Periodic Flow Hydrodynamic Resistance Parameters for ErPr Rare-Earth Regenerator Material at Cryogenic Temperatures

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Outline

- Introduction
- Past Work
- Experimental Setup
  - Cryogenic test chamber
  - ErPr Regenerator test section
  - Mass Flow Measurement
- CFD Modeling Approach
- Preliminary Results
- Future Work

Introduction

- The regenerator is a crucial component of pulse tube cryocoolers
- Hydrodynamics and thermal transport within the regenerator are not fully understood
- Hydrodynamic parameters determined at ambient temperature are assumed to be valid at cryogenic temps
- Pressing need exists to determine hydrodynamic parameters at cryogenic temperatures and verify foregoing assumption

Previous Work at GT Cryolab

- Mihir Pathak (2014)
- Measurement and correlation of hydrodynamic resistance parameters for ErPr rare-Earth regenerator filler material under steady and oscillatory flow conditions in room temperature
- Steady flow porous media hydrodynamic resistance parameters were different from their oscillatory flow counterparts
- The objective in this study is to perform similar tests at cryogenic temperatures

Room Temperature Correlations

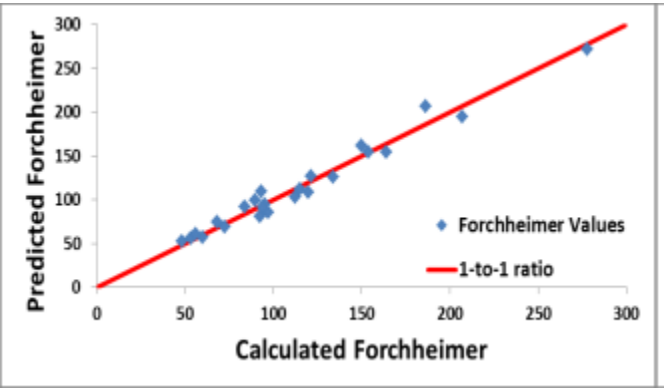
$$K = 1.93 \times 10^{-11}\ \mathrm{m}^2$$

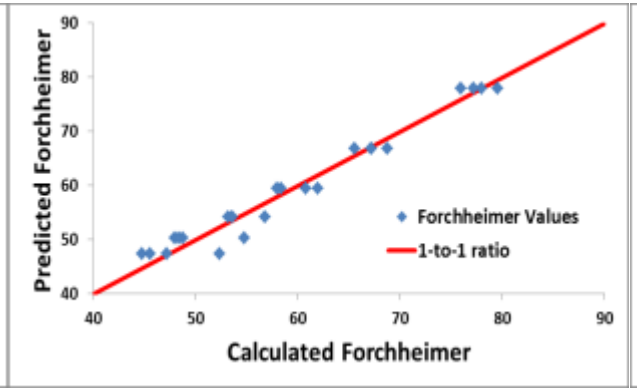
$$c_f = a \cdot {Re_K}^b + c$$

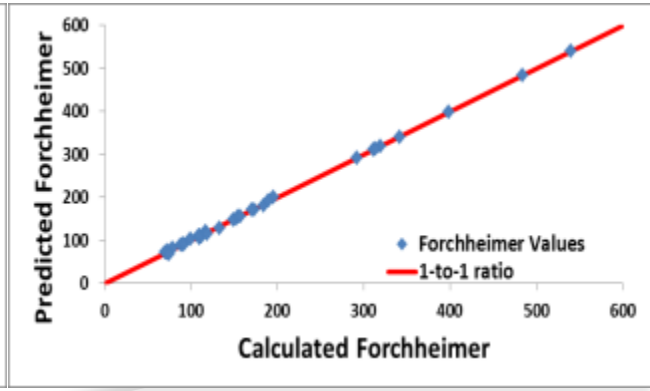
b = -1.4

Case	a	c
Periodic Flow, P*=1.034	16.2	20.6
Periodic Flow, P*=1.724	7.7	25.4
Steady Flow, P*>0.7 and Re_K>0.2	6.2	28.8

