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Seminar 65 – Compression Challenges for Low-GWP Refrigerants

Design Improvements of the Spool Compressor for Various Working Fluids using Comprehensive Modeling Techniques

Learning Objectives

1. Provide an overview of the novelty compressor designs
2. Evaluate the utility of the comprehensive model as a tool used for compressor design
3. Apply the new modeling tools for compressors
4. Describe the compression mechanism of a spool compressor

Acknowledgments

- Craig Bradshaw, Manager of Research and Development, Torad Engineering
- Greg Kemp, CEO, Torad Engineering
- Joe Orosz, COO, Torad Engineering

Outline

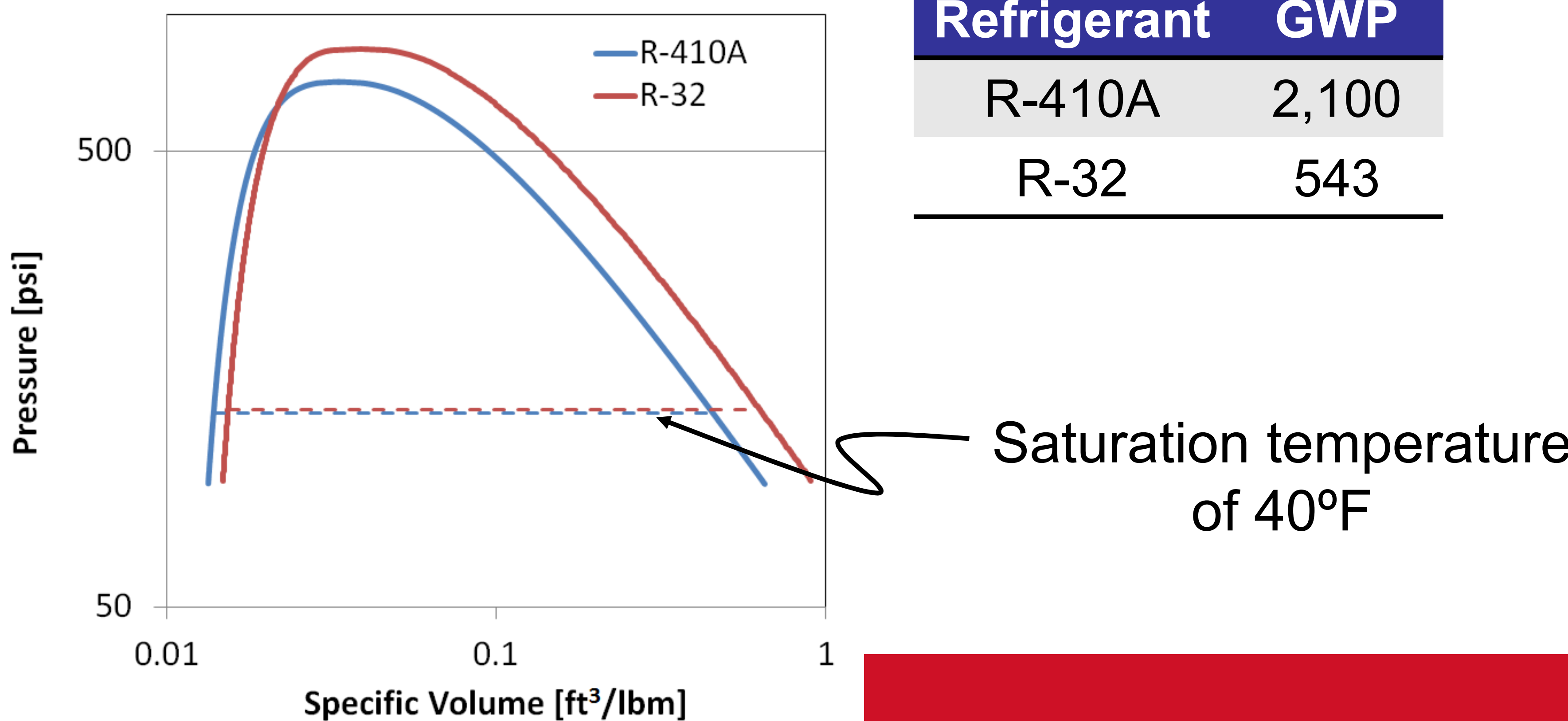
- Overview of study
  - Refrigerants
  - Operating conditions
  - Compressor geometry
- Comparison of R-410A and R-32
- Comparison of R-134a and R-1234yf
- Summary of modeling results

Overview of Drop-In Refrigerant Study

- Models provide tool for optimization of compressor geometry
  - Specify operating conditions
  - Specify target capacity
  - Vary key geometric parameters
- Running model with alternative refrigerants provides estimate of “drop-in” performance
  - Operating conditions unchanged
  - Same range of geometric parameters

Modeled Refrigerants: R-410A and R-32

- R-32 has lower GWP than R-410A with similar thermodynamic properties



Refrigerant	GWP
R-410A	2,100
R-32	543

Modeled Operating Conditions

Conditions:

- 40ºF (4°C) evaporating
- 15ºF (8°C) superheat
- Pressure ratio of 2.5

2.0% difference

Refrigerant	p_{evap} [psia]	p_{cond} [psia]	Δp [psia]	T_{cond} [ºF]
R-410A	133.1	332.0	198.9	99.9
R-32	135.6	338.5	202.8	99.6

Refrigerant	p_{evap} [kPa]	p_{cond} [kPa]	Δp [kPa]	T_{cond} [ºC]
R-410A	917	2289	1371	37.7
R-32	935	2334	1398	37.6

Modeling Alternative Refrigerants

- Requires source of thermophysical property data:
  - Equations of state (EOS)
  - Ideal gas EOS
  - Property databases
    - REFPROP
    - CoolProp
  - Empirical equations fitted to available data

- Additional Considerations:
  - Changes in lubricant properties or concentration

Modeled Geometries

1.5% Variation

- Maintain approximately constant displacement while varying:
  - Eccentricity ratio,

$$\frac{R_{rotor}}{R_{stator}}$$

  - Length to diameter ratio,

$$\frac{h_{stator}}{2R_{stator}}$$

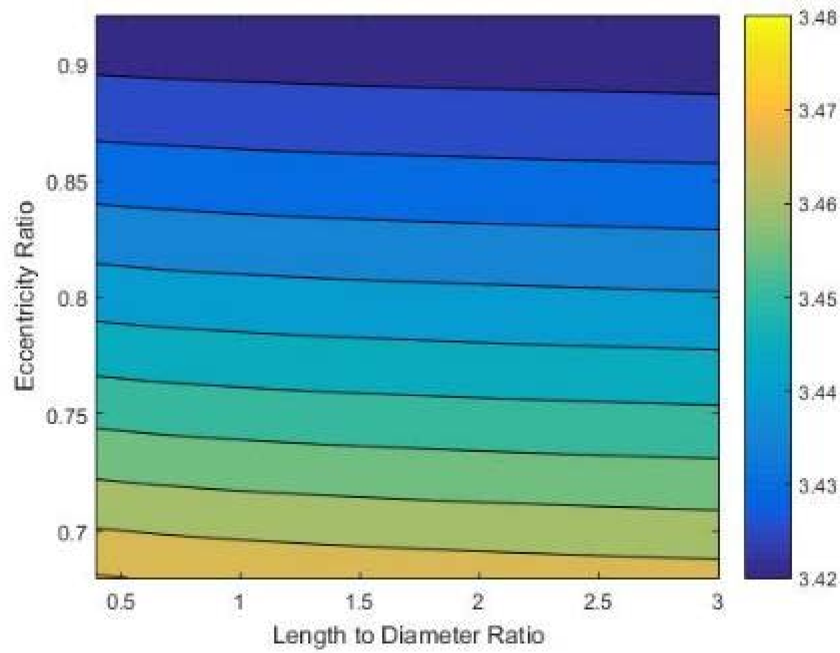


Figure 1: Displaced Volume [in^3]

