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A Bayesian Method to Predict Performance of Compressors Using Novel Lower-GWP Refrigerants Based on Test Data for Existing Refrigerants (Seminar-51)

Energy Efficiency of Novel and Conventional Compressors Using Low-GWP Refrigerants

(Systems & Equipment)

CHICAGO 2015 Winter Conference

Learning Objectives

- Define the key operating and thermophysical properties that determine the mass flow rate and power consumption of a compressors
- Describe the method of Kriging

Acknowledgements

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- Omar Abdelaziz, Oak Ridge National Laboratory

This work is an extension of the concepts presented in:
Abdelaziz O., and Shrestha, Som, 2014, “Development of Versatile Compressor Modeling using Approximation Techniques for Alternative Refrigerants Evaluation”, ASHRAE Conference, January 2014, New York.

Outline

- Introduction
- Objectives
- Proposed Method
- Kriging for Interpolation
- Data Analysis & Results
- Conclusion

Introduction

- Various novel alternative lower-GWP refrigerants are being investigated with the goal of reducing environmental foot print of HVAC&R systems
- Evaluating the performance of a novel working fluid requires significant modeling and testing efforts
- Compressor is a key component
- Performance metrics of interest in system design
  - Mass flow rate
  - Power consumption

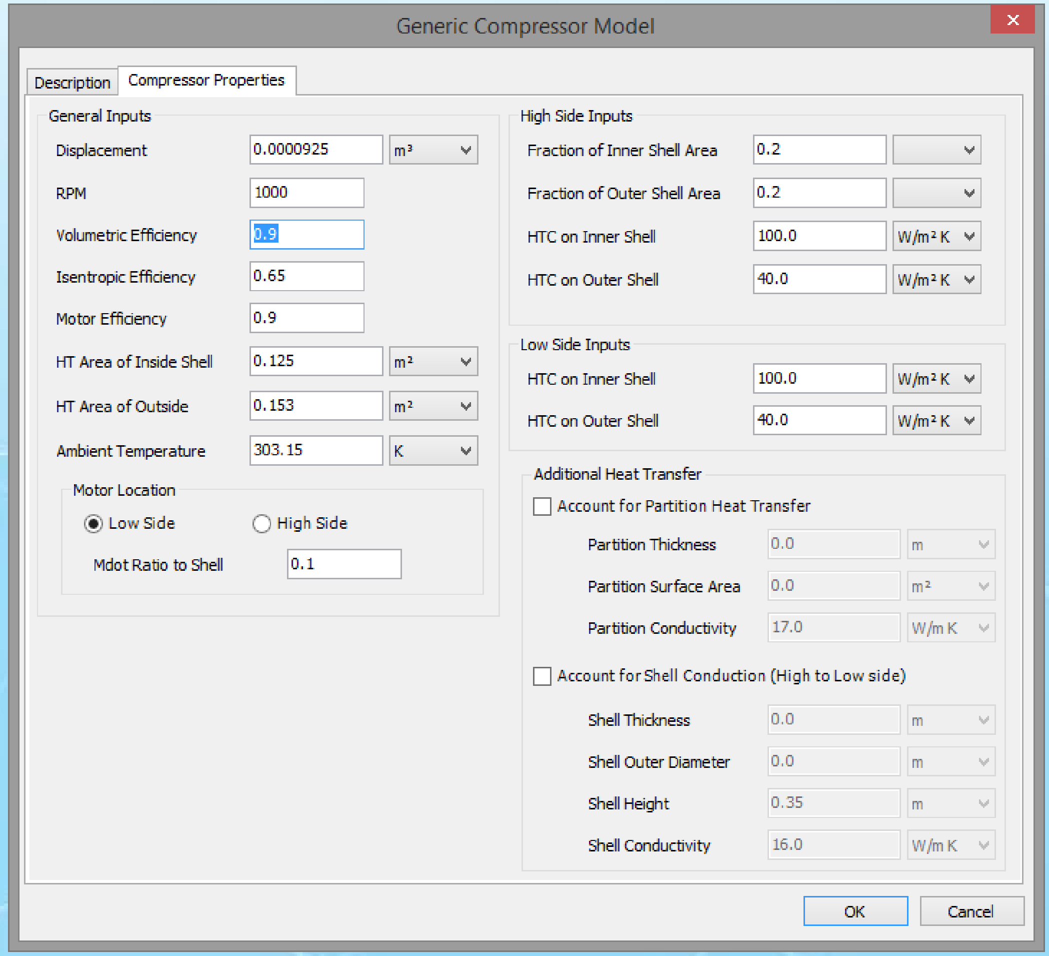
Objectives

- Given compressor performance data for two or more refrigerants

Predict the performance of a novel lower-GWP alternative refrigerant in the ***same*** compressor under ***similar*** operating conditions

Existing Models

- Various physics based models are available for compressor performance prediction



General Inputs

Displacement	0.0000925	m^3
RPM	1000	
Volumetric Efficiency	0.9	
Isentropic Efficiency	0.65	
Motor Efficiency	0.9	
HT Area of Inside Shell	0.125	m^2
HT Area of Outside	0.153	m^2
Ambient Temperature	303.15	K