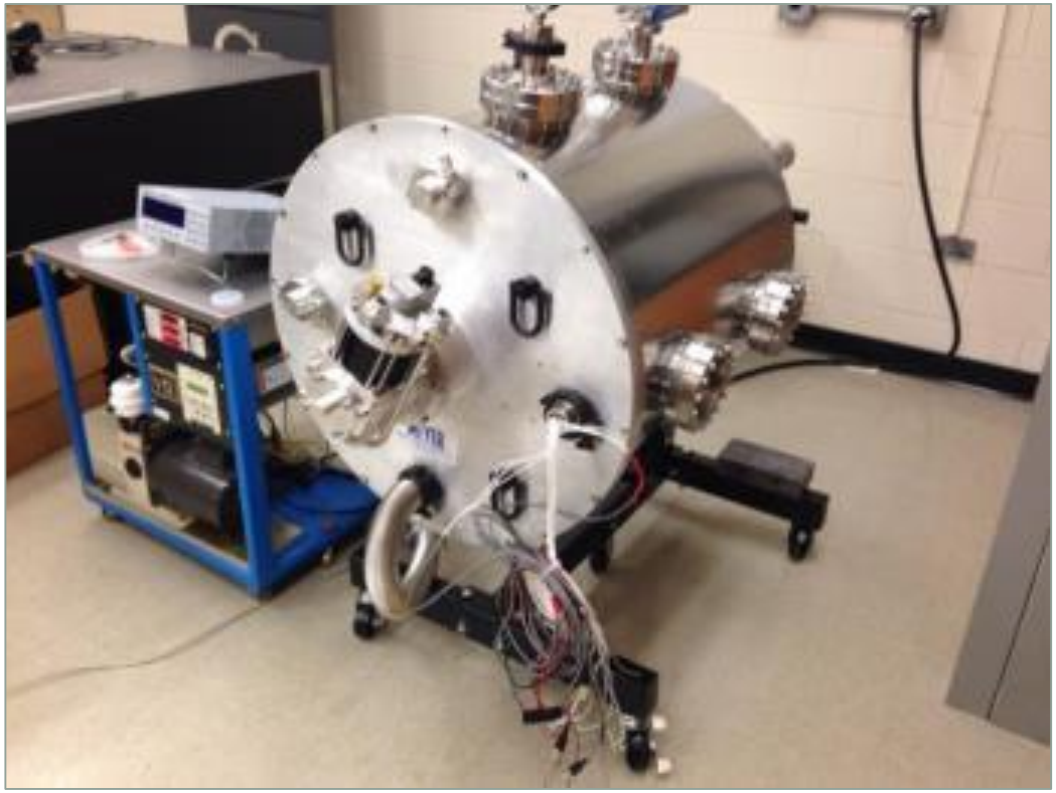
P*	a	b	c
0.345	91.9	-0.52	-119.4
0.517	0.4	-2.05	98.1
0.689	3.4	-1.38	56.4
0.862	4.7	-1.32	45.8
1.034	5.5	-1.26	43.4
1.379	3.1	-1.53	50.8
1.724	2.2	-1.71	63.4







Cryogenic test chamber



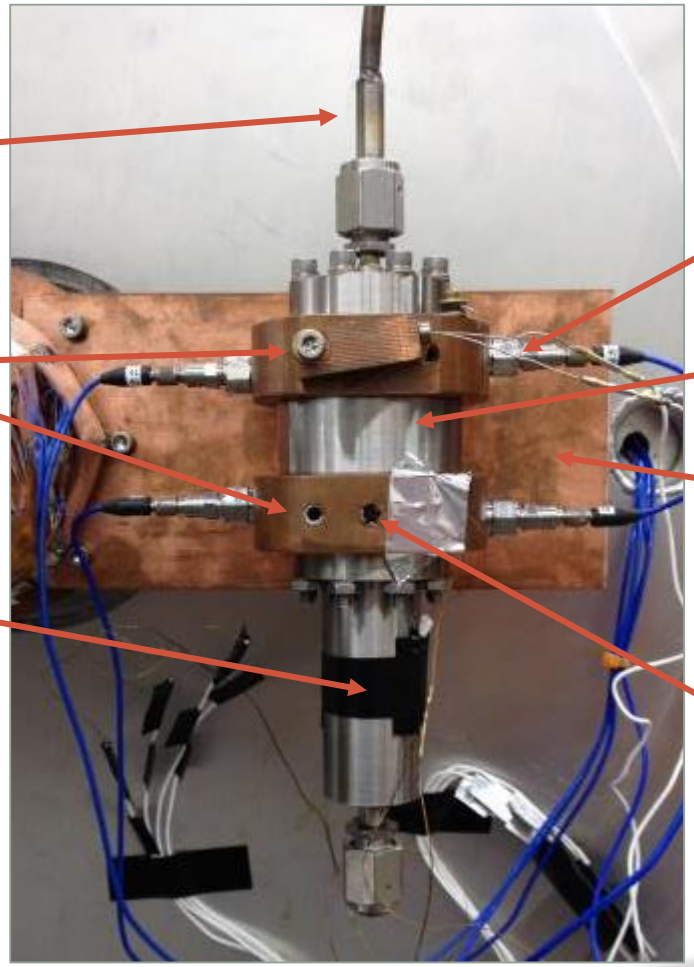
- Vacuum-sealed dewar with modular feedthroughs
- Insulating vacuum of 1E-6 torr
- Sumitiomo GM Cryocooler with 32K 1st stage and 6K 2nd stage cold heads

Regenerator Test Section

SS transfer tube to Pressure Wave Generator (PWG)

Copper heat exchanger (CHX)

50cc Surge Volume (SV)