Capacity (5 ton unit)

$$\dot{Q} = \dot{m}\Delta h_{evap}$$

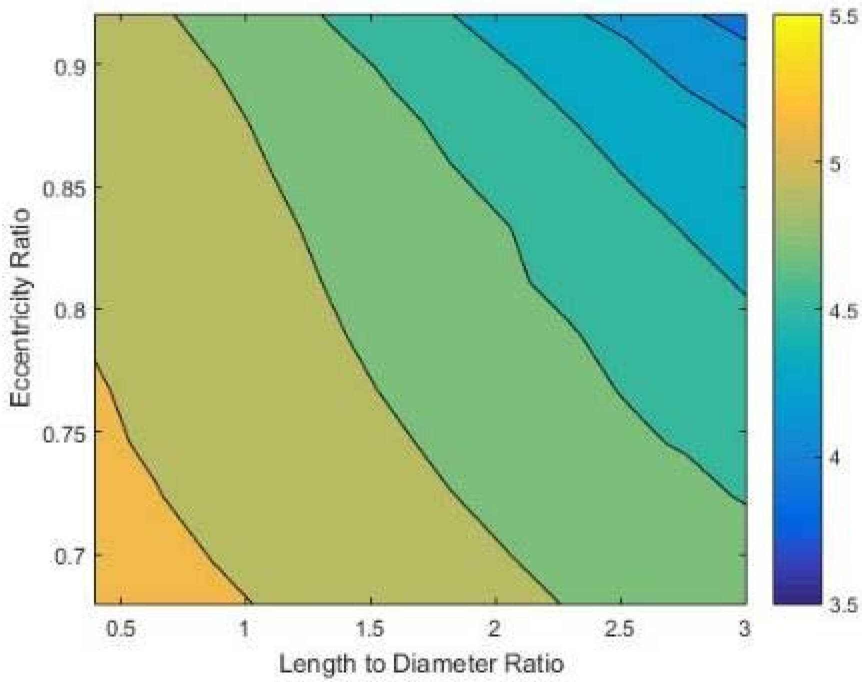


Figure 2a:
Capacity with R-410A [tons]

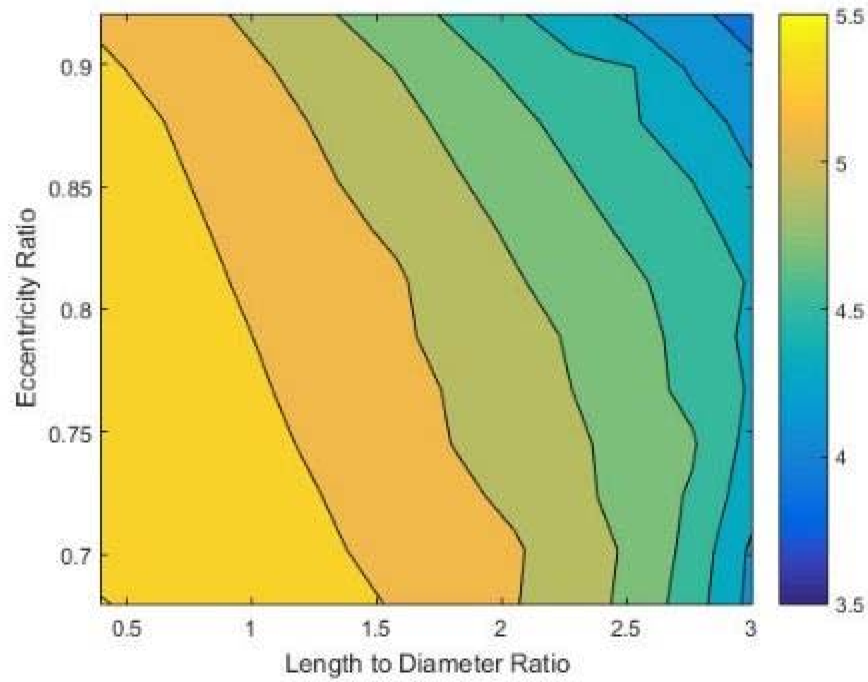


Figure 2b:
Capacity with R-32 [tons]

Capacity per Unit Mass Flow

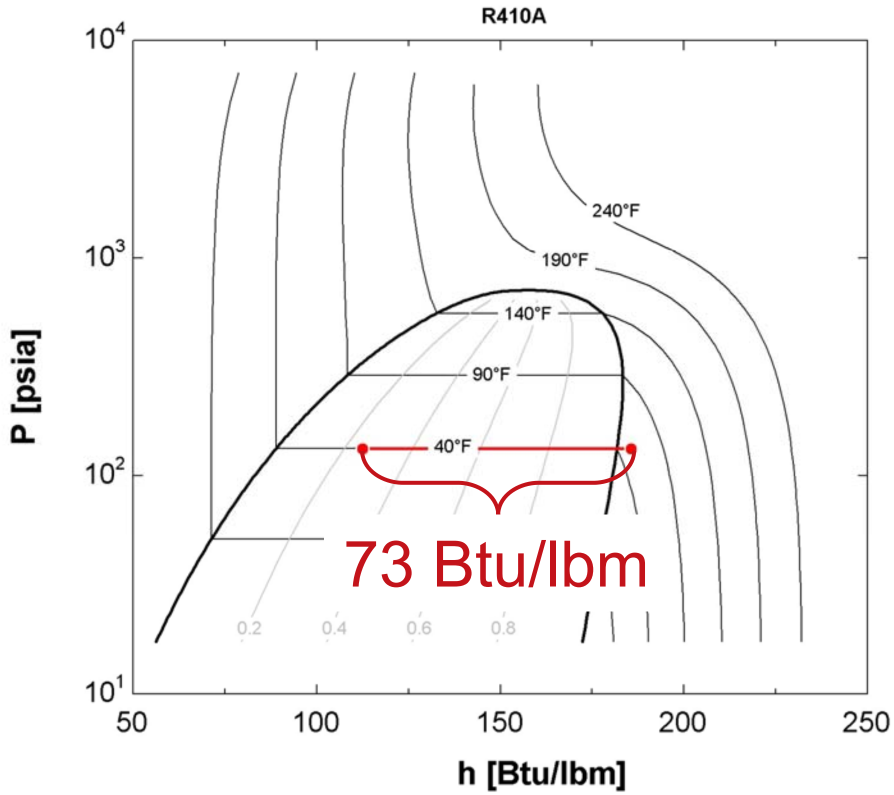


Figure 3a:
P-h for R-410A

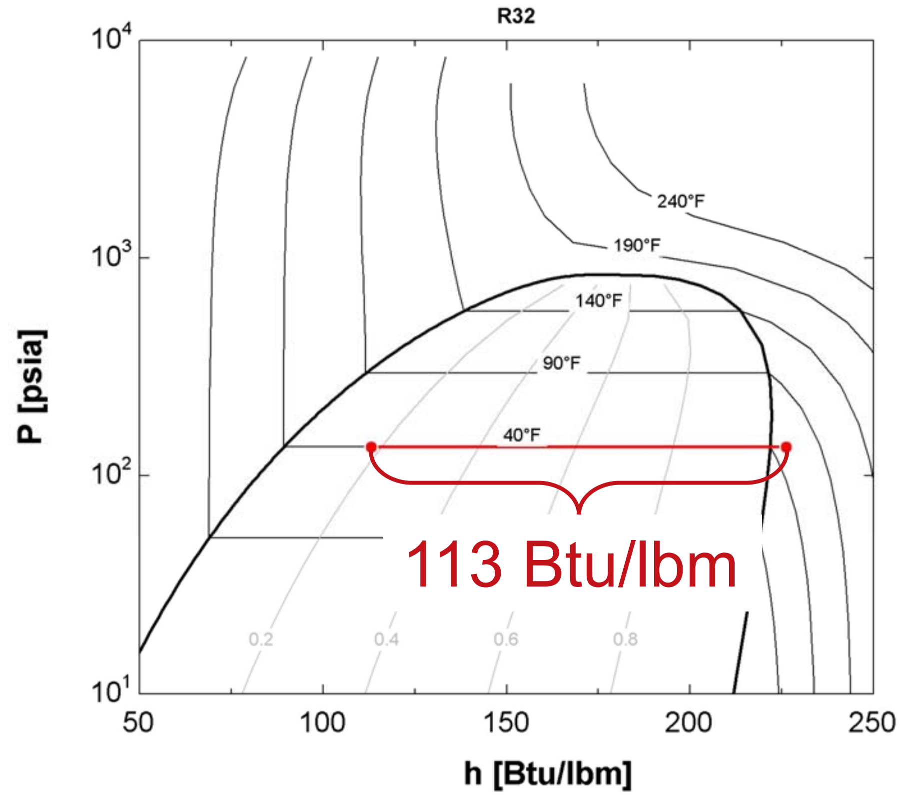


Figure 3b:
P-h for R-32

Mass Flow Rate (5 ton unit)

