CENTER FOR INTEGRATED BUILDING SYSTEMS
College of Engineering, Architecture and Technology

Seminar 37: Reduced Order Modeling for HVAC&R Systems and their Components

Semi-Empirical Compressor Model Evaluation Considering Modulation and Extrapolation Performance

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Learning Objectives

- Understand the differences of data-driven models for positive displacement compressors
- **Show legacy model performance in extrapolation and modulation scenarios**
- How to convert a compressor map from a baseline refrigerant to a new refrigerant with lower GWP.
- Understand technical challenges associated with implementing nonlinear model order reduction approaches to Vapor Compression Cycle (VCC) applications.

Acknowledgements

- Department of Mechanical and Aerospace Engineering, Oklahoma State University
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Contents

- Overview
- Selected Compressor Models
- Data Collection
- Testing Methodology
- Testing & Evaluation Results
- Future Model Development

Overview

- Broad Approach

Semi-Empirical Compressor Modeling

Literature Review

Find representative compressor models

Compressor Technologies

Targeted Multiple Technologies and Refrigerants

Model Testing

Codified 4 models in Python plus a machine learning implementation

Training Data

From Experiments

Hot Gas Bypass or Compressor Calorimeter

High Fidelity Data

Collected to a cited standard

Selected Compressor Models

AHRI Model [1]

- Black box model
- 10 coefficient polynomial
- Well-known limitations

Shao Model [2]

- Black box model
- Formulated for capturing modulation
- Utilizes performance at base and variable frequency

Winandy Model [3]

- Grey box model - semi empirical
- Four parameters to characterize mass flow rate, three parameters for power
- Model incorporates a fictitious isothermal wall

ANN Model

- Black box model
- Can be applied to any technology with data
- Used compact architecture to minimize train time

Popovic & Shapiro Model [4]

- Grey Box – semi empirical
- 8 parameters needed to capture mass flow rate and power
- Mass flow based on volumetric efficiency calculation

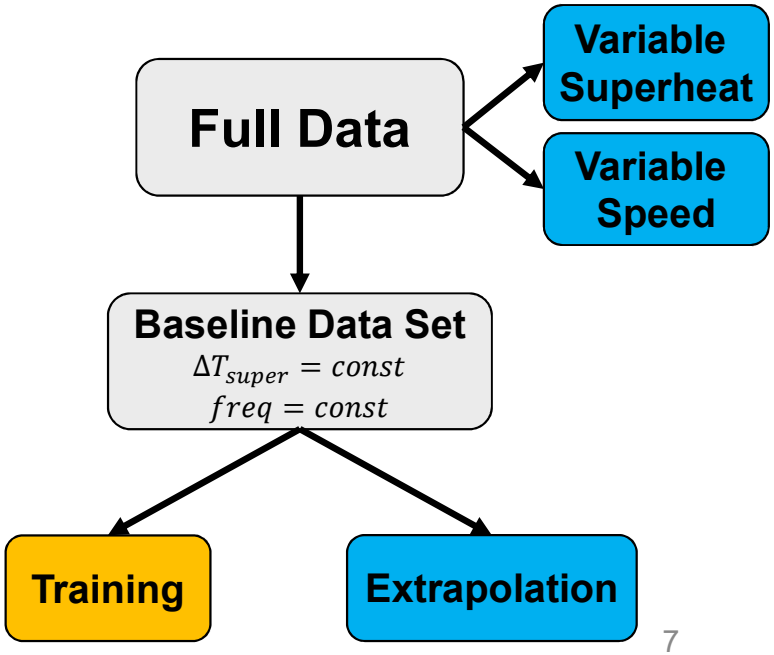
Models codified in EES and Python

Data Collection

- Each Data set was broken into multiple subsets
  - » **Baseline Set** – constant superheat and speed points from data
  - » **Training Set** – subset of Baseline Data that are deemed interior envelope points
  - » **Extrapolation Set** – points with operating conditions beyond that of the training data
  - » **Variable Speed** – points with speeds different than what was trained with
  - » **Variable Superheat** – points with superheat different than what was trained with
  - » **Full Data Set** – all data