Motor Location

● Low Side ○ High Side

Mdot Ratio to Shell 0.1

High Side Inputs

Fraction of Inner Shell Area	0.2	
Fraction of Outer Shell Area	0.2	
HTC on Inner Shell	100.0	$W/m^2 K$
HTC on Outer Shell	40.0	$W/m^2 K$

Low Side Inputs

HTC on Inner Shell	100.0	$W/m^2 K$
HTC on Outer Shell	40.0	$W/m^2 K$

Additional Heat Transfer

☐ Account for Partition Heat Transfer

Partition Thickness	0.0	m
Partition Surface Area	0.0	m^2
Partition Conductivity	17.0	W/m K

☐ Account for Shell Conduction (High to Low side)

Shell Thickness	0.0	m
Shell Outer Diameter	0.0	m
Shell Height	0.35	m
Shell Conductivity	16.0	W/m K

Practical Challenges

- Detailed compressor geometry is seldom available
- Need appropriate equations and tuning for the different efficiencies
- Typical compressor performance data includes
  - Power consumption and mass flow rates at various operating conditions
  - Te [F], Tc [F], Superheat [F], M [lbm/hr], P [W],

Methodology

- Source data for two or more refrigerants
  - Refrigerant properties
  - Operating parameters
  - Measured performance
- Develop a Bayesian interpolation model
- For new refrigerants, given the properties and operating parameters, predict the performance
- Validate the predictions against measured data

Data Sets

- Source & verification data
  - – Published by manufacturer (10 coefficients)
  - – Publicly available data (AHRI AREP Report)
- Total of 3 data sets
  - – 2 Conventional refrigerants
  - – 1 Alternative lower GWP refrigerants

Data Set	Type	Refrigerants
Set-1	Scroll	R134a, R404A, R507A, R407A, R407F, R22
Set-2	Scroll	R134a, R404A, R507A, R407A, R407C
Set-3	Scroll	R410A, R32, DR5, L41a

Model Parameters

Inputs	Outputs
Suction Pressure (Pe)	Mass flow rate
Discharge Pressure (Pc)	Power Consumption
Suction Temperature (T)	
Specific heat ratios @ Suction (k)	
Pressure Ratio (Pr)	
Suction Density (rho)	
[(k-1)/k]	

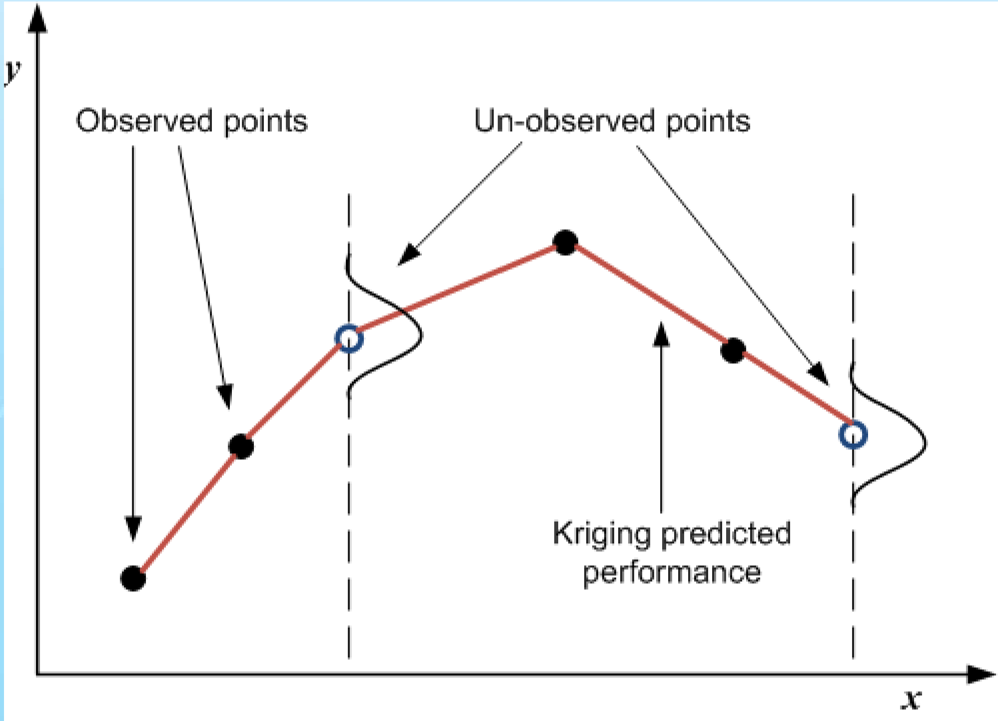
Notes:
Compressor speed is constant
Suction superheat is constant (can change)
For 7 parameters, we need at least 37 data points

Goal: Find the best curve fit
Power = F (Pe, Pc, Te, k, Pr, rho, …)

Kriging

- Interpolation method from geostatistics

$$\mathbf{y} = \mathbf{f}(\mathbf{x}_1, ..., \mathbf{x}_m) \Rightarrow \mathbf{Y} = \boldsymbol{\mu} + \mathbf{Z}(\mathbf{x}_1, ..., \mathbf{x}_m)$$



μ : constant mean, F (**X**)
Z : random process with zero mean and Covariance
Covariance = $\boldsymbol{\sigma}^2$ R
R = Correlation function based on the distance in x space

$$R(x_k) = \exp(-\sum_{i=1}^{l} \theta_l \, || \, x_{0i} - x_{ki} \, ||^{pl})$$

Y (X0) = F (**X**) + G (**X** – X0)

Traditional vs. Kriging

Traditional Methods	**Kriging**
Need functional form	No functional form
Least squares estimate (easy)	Maximum Likelihood estimate (difficult)
Don’t need source data for evaluation	Needs source data for evaluation
Cannot reproduce source data	Reproduce source data exactly
Error bounds are constant	Error bounds depend on location in space

Kriging (contd.)