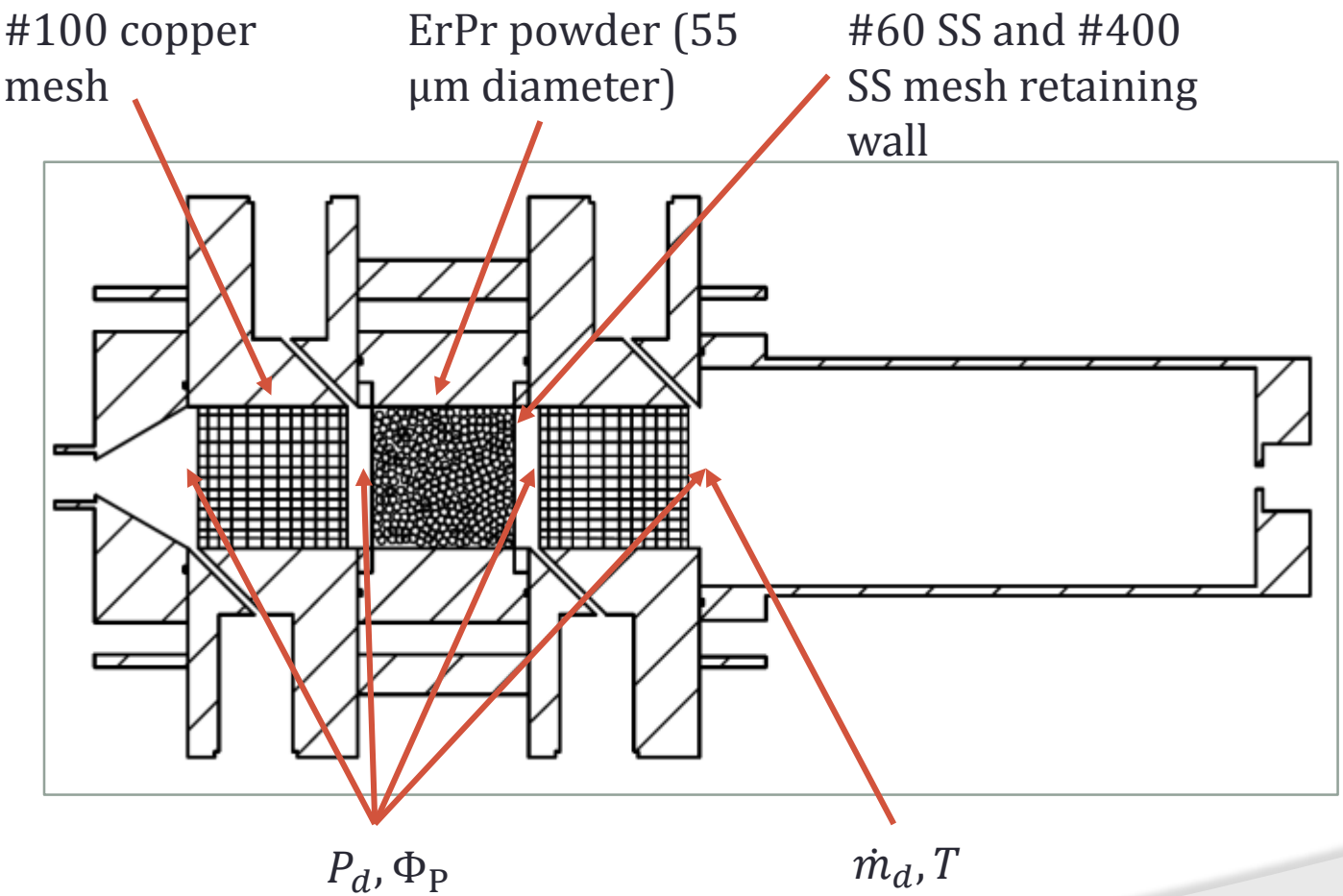
PCB 102A10 and 102A05 pressure sensors

Regenerator

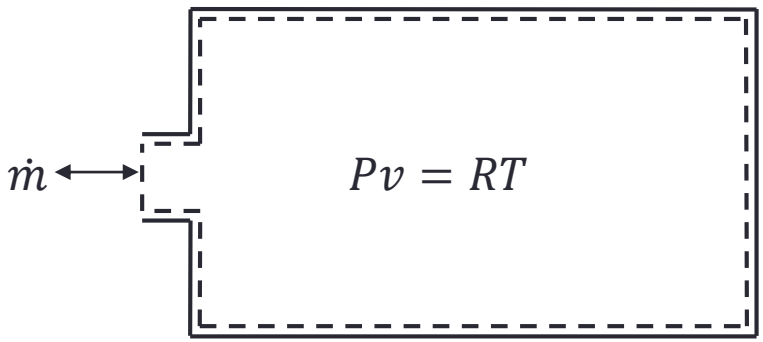
Thermal Bus Bar

Cryocon S900-A silicon temperature diode

Regenerator Test Section cont.