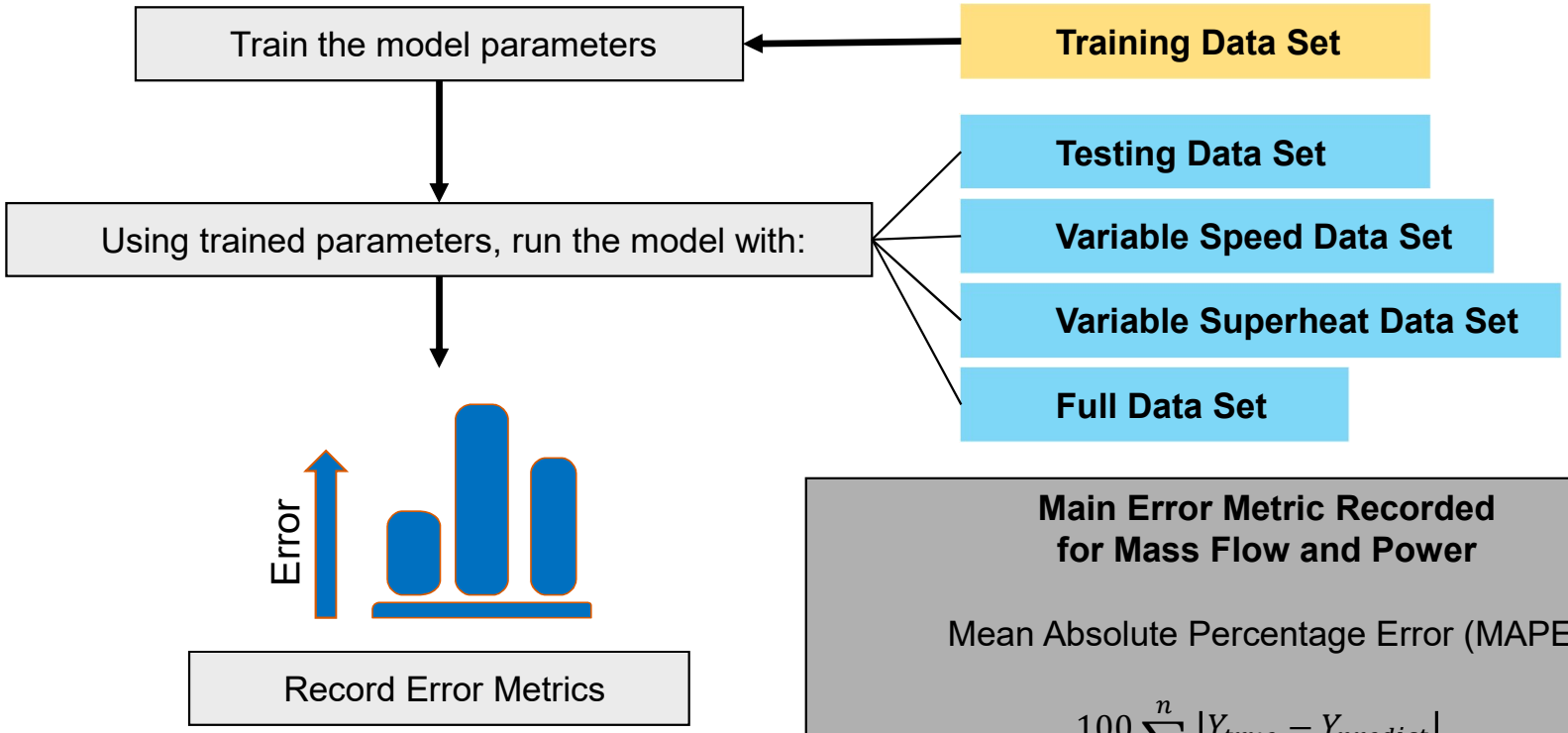
Total number of data sets used	5
Number of technologies used	4
Number of refrigerants used	4
Total number of data points	327

Example Data Set – Spool R134a	
Parameter	Range
SDT	23-55 [C]
SST	-23-10 [C]
Speed	35-60 [Hz]
Superheat	8-42 [K]