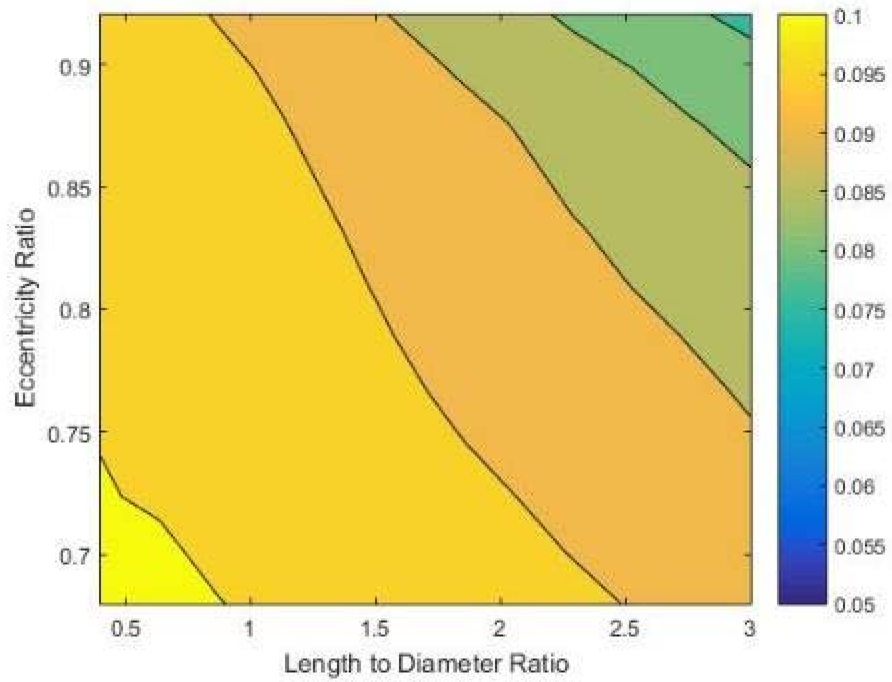


Figure 4a:
Mass flow with R-410A [kg/s]

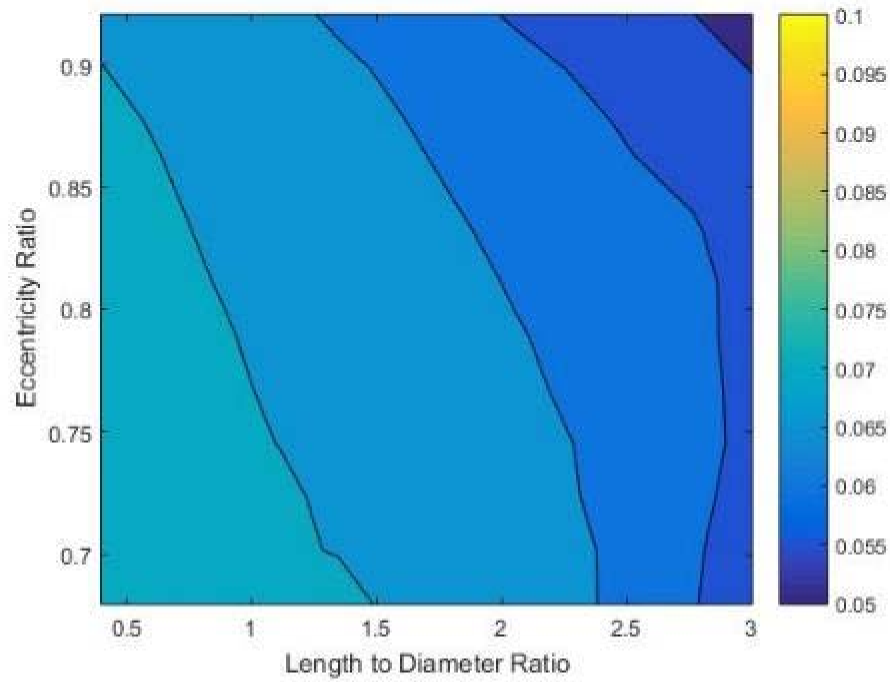


Figure 4b:
Mass flow with R-32 [kg/s]

Mass Flow Rate

$$\dot{m} = \eta_v \left(\frac{\dot{V}_{ideal}}{v_{in}}\right)$$

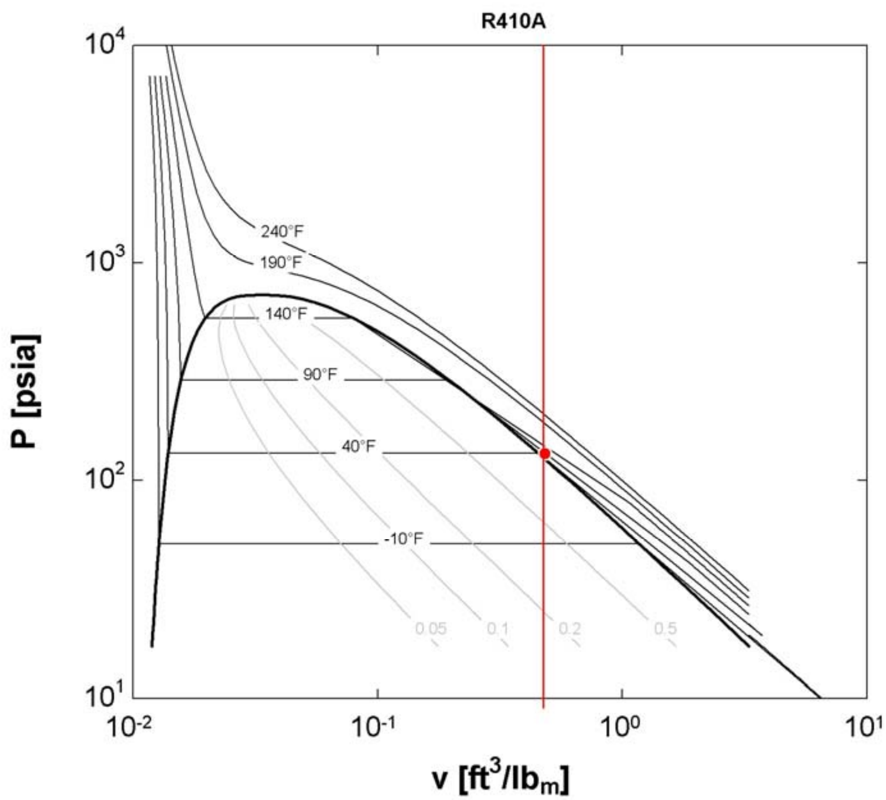


Figure 5a:
P-v for R-410A

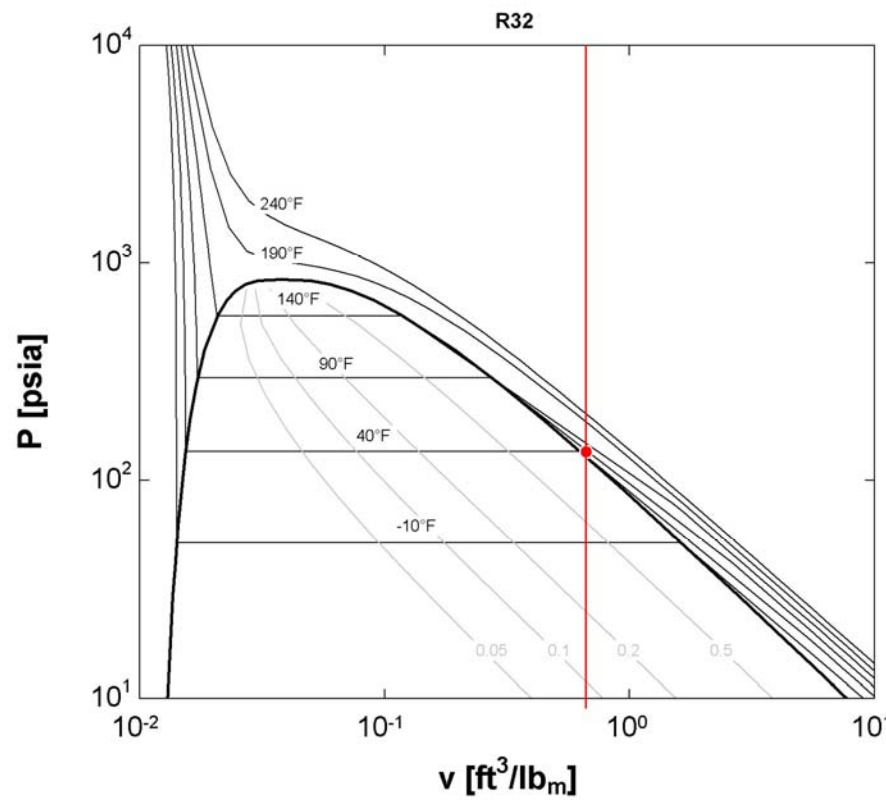


Figure 5b:
P-v for R-32

Volumetric Efficiency (5 ton unit)