Mass Flow Measurement



- Hot-wire anemometry is not feasible at cryogenic temperatures
- Indirect $|\dot{m}|$ measurement taken from instantaneous SV temperature and pressure

$$\dot{Q} - \dot{W} = \frac{\mathrm{d}E}{\mathrm{d}t} \pm \dot{m}h = 0$$

$$\dot{m}c_pT = \frac{d}{dt}(\rho c_v TV)$$

$$\dot{m}c_pT = \frac{d}{dt}\left(\frac{c_v PV}{R}\right)$$

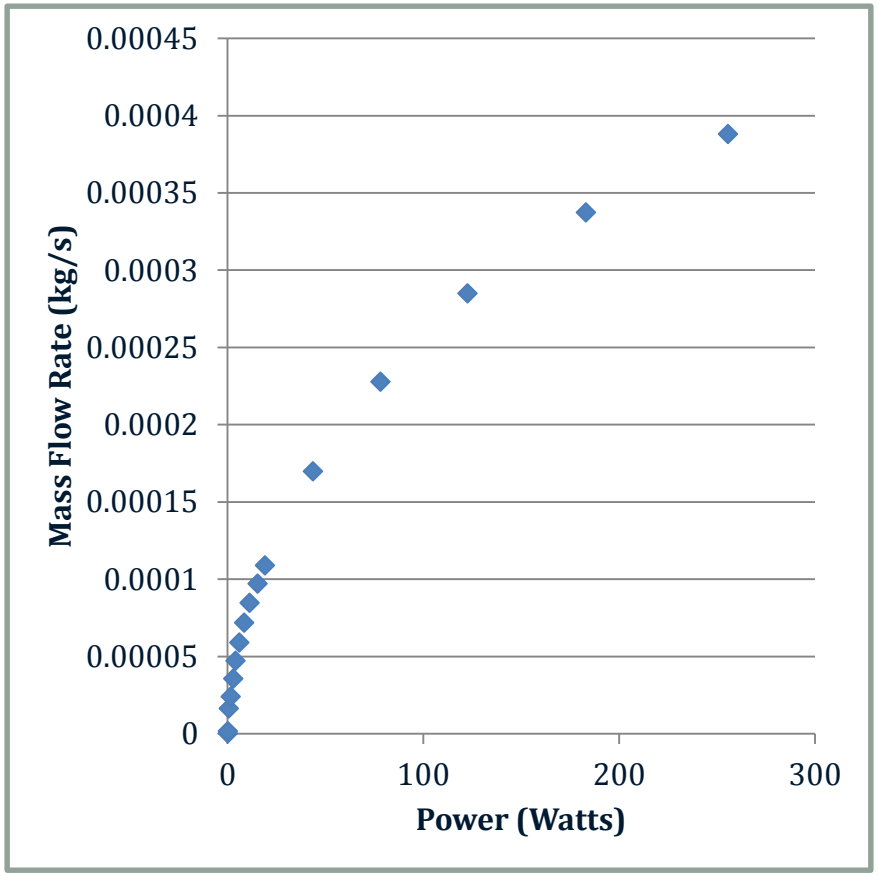
$$\dot{m} = \frac{dP}{dt}\frac{V}{\gamma RT}$$

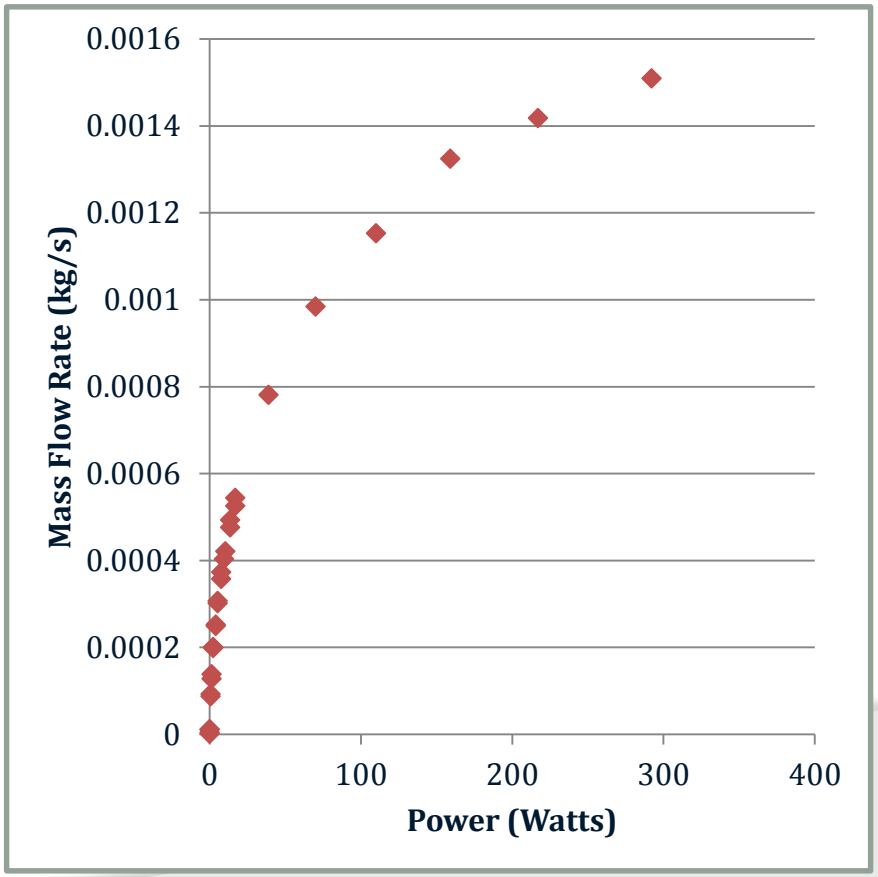
$$\boxed{\dot{m}_d = |\dot{m}| = P_d\omega\frac{V}{\gamma RT}}$$