Methodology

- Overview of approach taken



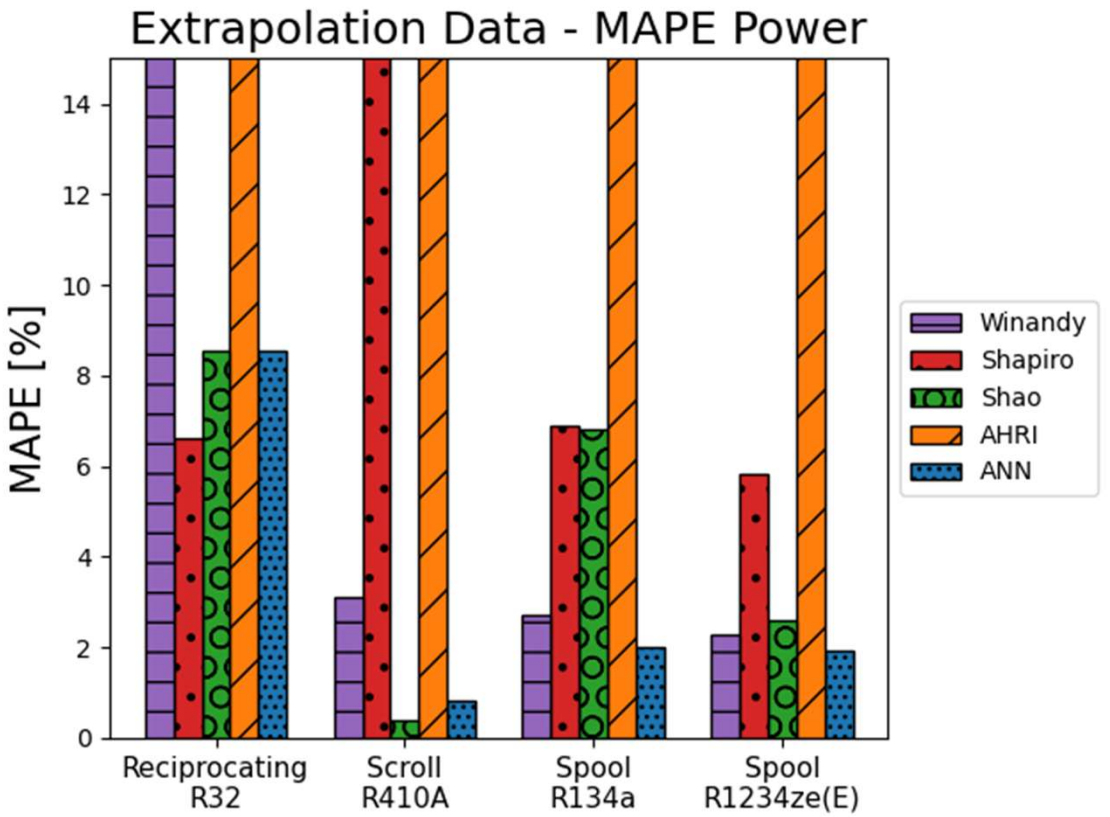
Main Error Metric Recorded for Mass Flow and Power

Mean Absolute Percentage Error (MAPE)

$$MAPE = \frac{100}{n}\sum_{n=0}^{n}\left|\frac{Y_{true} - Y_{predict}}{Y_{true}}\right|$$

Model Performance Evaluation

- **Extrapolation – Testing Data Set**
- **MAPE - Mass Flow / Power**
- General Trends
  - » Winandy doesn't adequately predict reciprocating compressor mass flow rate
  - » Shapiro & Popovic doesn't adequately predict scroll compressor mass flow rate
  - » Errors in mass flow for the two semi-empirical models propagates to power calculation



Model Performance Evaluation

- **Extrapolation Performance Summary**

Mass Flow Rate

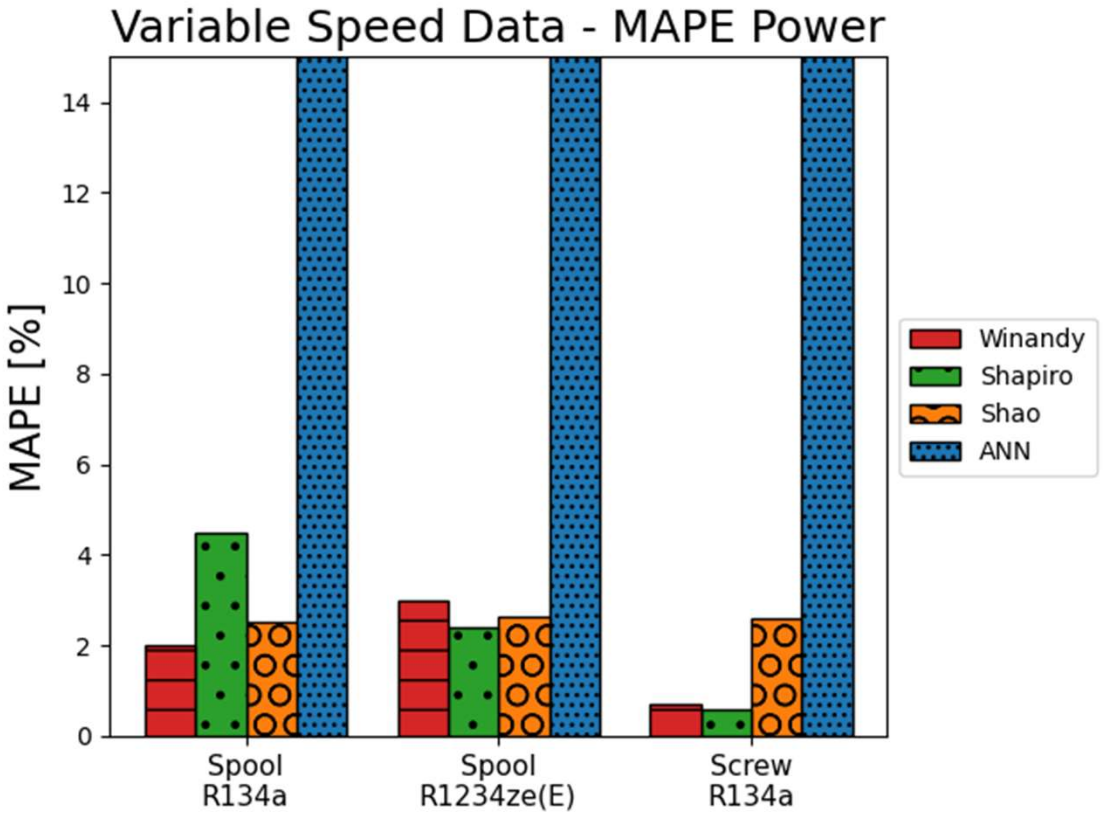
1. All models exhibit errors >10% in at least one extrapolation data set
2. ANN model extrapolates to errors under 4% except Spool R134a data, where its 11.7%
3. Semi empirical formulations perform best on 2 data sets
4. Empirical formulations perform best on 2 data sets