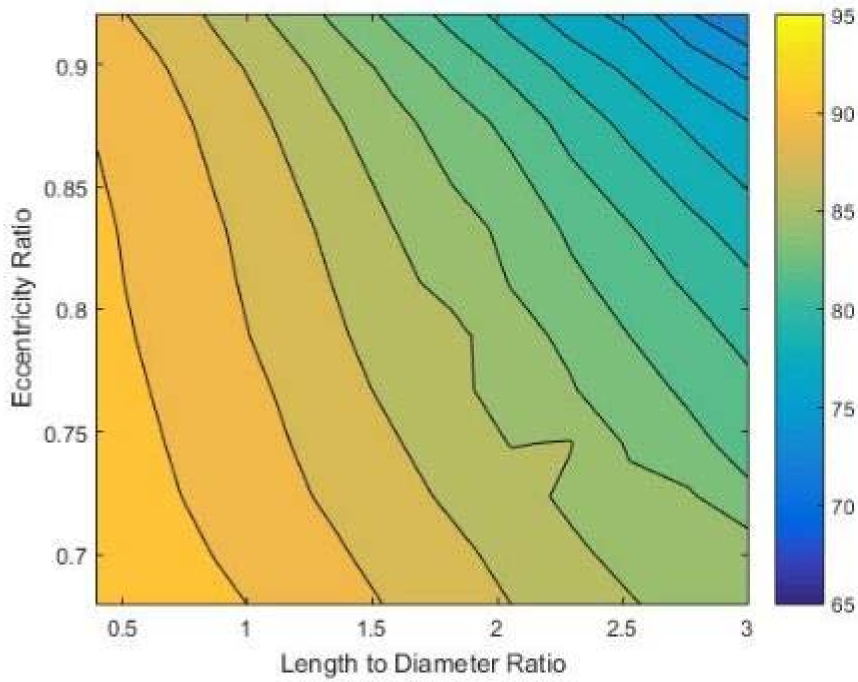


Figure 6a:
Volumetric efficiency
with R-410A [%]

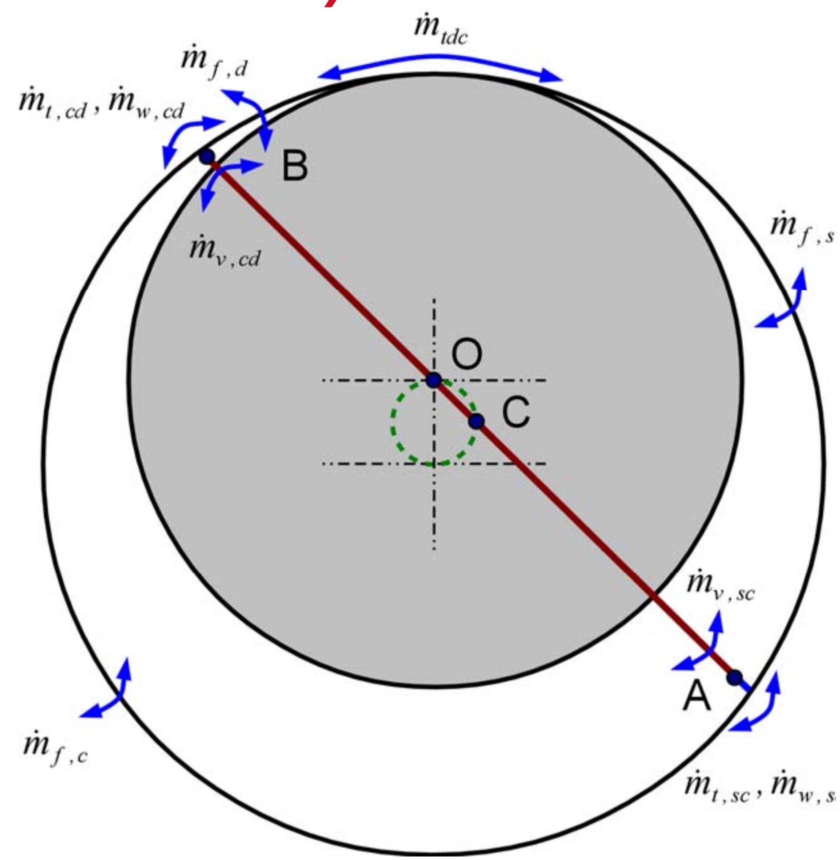


Figure 6b:
Leakage path definitions
(Bradshaw and Groll, 2013)

Face Seal Leakage Ratio (5 ton unit)

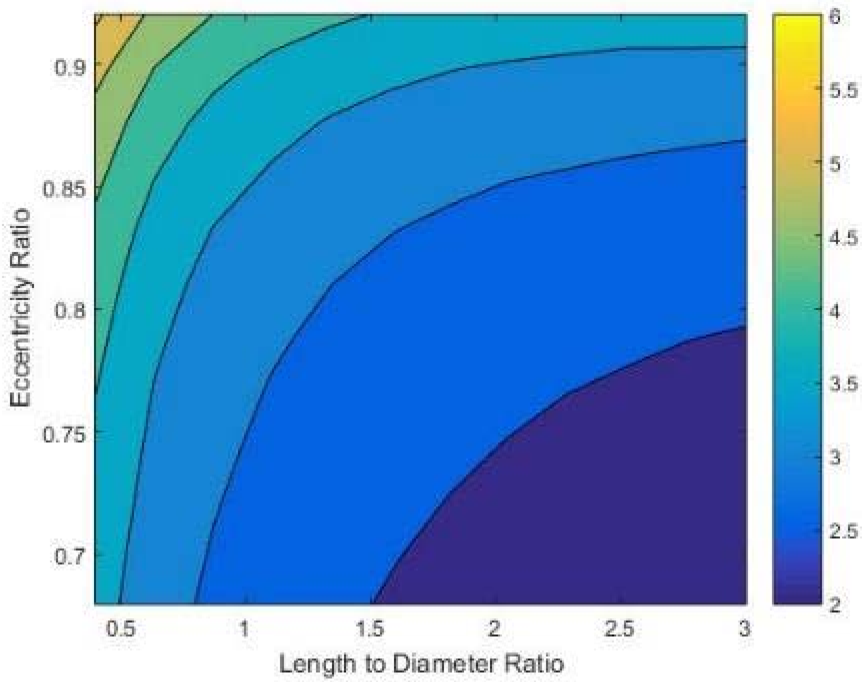


Figure 7a:
Ratio of seal leakage to mass flow rate with R-410A [%]

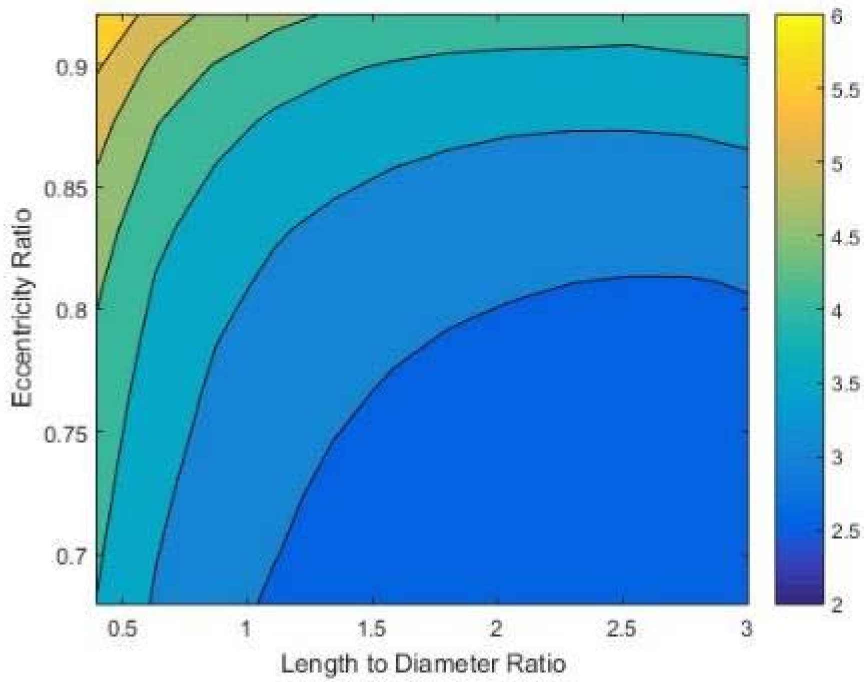


Figure 7b:
Ratio of seal leakage to mass flow rate with R-32 [%]