$$P(t) = P_d\sin(\omega t + \phi_P)$$

$$\dot{m}(t) = \dot{m}_d\sin(\omega t + \phi_m)$$

Compressor Performance





Porous Media Equations

Mass

$$\frac{\partial \varepsilon\rho}{\partial t} + \nabla \cdot (\varepsilon\rho\vec{u}) = 0$$

Momentum

$$\frac{\partial(\varepsilon\rho\vec{u})}{\partial t} + \nabla \cdot (\varepsilon\rho\vec{u}\vec{u}) + \varepsilon\nabla P + \nabla \cdot (\varepsilon\overline{\overline{\tau}}) = -(\frac{\mu}{\overline{\overline{\beta}}} \cdot \vec{u} + \frac{\overline{\overline{C}}\rho}{2} \cdot |\vec{u}|\vec{u})$$

Permeability

$$K = \frac{\varepsilon^2}{\beta}$$

Forchheimer

$$c_f = \frac{CK^{0.5}}{2\varepsilon^3}$$

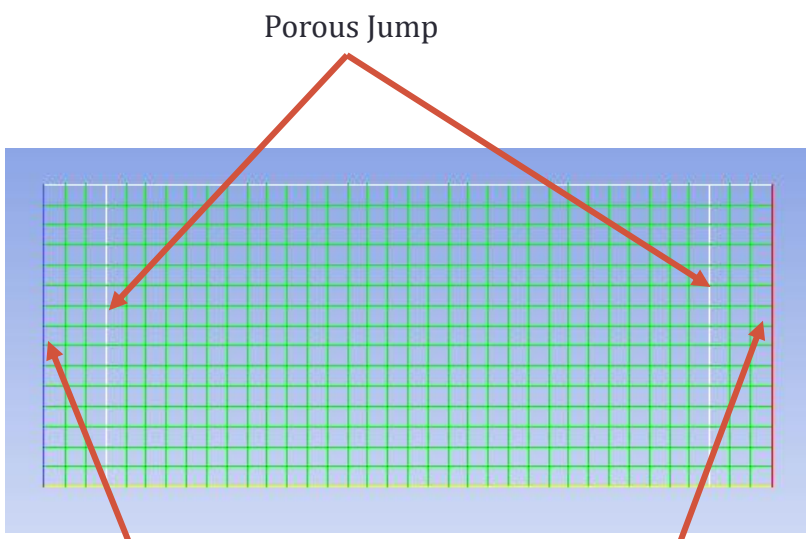
Pore-based Reynolds

$$Re_K = \frac{\dot{m}K^{0.5}}{\mu A}$$

Energy

$$\nabla \cdot [(\varepsilon k_f + (1-\varepsilon)k_s)\nabla T + (\overline{\overline{\tau}} \cdot \varepsilon\vec{u})] = \frac{\partial}{\partial t}(\varepsilon\rho_f E_f + (1-\varepsilon)\rho_s E_s) + \nabla \cdot (\varepsilon\vec{u}(\rho_f E_f + P))$$

CFD Modeling



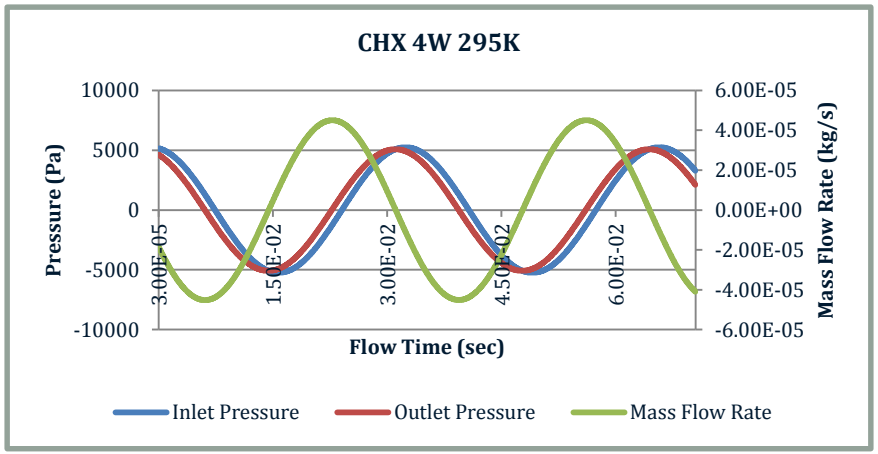
$$P_1(t) = \sum_{n=1}^{\infty} P_n \sin(\omega t + \phi_n)$$