Power

1. ANN extrapolates to power best overall
2. Shao model exhibits less than 10% MAPE in all data sets
3. Winandy model extrapolates to under 5% MAPE for Scroll & Spool data sets
4. Shapiro model extrapolates to around 5-7% MAPE for the data sets it predicts

Model Performance Evaluation

- **Modulation - Variable Speed**
- **MAPE - Mass Flow / Power**
- General Trends
  - » ANN does not predict variable speed performance adequately
  - » The two semi empirical models perform under 5% MAPE for the modulation data sets, in power and mass flow
  - » It should be noted:
    - – The Shao model takes variable speed data in the fitting process, the semi empirical models don't



Overall Performance Summary

Model Limitations Identified

Training Data

1. The Shapiro & Popovic model needs comprehensive training data to fit parameters
2. The Shao model needs variable speed data to fit all coefficients

Performance Prediction

1. The Winandy model does not predict reciprocating compressor performance in its current form
2. The Shapiro model does not predict scroll compressor performance in its current form
3. ANN formulation does not accurately predict modulation data

Where to from here?

Key Conclusions

Given a model predicts the technology:

1. Semi empirical models capture modulation and extrapolation
2. Semi empirical models capture variable superheat reasonably well
3. The Winandy model *outperforms* the Shapiro and Popovic model overall