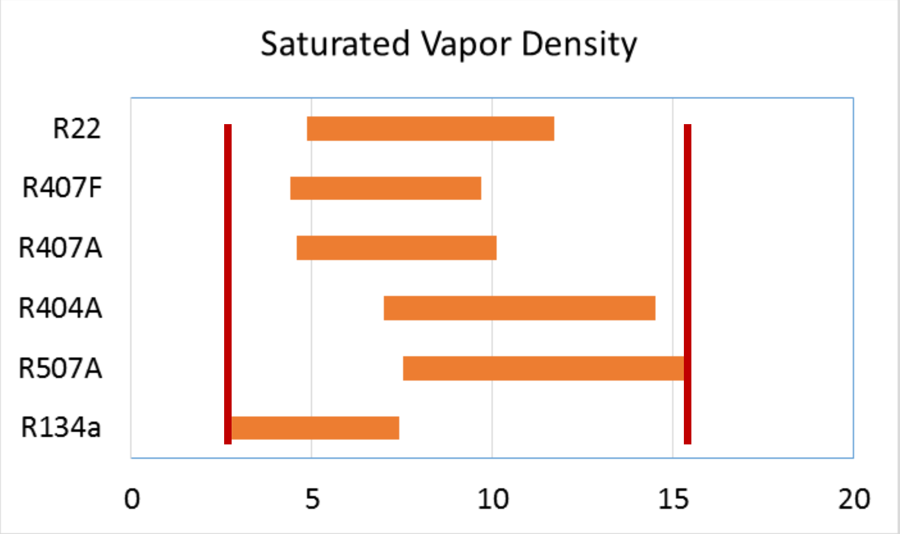
- Extremely flexible, does not require functional form
- Shown to work well with highly nonlinear functions
- Suitable for problems with less than 50 inputs
- Complex implementations

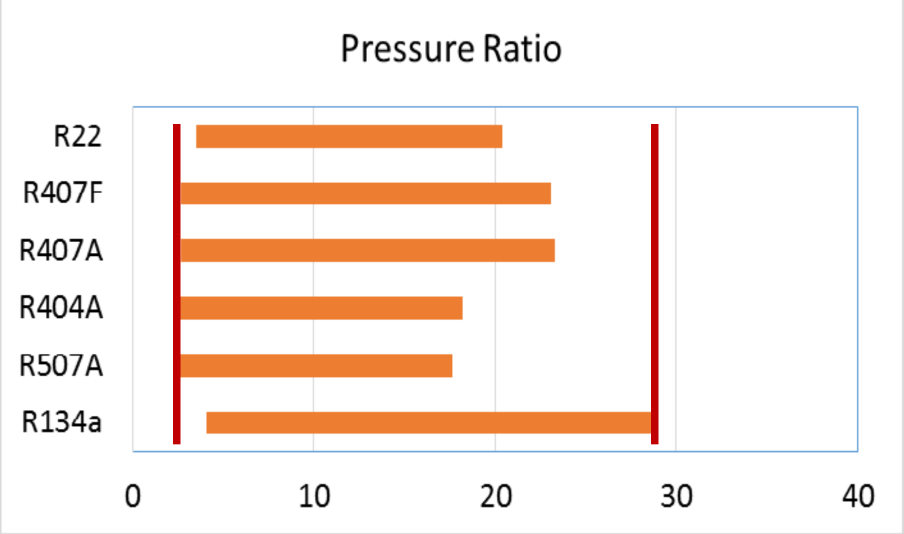
Kriging Resources:
DACE Toolbox: http://www.imm.dtu.dk/~hbni/dace/
Dakota Framework: http://dakota.sandia.gov/publications.html