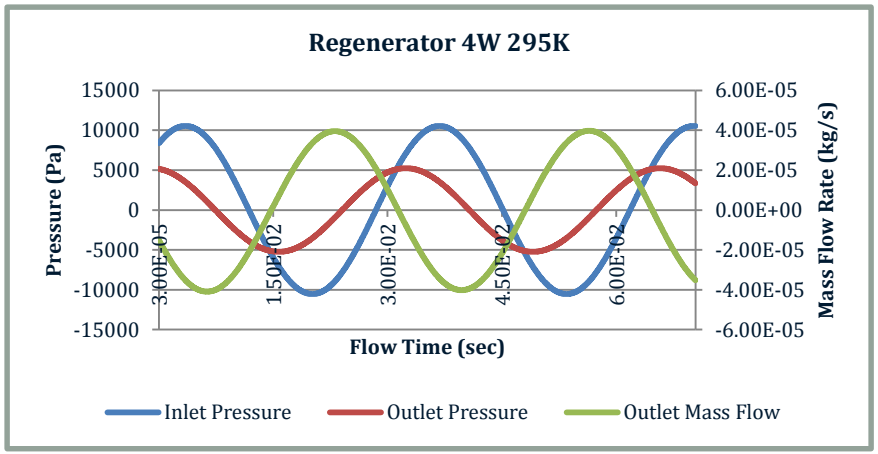
$$P_2(t) = \sum_{n=1}^{\infty} P_n \sin(\omega t + \phi_n)$$

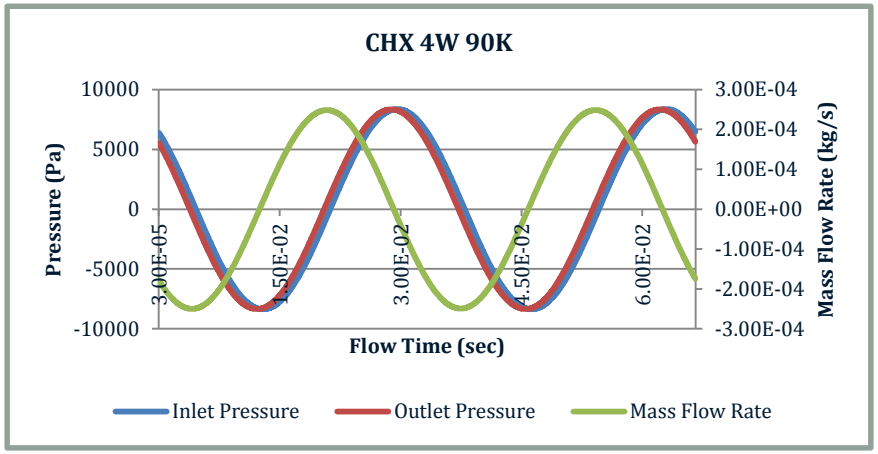
$$\dot{m}_2(t) = \sum_{n=1}^{\infty} \dot{m}_n \sin(\omega t + \phi_n)$$

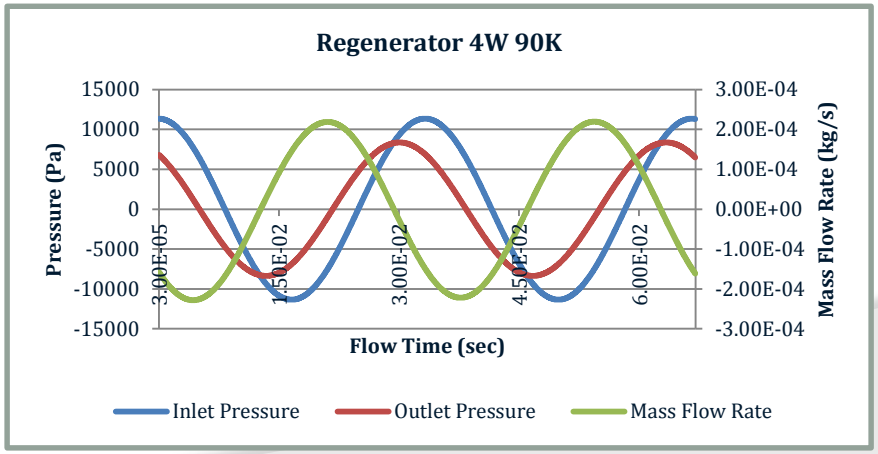
- CHX and Regenerator modeled separately in ANSYS Fluent
- 2D, axisymmetric, laminar, isothermal, homogeneous, and isotropic
- User define function (UDF) used to apply oscillatory pressure boundary conditions
- Inertial resistance at lowest flow rates neglected
- Viscous resistance varied to match $\dot{m}_d$ with experiments
- Simulated $\dot{m}_d$ at CHX inlet used as Regenerator outlet