Volumetric Efficiency (5 ton unit)

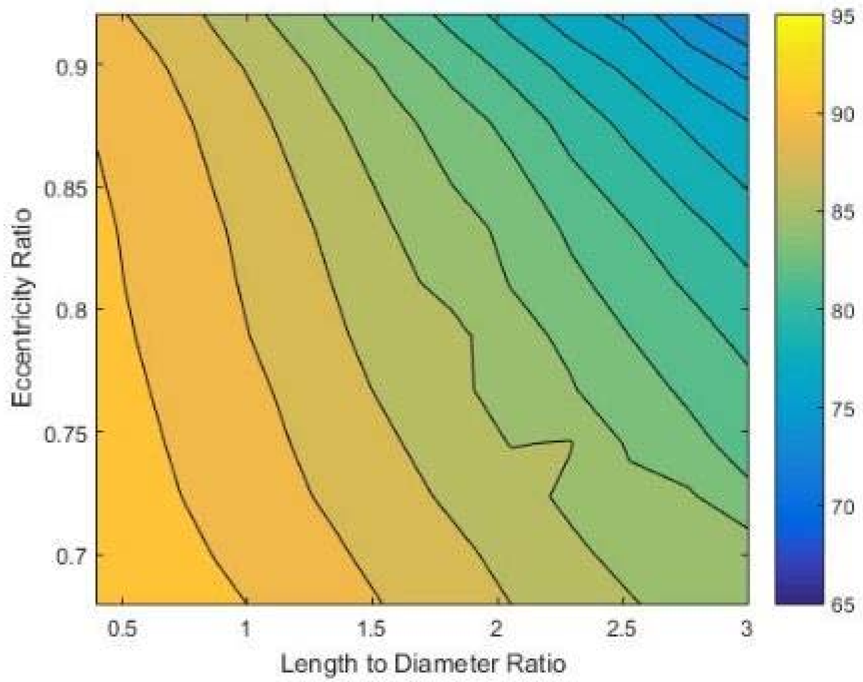


Figure 6a:
Volumetric efficiency
with R-410A [%]

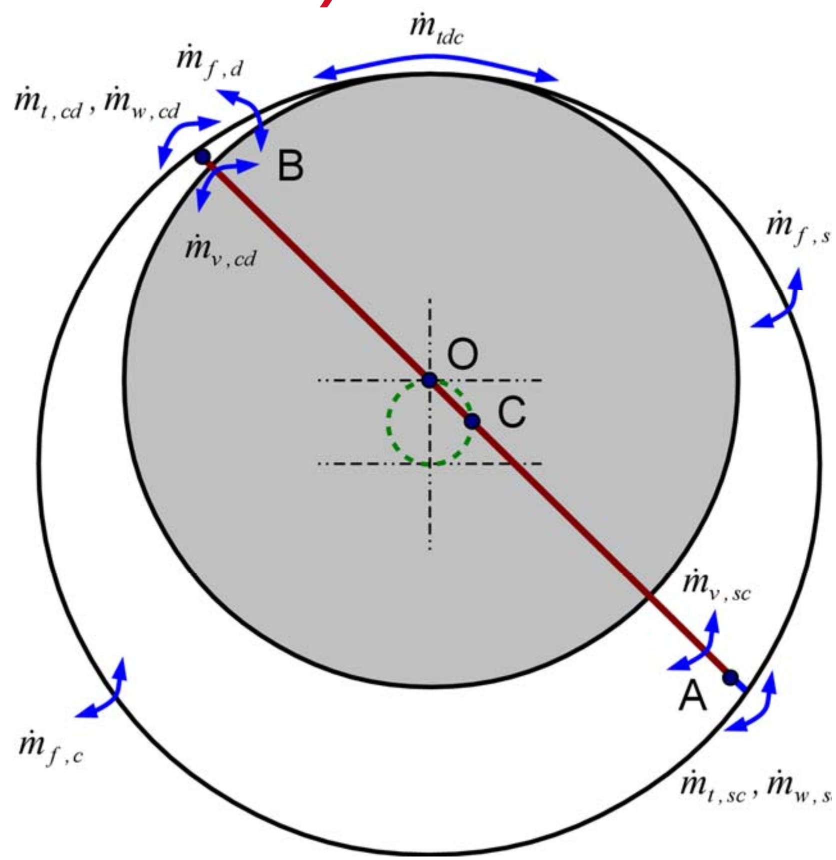


Figure 6b:
Leakage path definitions
(Bradshaw and Groll, 2013)

Volumetric Efficiency (5 ton unit)

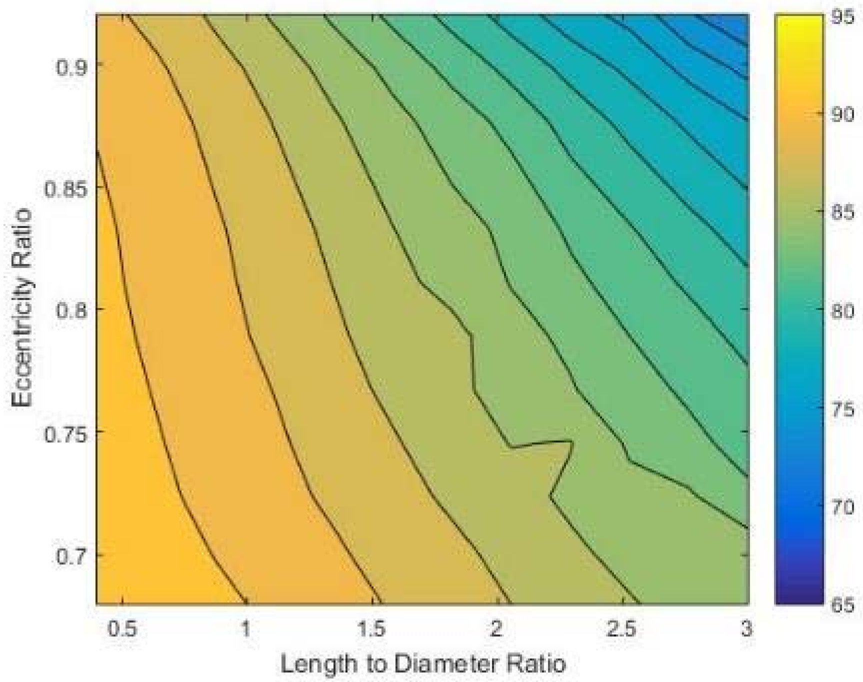


Figure 6a:
Volumetric efficiency
with R-410A [%]

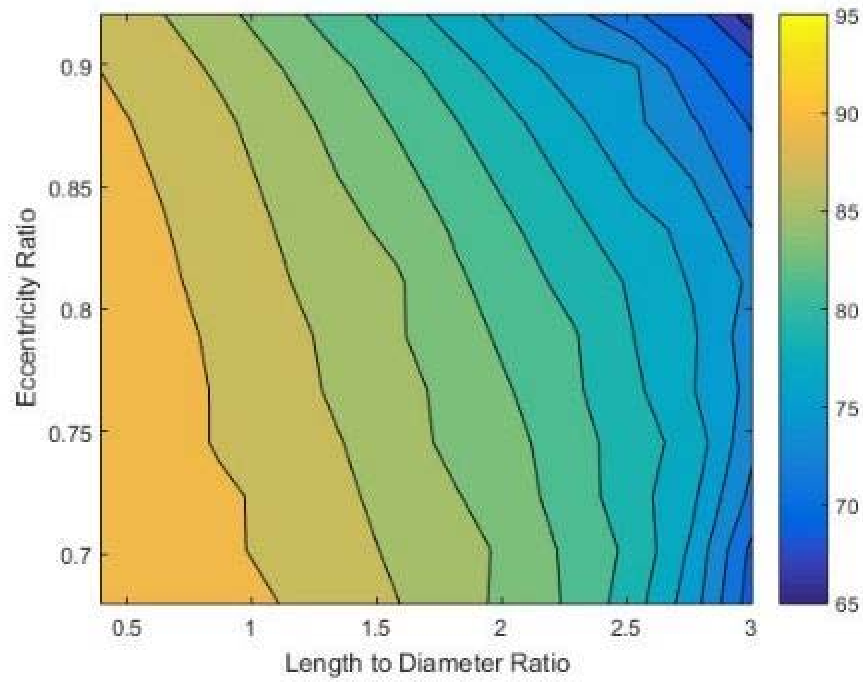


Figure 6c:
Volumetric efficiency
with R-32 [%]