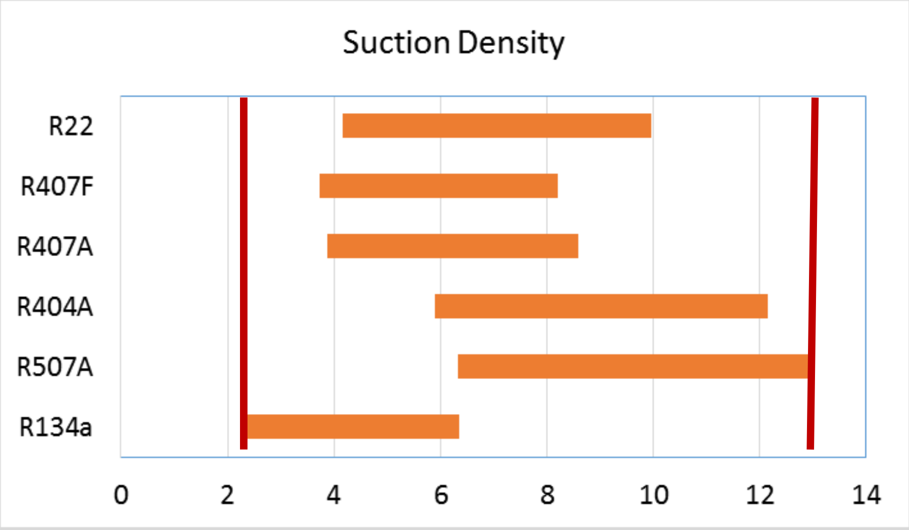
Error Metrics

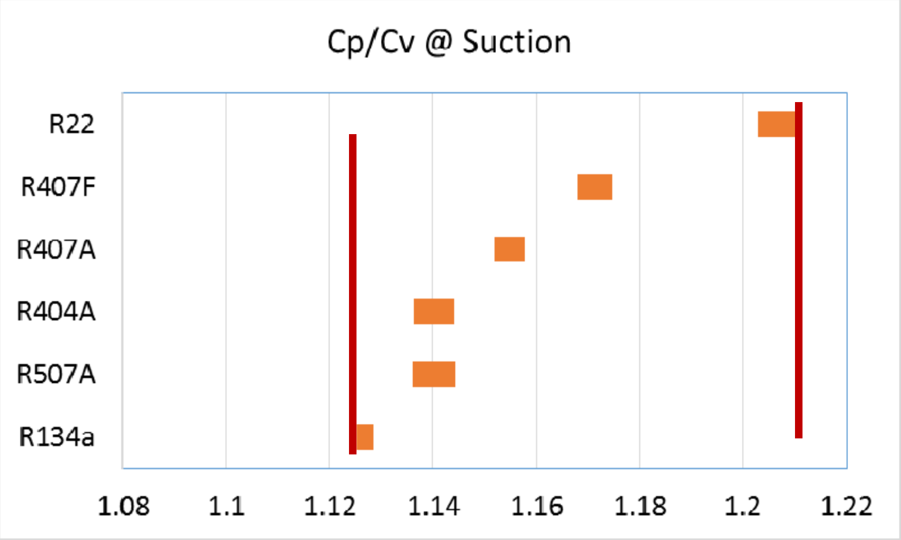
- Avg. Absolute Percent Error (AAPE)
- Maximum Absolute Percent Error (MAPE)
- Model Acceptability Score (MAS)
  - MAS10: % of points predicted within 10%
  - MAS05: % of points predicted within 5%