Pressure and Mass Flow Rates

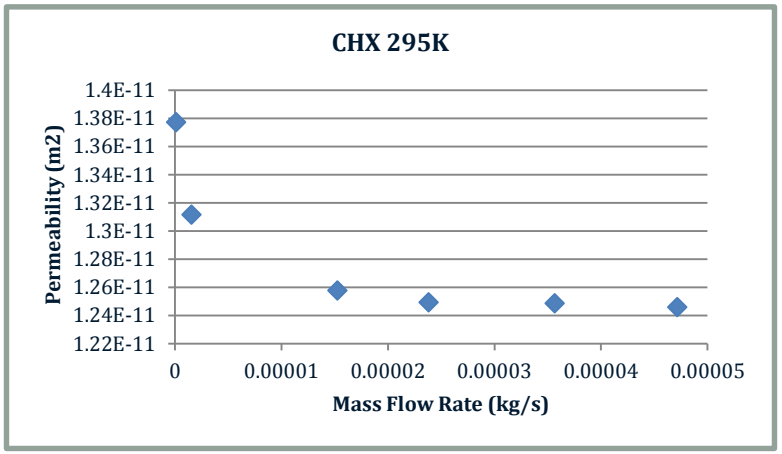


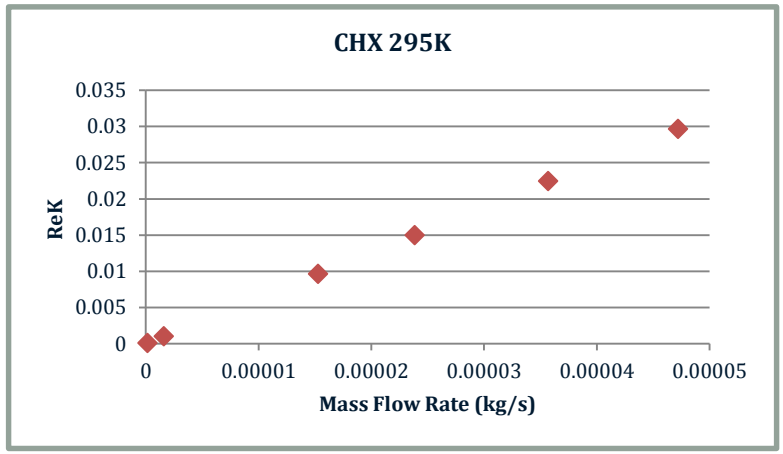


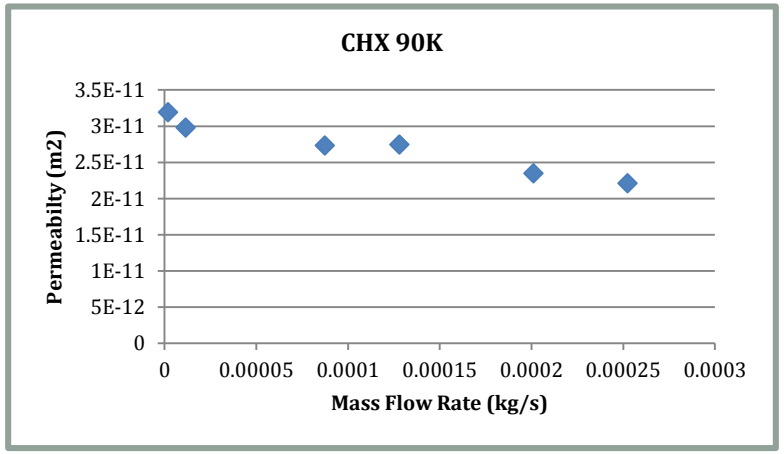


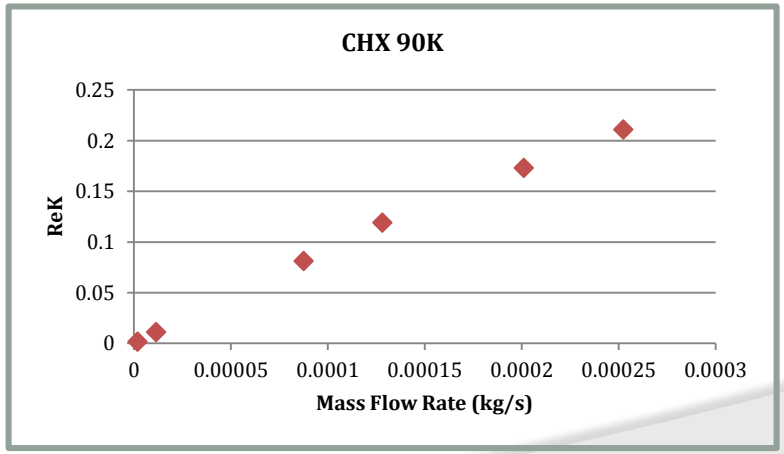


CHX Permeability

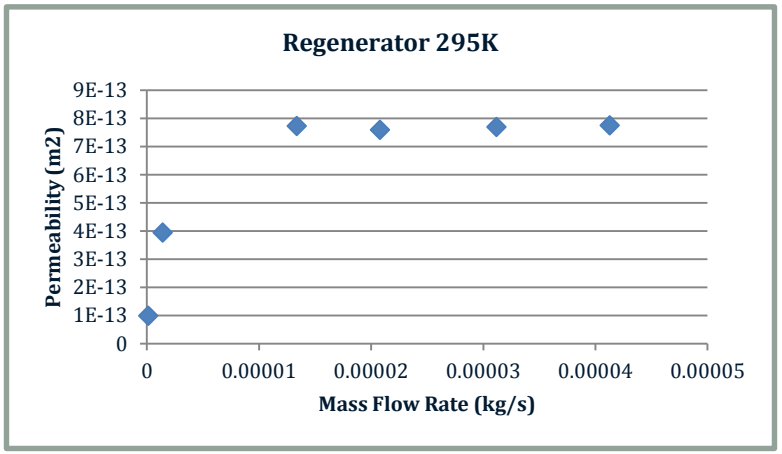


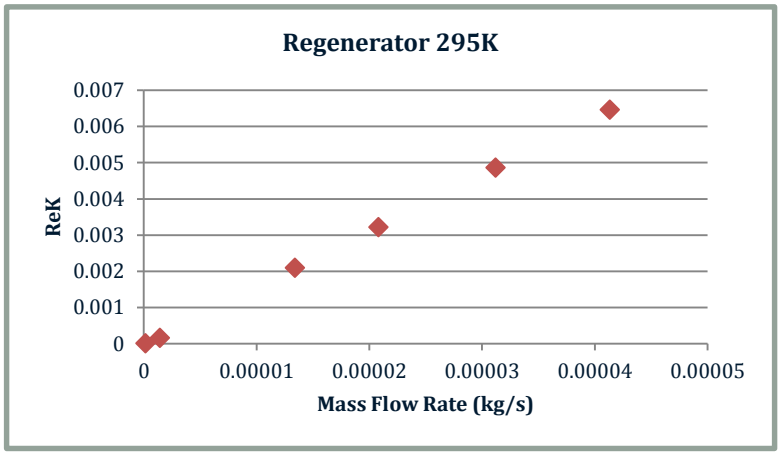


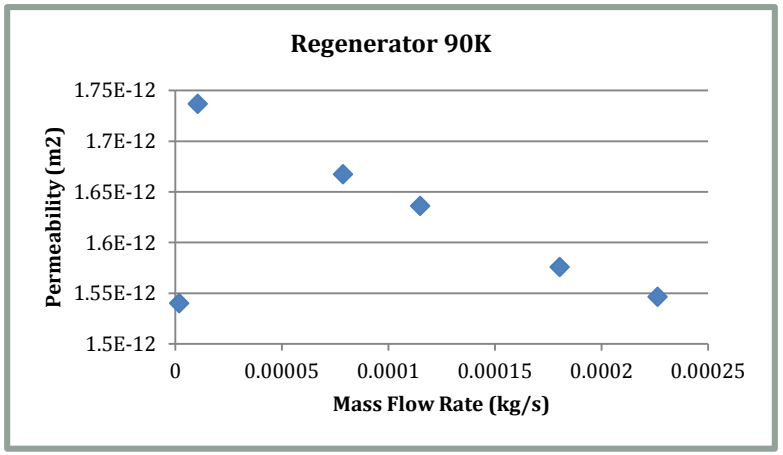


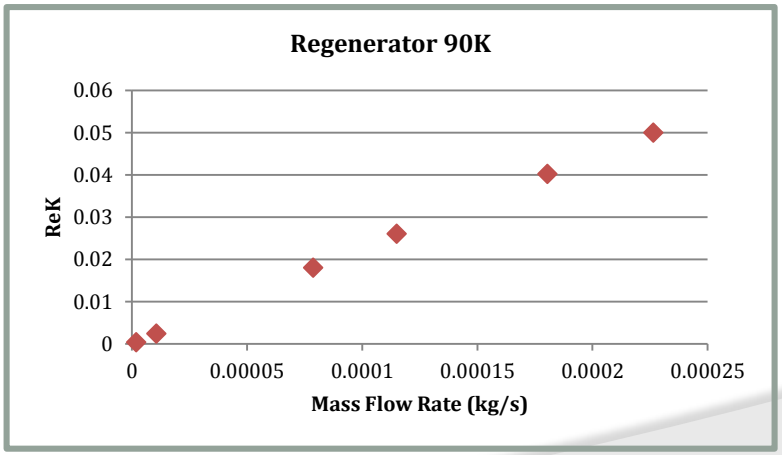


Regenerator Permeability









Future Work

- Complete CFD analysis of CHX an Regenerator at 90K (Experiments completed)
- Using high-flow data points determine inertial resistance for CHX and Regenerator at higher mass flow rates
- Perform additional experiments and analysis to ascertain repeatability and correctness, and at other operating temperatures