Volumetric Efficiency (5 ton unit)

Leakage modeled as isentropic compressible flow:

$$\dot{m} = A\sqrt{p_{up}\rho_{up}}\sqrt{\frac{2k}{k-1}\left(p_{ratio}^{2/k} - p_{ratio}^{(k+1)/k}\right)}$$

where

$$p_{ratio} = \begin{cases} p_{choked} & \text{If } \dfrac{p_{down}}{p_{up}} > p_{choked} \\ \dfrac{p_{down}}{p_{up}} & \text{If } \dfrac{p_{down}}{p_{up}} \le p_{choked} \end{cases}$$

and

$$p_{choked} = \left(1 + \frac{k-1}{2}\right)^{\frac{k}{1-k}}$$

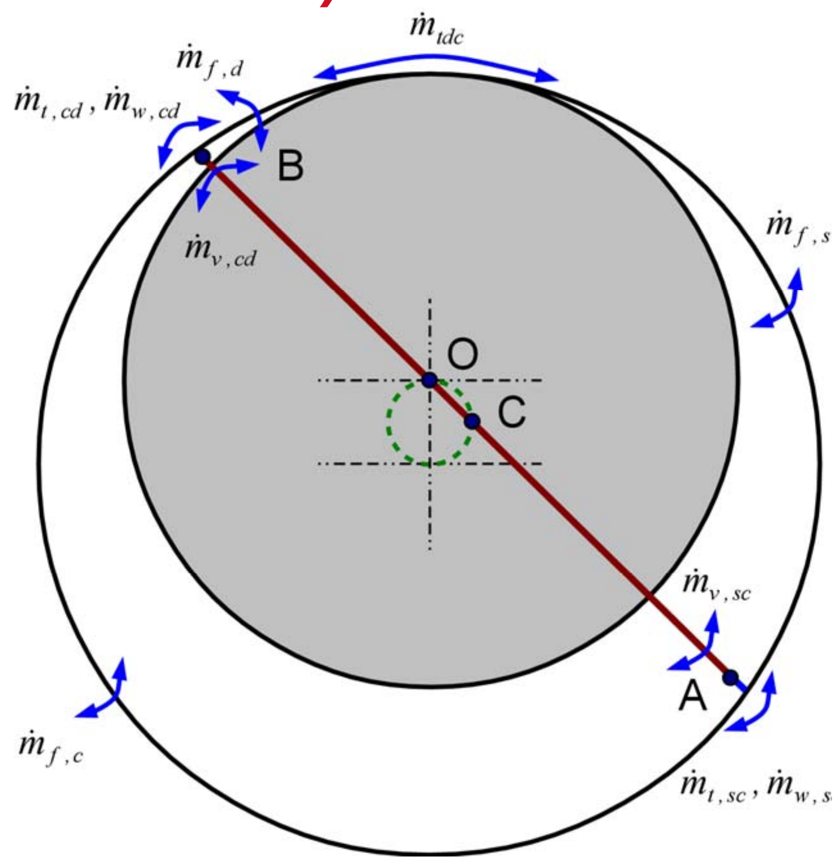


Figure 6b:
Leakage path definitions
(Bradshaw and Groll, 2013)

Volumetric Efficiency (5 ton unit)

- Consider leakage from discharge to suction pressure
  - Estimate discharge temperature assuming isentropic efficiency of 80%
  - Determine flow would be choked
  - Calculate leakage mass flow per unit leak area

	η_s	Choked Pressure Ratio	Suction Density [lbm/ft³]	Leakage Flow per Unit Leak Area [kg/s·m²]
R-410A	80%	0.53	2.07	26.9
R-32	80%	0.52	1.50	22.4
Difference	0%	-1%	-28%	-17%

Discharge Temperature (5 ton unit)

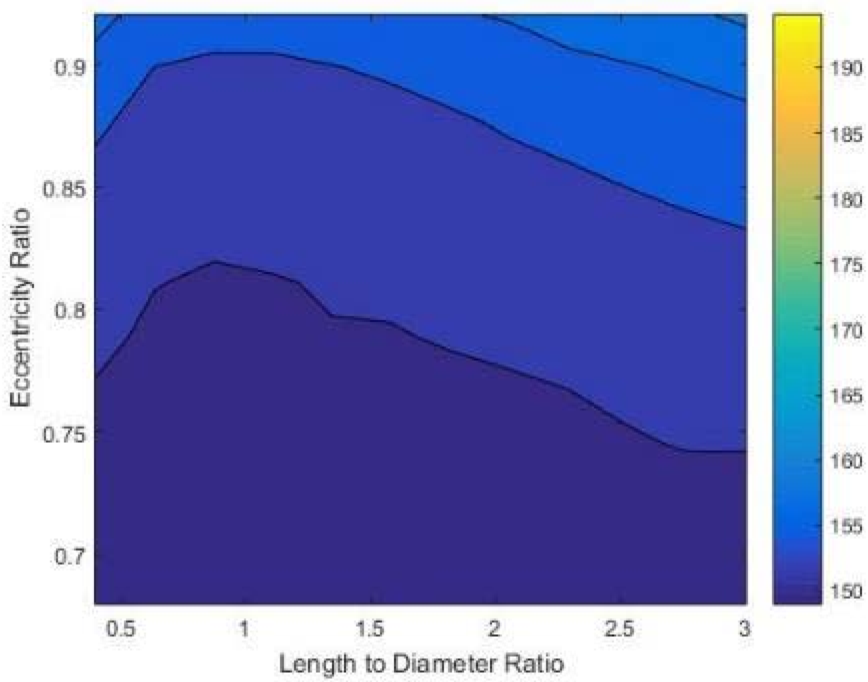


Figure 7a:
Discharge temperature
with R-410A [°F]

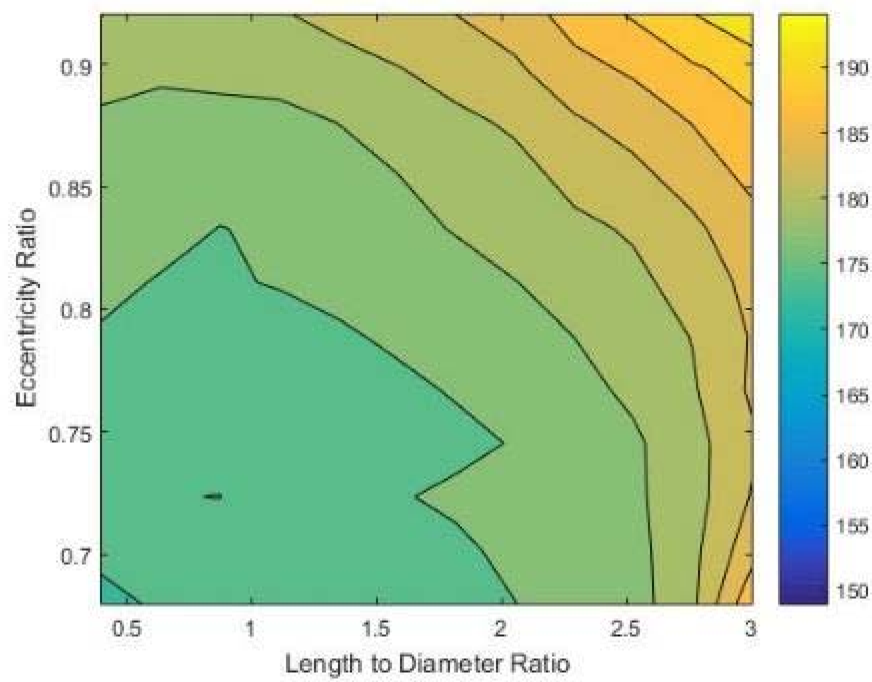


Figure 7b:
Discharge temperature
with R-32 [°F]