Data Set-1

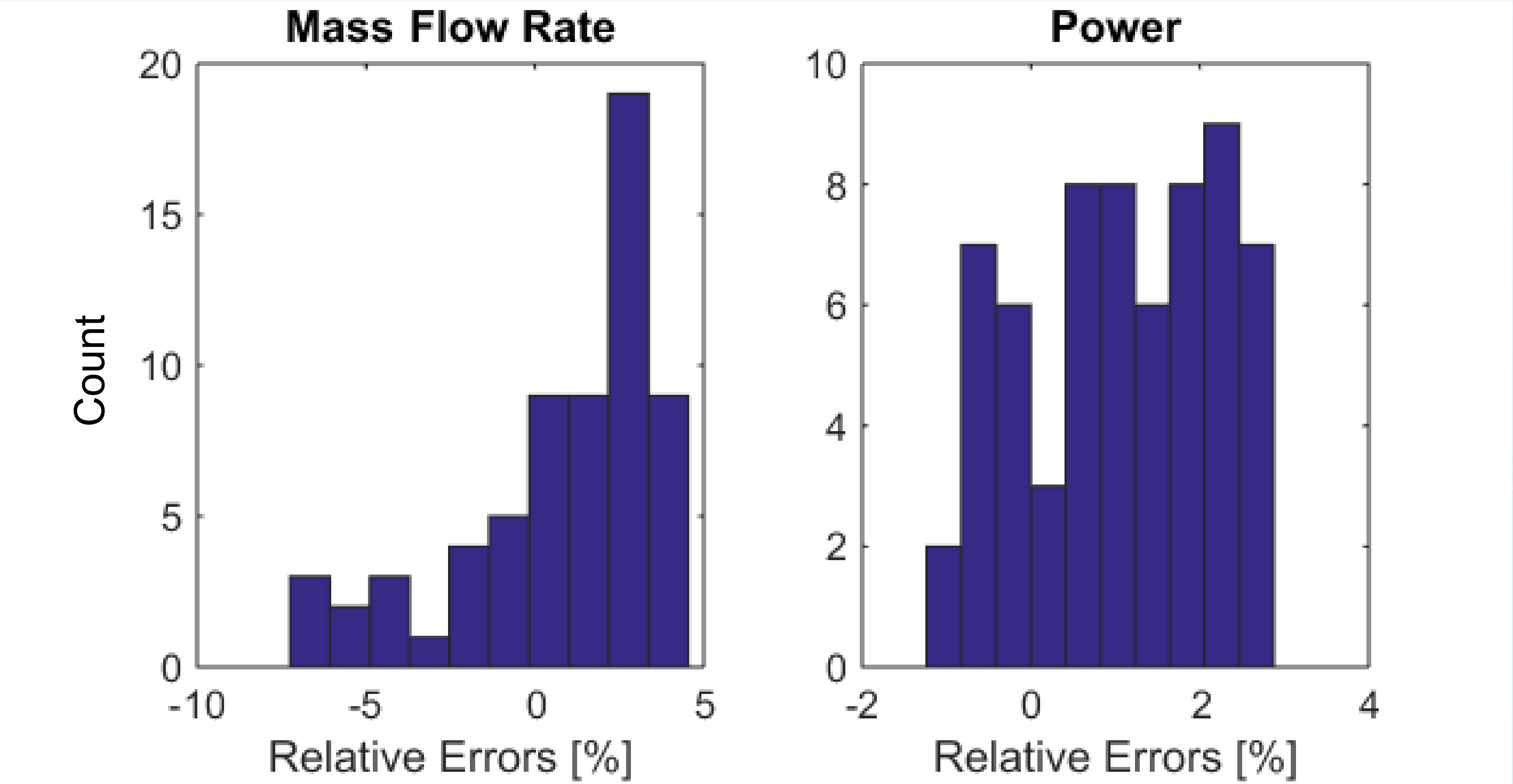

Saturated Vapor Density


Pressure Ratio


Suction Density

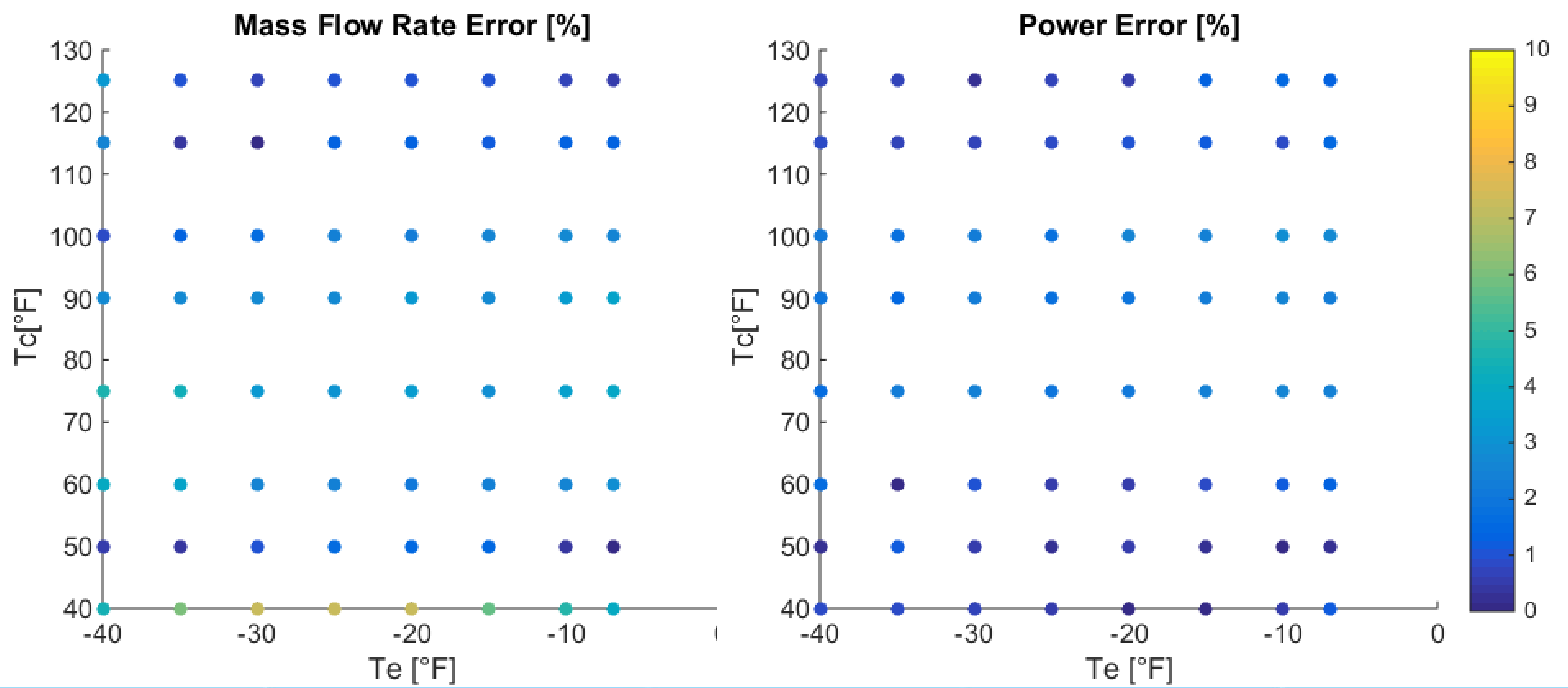

Cp/Cv @ Suction

Data Set-1: Results



R134a, R407A, R507A → R404A
Mass flow rate: MAS10=100%, MAS05 = 92%, MAE = 7.2%
Power: MAS10 = 100%, MAS05 = 100%, MAE = 2.8%