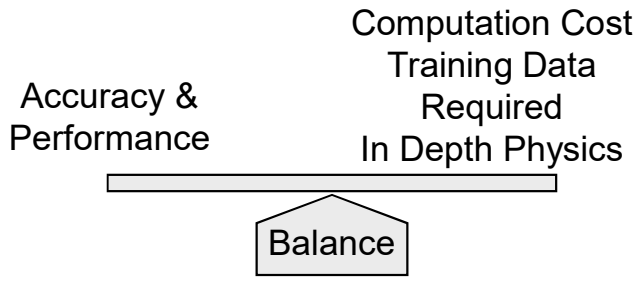
Other Takeaways

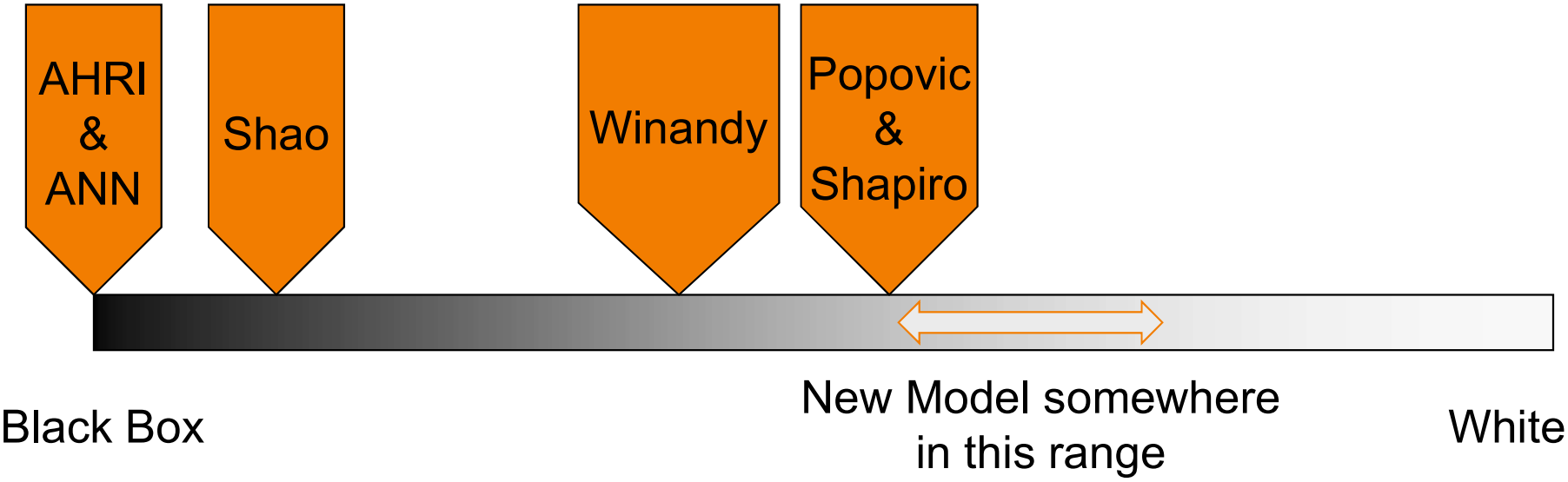
- ANN approach will not be used in model development because it does not capture modulation
- Shao model will not be pursued because of training data requirement and it's degree of empiricism
- Winandy formulation will be pursued

Future Model Direction

Proposed Model on the Spectrum

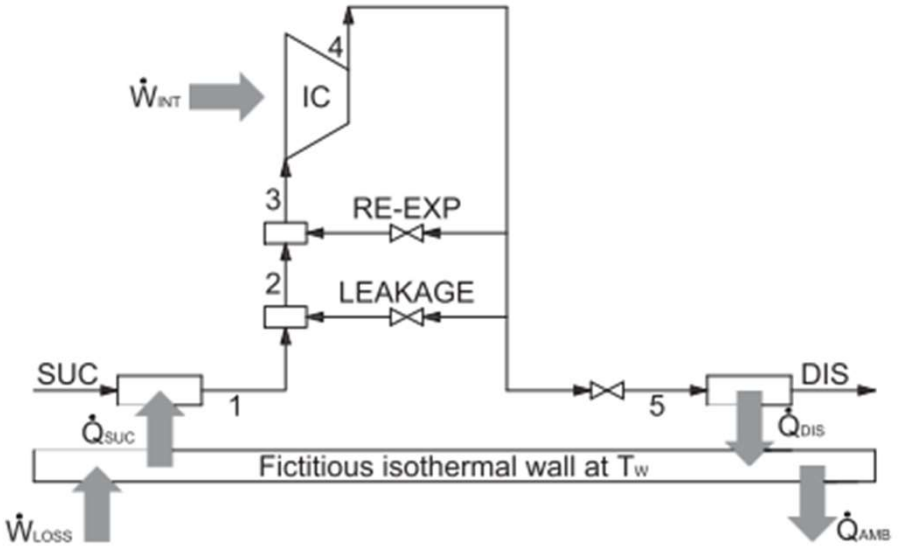
Goal: Develop model that outperforms current models in extrapolation, modulation, and variable superheat scenarios while capturing multiple compressor technologies





Future Model Direction

- **New Semi Empirical Model – Modification to Winandy**
  - » No literature found attempts to adapt one model to work for multiple different compressor technologies
  - » Winandy formulation is consistent when it works
    - – Literature has adaptations of this model to reciprocating, rolling piston, and screw compressors
  - » Presently, Winandy captures Spool, Scroll, and Screw performance in extrapolation modulation scenarios
  - » Add fidelity to capture additional phenomena
    - – Suction Pressure drop
    - – Discharge Pressure drop
    - – Leakage
    - – Gas re-expansion



Adaptation of Winandy model from Molinaroli et. al [5]

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Picture References

https://www.google.com/search?q=curve+fit&tbm=isch&chips=q:curve+fit,g_1:python:OpI8Vyx5fmA%3D&rlz=1C1GCEU_enUS892US892&hl=en&sa=X&ved=2ahUKEwiHz_fK98_1AhWRGM0KHRLuD58Q4lYoAHoECAEQHA&biw=1063&bih=1720#imgrc=QTb9lPOW0cmf_M – Curve Fit Picture Slide 6

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Questions?