Seal Work Losses (5 tons)

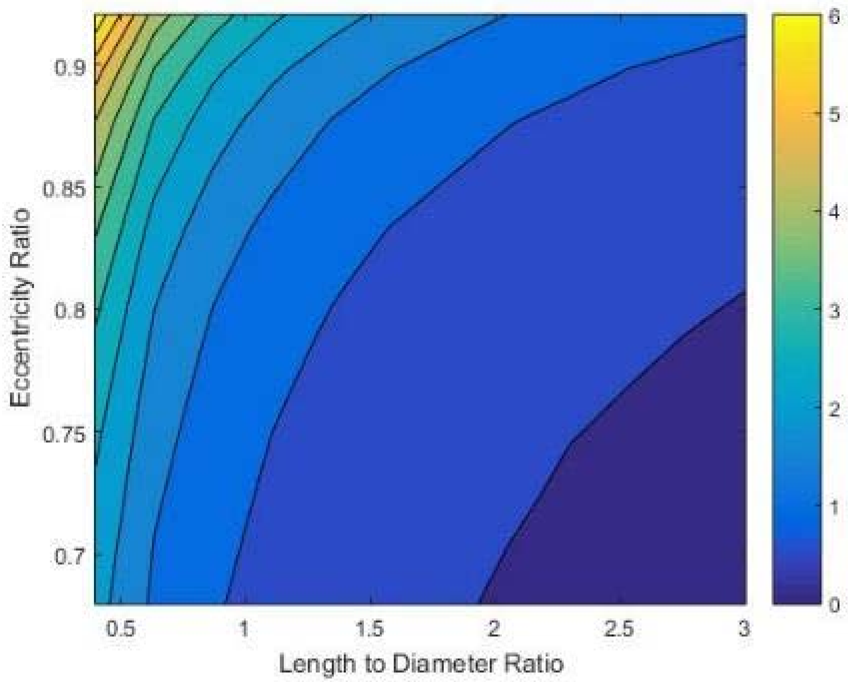


Figure 8a:
Ratio of seal work to input work with R-410A [%]

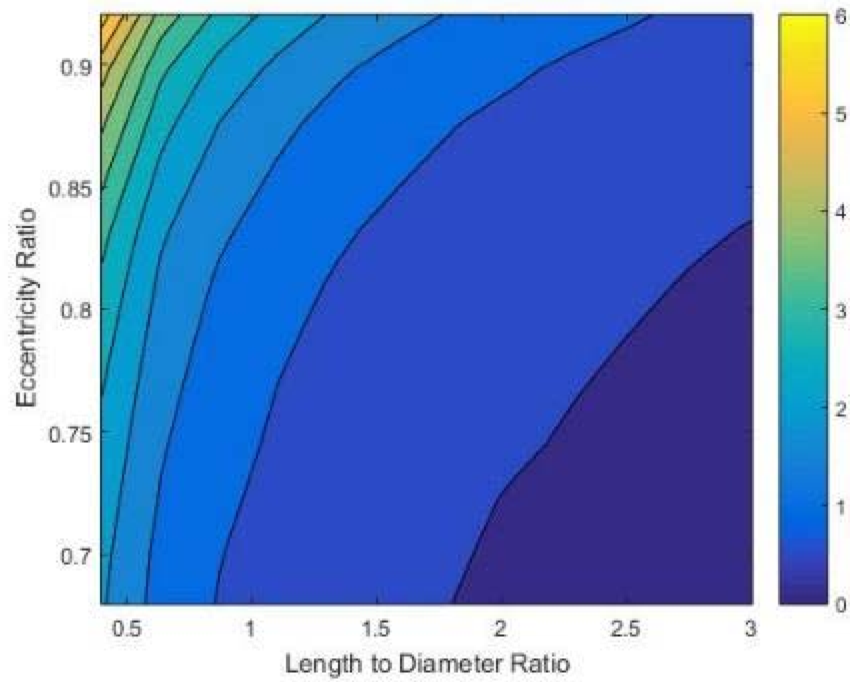


Figure 8b:
Ratio of seal work to input work with R-32 [%]

Discharge Temperature (5 ton unit)

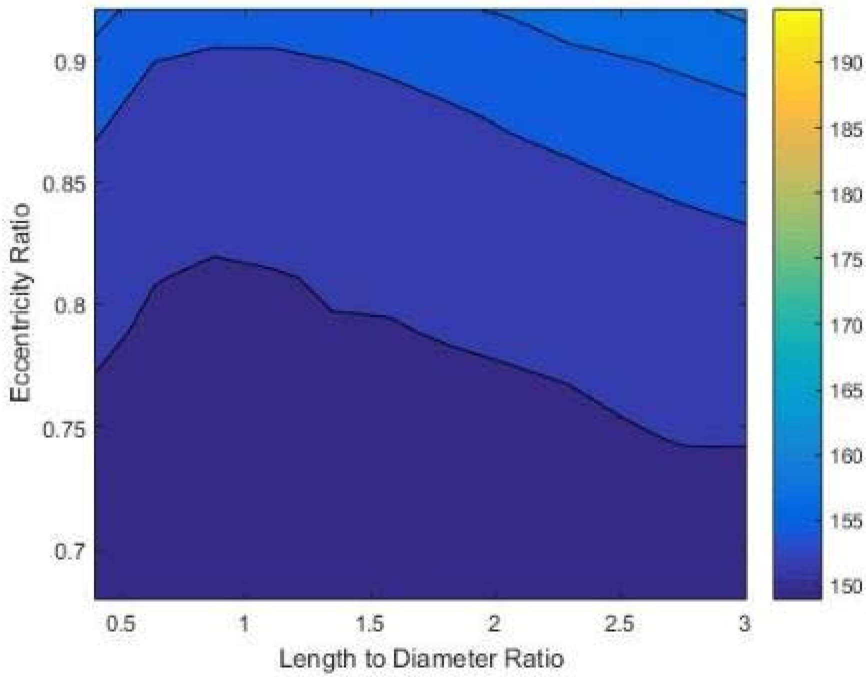


Figure 7a:
Discharge temperature
with R-410A [°F]

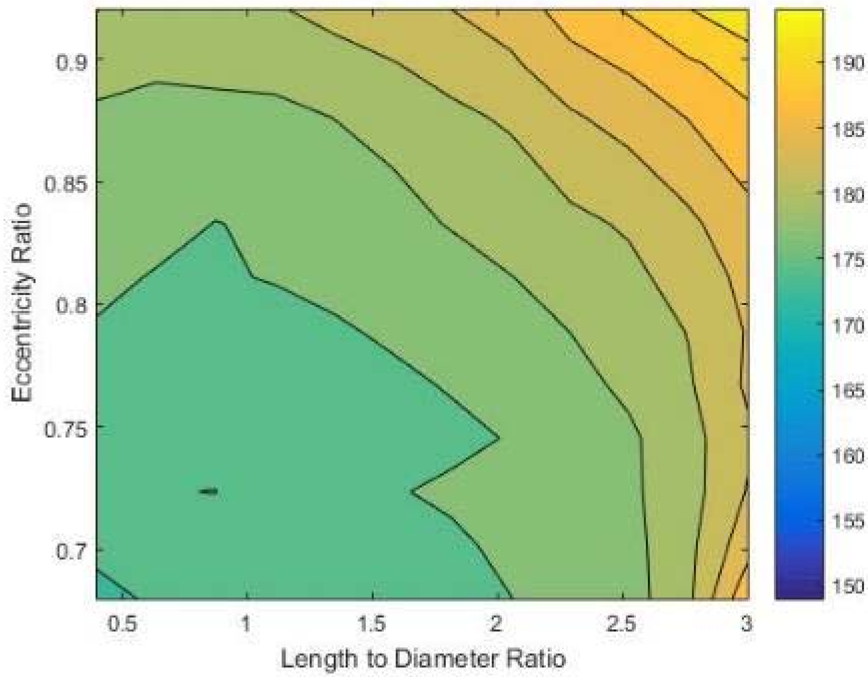


Figure 7b:
Discharge temperature
with R-32 [°F]

Discharge Temperature (Isentropic)

