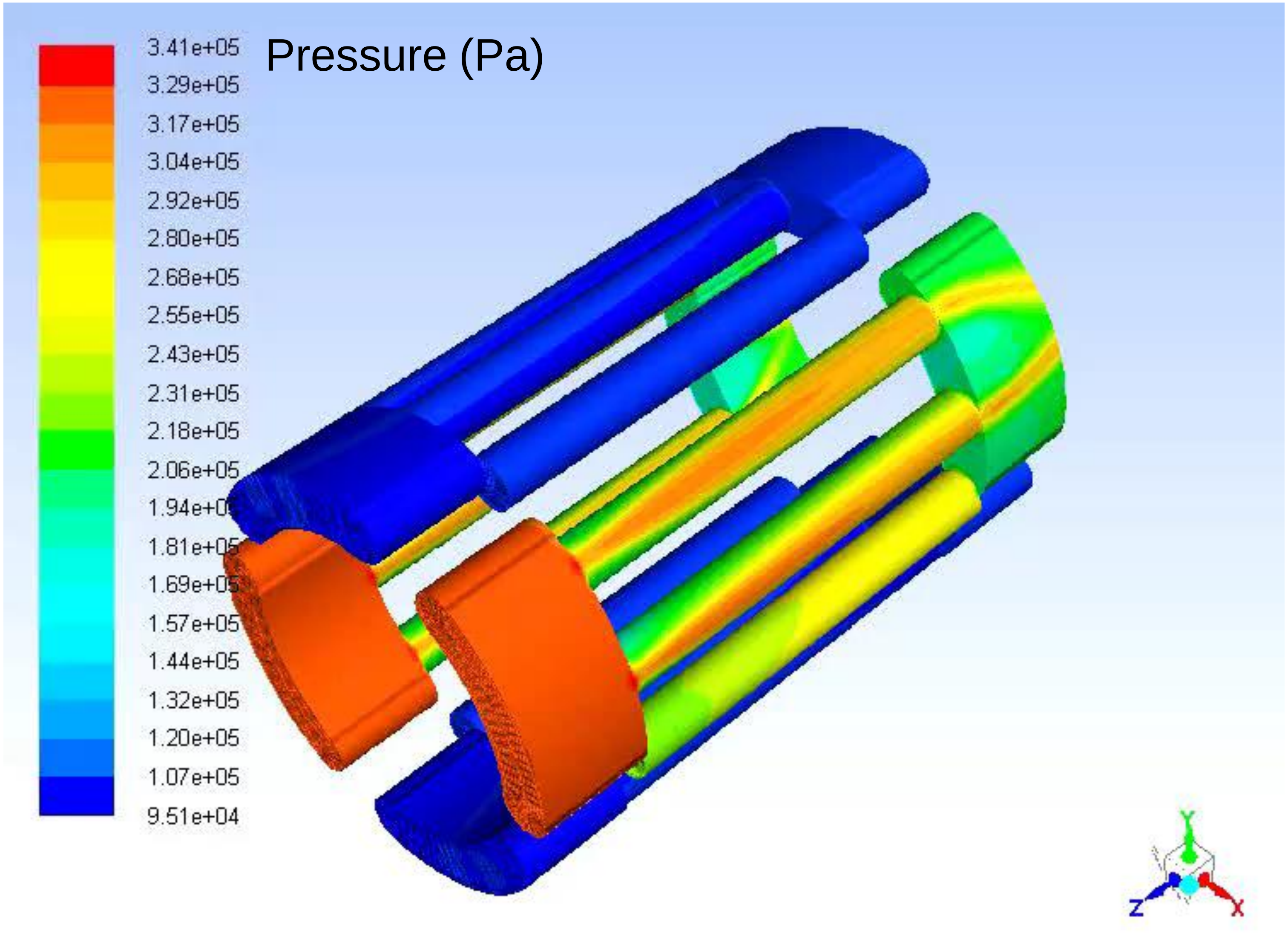
$$R_{lost,PX} = \Delta R_{HP} - \Delta R_{LP}$$

Progress — Numerical Analysis

- Performance of PX modeled with computational fluid dynamics (CFD) software package
- Model assumptions:
  - Stationary inlet/outlet ports
  - Rotor (1,000 RPM)
  - 12 channels in rotor
  - Channel length = 0.19 m
  - Channel diameter = 0.02 m
  - Rotor outside diameter = 0.18 m
  - Stationary port depth = 0.05 m