Data Set-1: Results



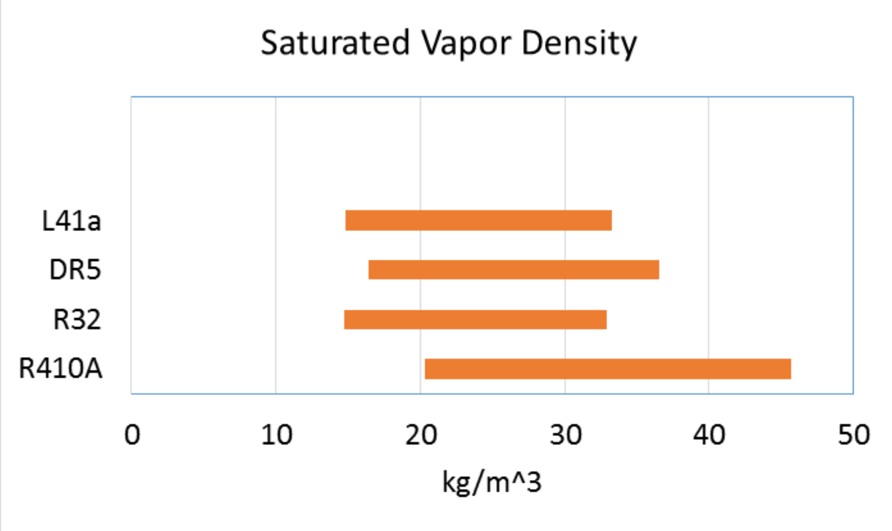
R134a, R407A, R507A ➔ R404A

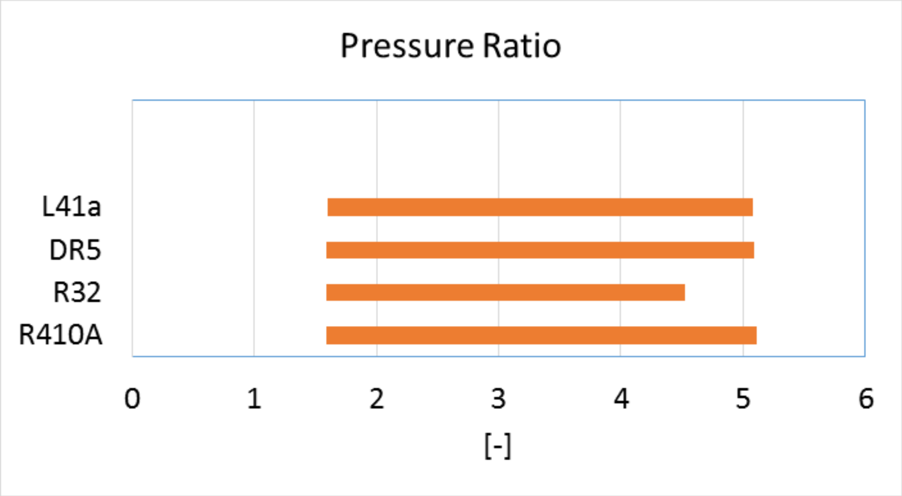
Mass flow rate: MAS10=100%, MAS05 = 92%, MAE = 7.2%

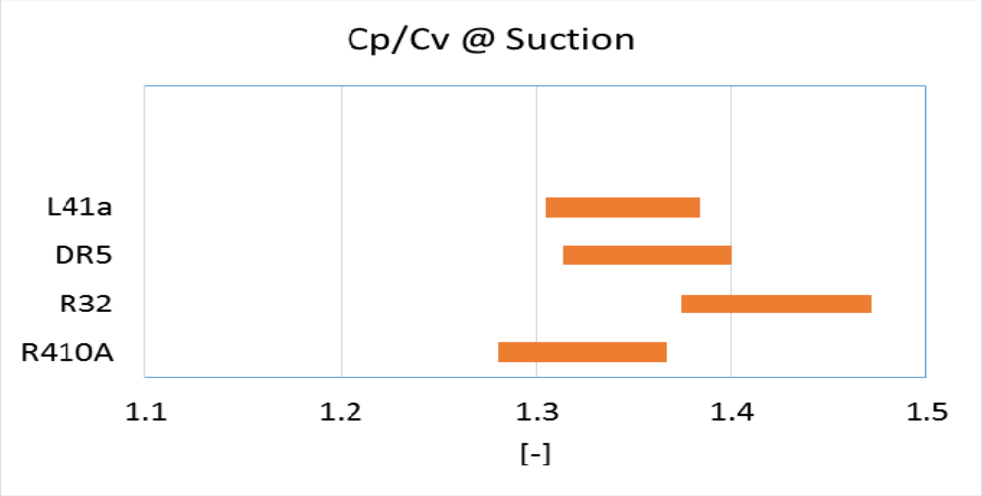
Power: MAS10 = 100%, MAS05 = 100%, MAE = 2.8%