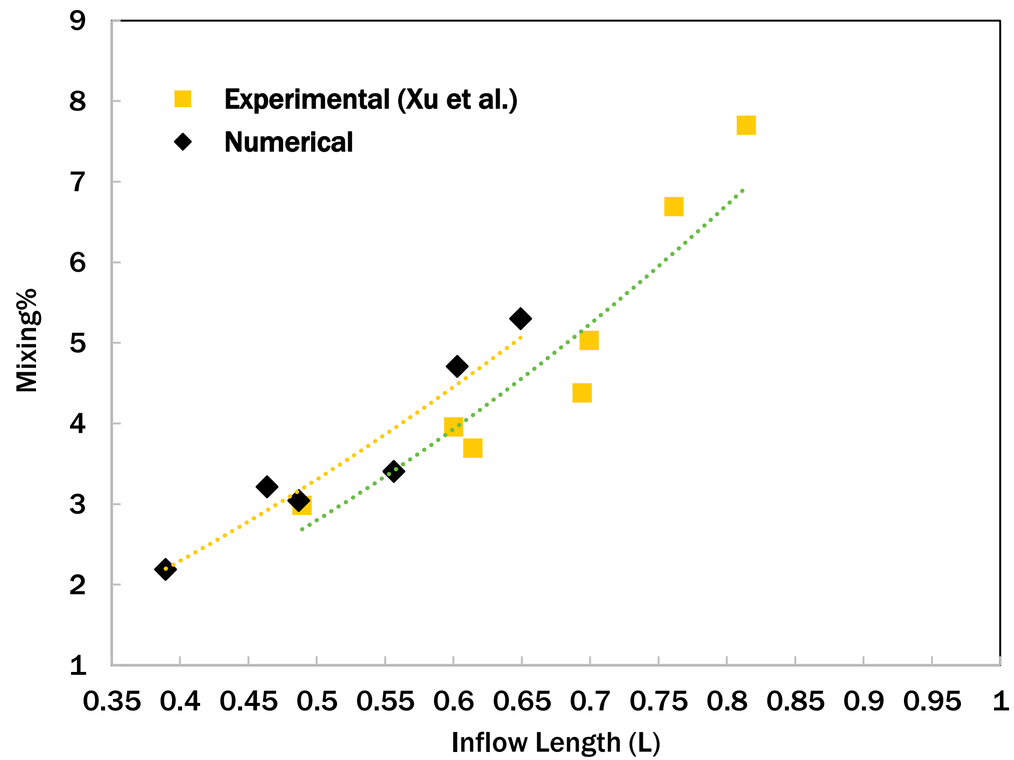


Progress — Numerical Analysis



Progress — Numerical Analysis

- **Comparison of CFD model with existing experimental data (desalination data)**
  - Inflow length is defined as the total travelling distance of any flow inside the rotor duct
  - Mixing is the term that quantifies the amount of mixing that occurs between the primary and secondary flow inside the PX



Enle Xu, Yue Wang, Liming Wu, Shichang Xu, Yuxin Wang, and Shichang Wang, "Computational Fluid Dynamics Simulation of Brine−Seawater Mixing in a Rotary Energy Recovery Device," *Ind. Eng. Chem. Res.*, 53, 18304−18310, 2014.

Stakeholder Engagement

- **Development of the technology**
  - Energy Recovery, Inc.
  - Non-disclosure agreement
  - Preliminary analysis
  - Prototype PX development
- **Meetings with experts at technical forums**
  - ASHRAE (TC 10.7)
  - Purdue conferences
- **Presentations/conference papers**
  - Paper to be presented at upcoming 25th International Congress of Refrigeration (August 24–30, 2019, Montreal)

Remaining Project Work

- Development of a pressure exchanger test apparatus and prototype pressure exchanger for R744 applications
- Experimental evaluation of pressure exchanger performance using R744
- Retrofit pressure exchanger in R744 refrigeration system

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $870K
Cost to Date: $615K
Additional Funding: Cost share from industry partner, $25K

Budget History					
1 Oct 2017 – FY 2018 (past)		FY 2019 (current)		FY 2020 – Insert End Date (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$382k	$0	$276k	$0	$212k	$25k

Project Plan and Schedule

Project Schedule								
Project Start: 1 Oct 2017		◆	Milestone (originally planned)					
Project End: 30 Sept 2020		◆	Milestone (actual)					
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
FY19								
Q1 Milestone: Formalize collaboration with industry	◆							
Q2 Milestone: Refrigeration system model with pressure exchanger		◆						
Q3 Milestone: Pressure exchanger test apparatus								
FY20								
Q1 Milestone: Pressure exchanger performance evaluation								
Q2 Milestone: Pressure exchanger compatible with refrigeration system operating conditions								
Q4 Milestone: Retrofit pressure exchanger in refrigeration system								
Q4 Milestone: Implementation plan								