Data Set-2

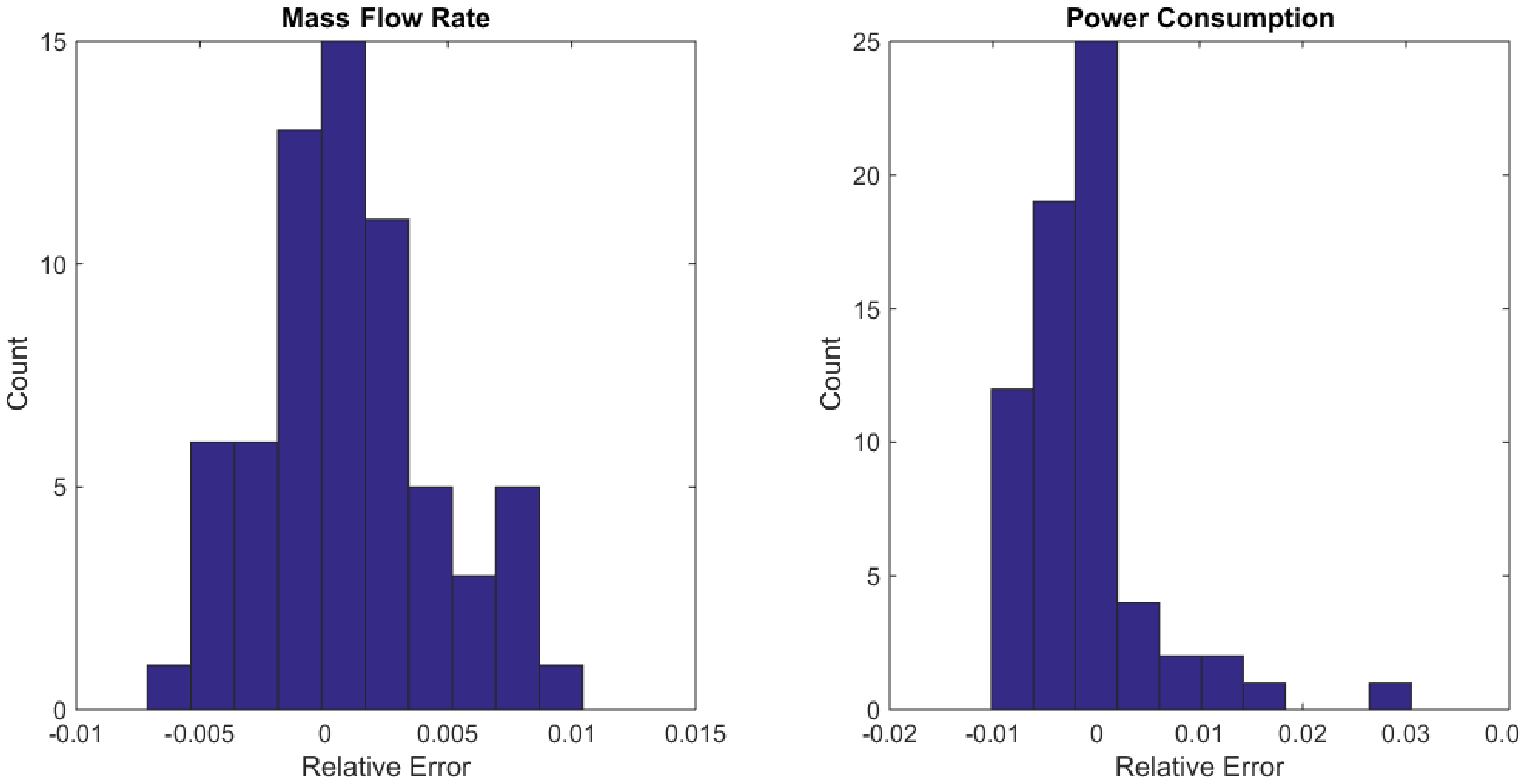
- 60 points for each refrigerant







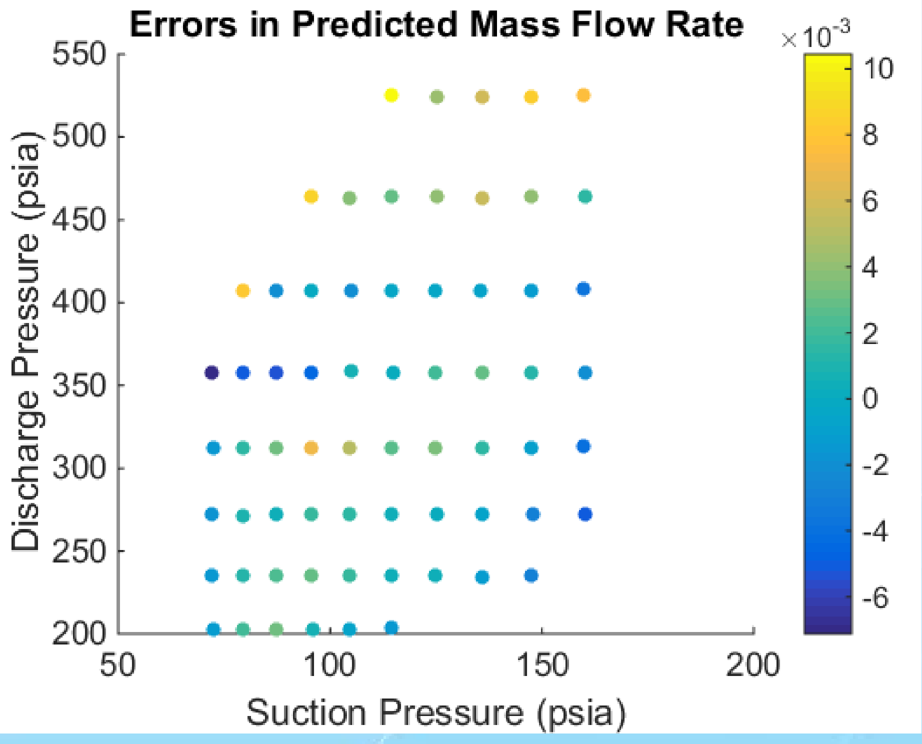
Results

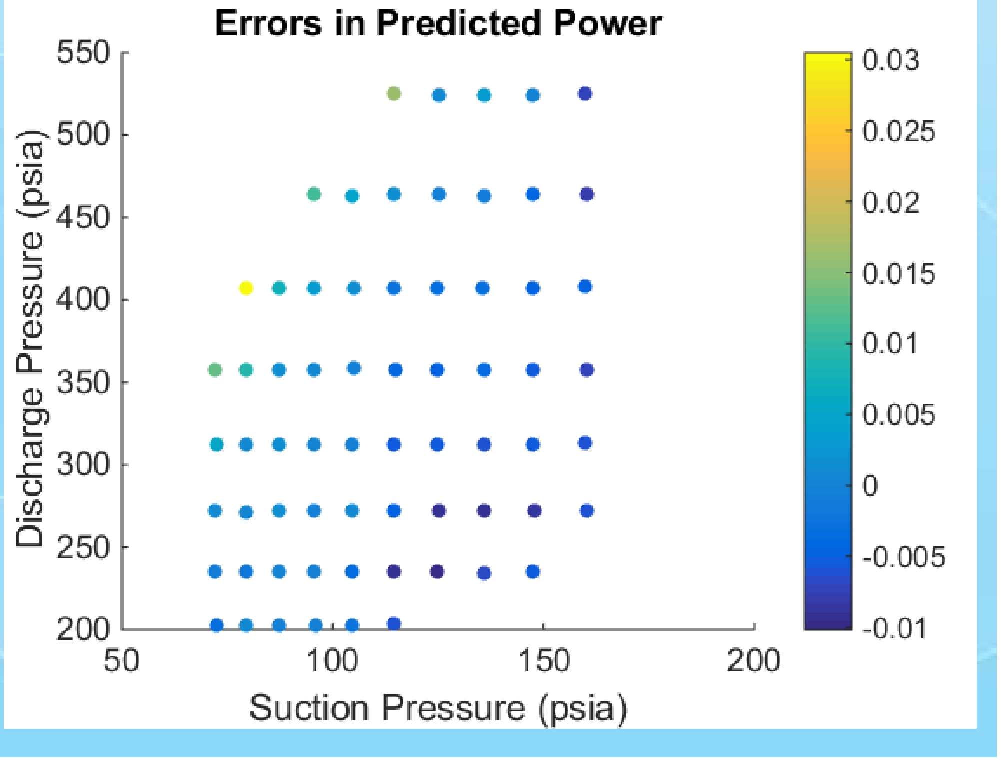


Points: 66
Maximum Absolute Error: 1.04%
AAPE: 0.4 %

Points: 66
Maximum Absolute Error: 3.05%
AAPE: 0.6%

Prediction Errors





Results Summary

Data Set	Set-11	Set-12	Set-13	Set-21	Set-3
Source	R134a, R407A, R507A	R134a,R404A, R407C	R134a, R404A, R407C	R134a, R404a, R22	R410A,R32
Candidate	R404A	R507A	R407A	R507A	DR5,L41a
Mass flow, MAS10	100	89	100	95	100
Mass flow, MAS05	92.1	76	60	73	100
Mass flow AAPE	3.08	5.9	5.2	4.4	0.3
Mass flow, MAPE	7.25	20.87	8.8	10.6	1.04
Power, MAS10	100	100	100	100	100
Power, MAS05	100	100	84	100	100
Power, AAPE	1.53	1.71	3.6	2.5	0.6
Power, MAPE	2.88	3.2	5.6	4.4	3.05

Usage Notes

- Appropriate selection of Kriging parameters is crucial
  - Gaussian correlation
  - First order polynomial mean
- Kriging is computationally expensive, especially for use in system simulation
- Remedy
  - Use Kriging to predict the performance for ~50 points in the operating envelope
  - Points can be chosen randomly or through sampling
  - Develop polynomials (AHRI-540 standard) for mass flow rate and power consumption
  - Use polynomials in system simulation

Conclusions

- Demonstrated the application of Kriging for prediction of compressor performance of alternative refrigerants for drop-in applications
- Preliminary results are encouraging
- Predictions were validated against measured data; for the best case:
  - Maximum error in mass flow rate was 1%
  - Maximum error in power consumption was 3%
- Can help reduce the testing burden during evaluation of alternative refrigerants, especially when coupled with design of experiments
- Kriging is a powerful technique and has wide-spread applications in HVAC&R

Thank You!

Bibliography

[1] Abdelaziz O., and Shrestha, Som, 2014, “Development of Versatile Compressor Modeling using Approximation Techniques for Alternative Refrigerants Evaluation”, ASHRAE Conference, January 2014, New York.

[2] Shreshta et al., 2013, “Compressor calorimeter test of R410A alternatives R32, DR-5 and L-41a”, AHRI AREP Test Report #11.

Questions?

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