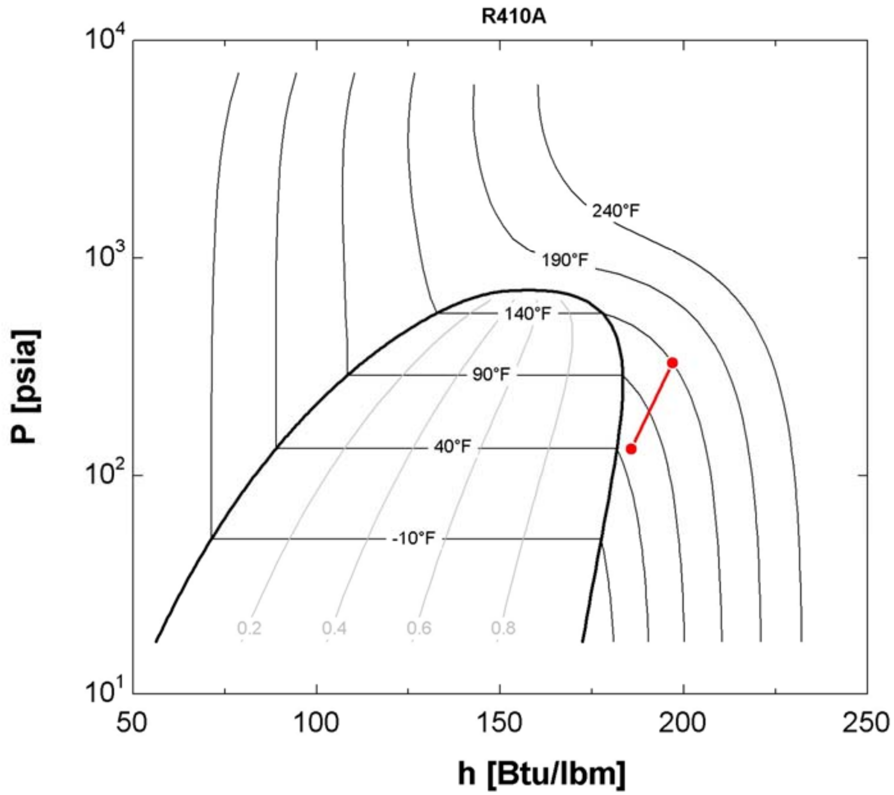


Figure 9a:
P-h for R-410A

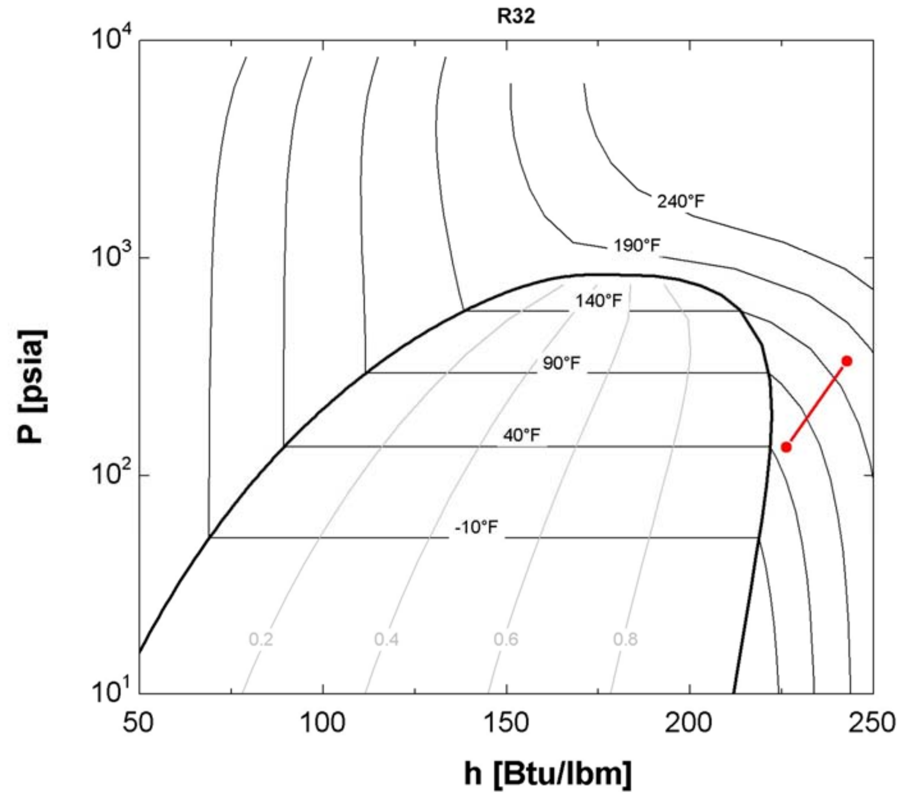


Figure 9b:
P-h for R-32

Isentropic Efficiency (5 ton unit)

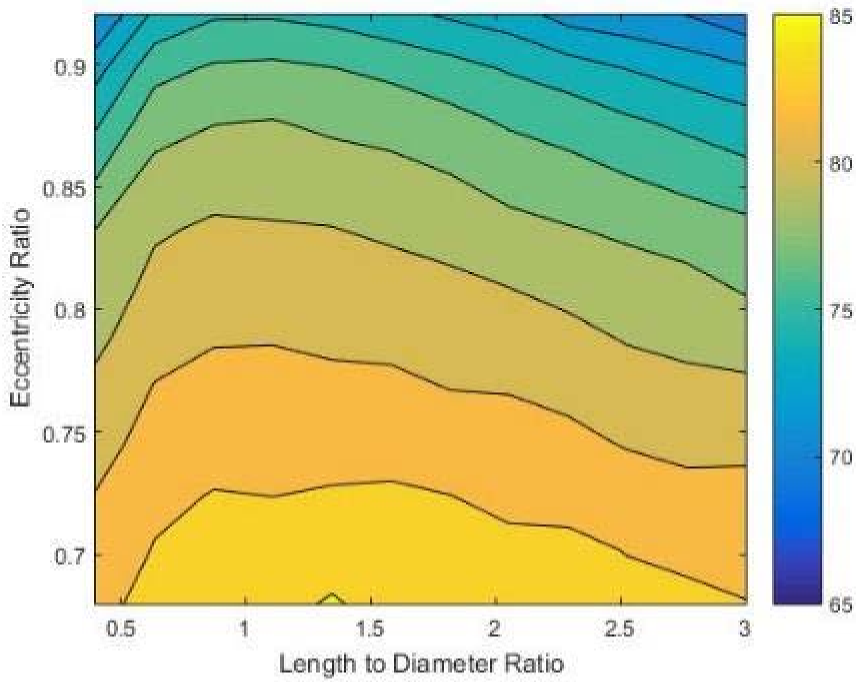


Figure 10a:
Isentropic efficiency
with R-410A

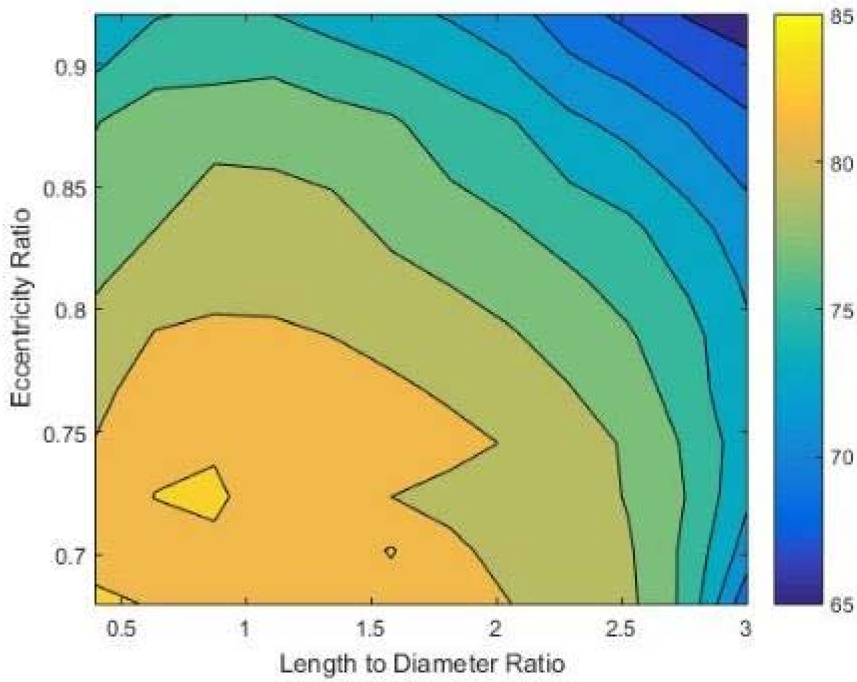


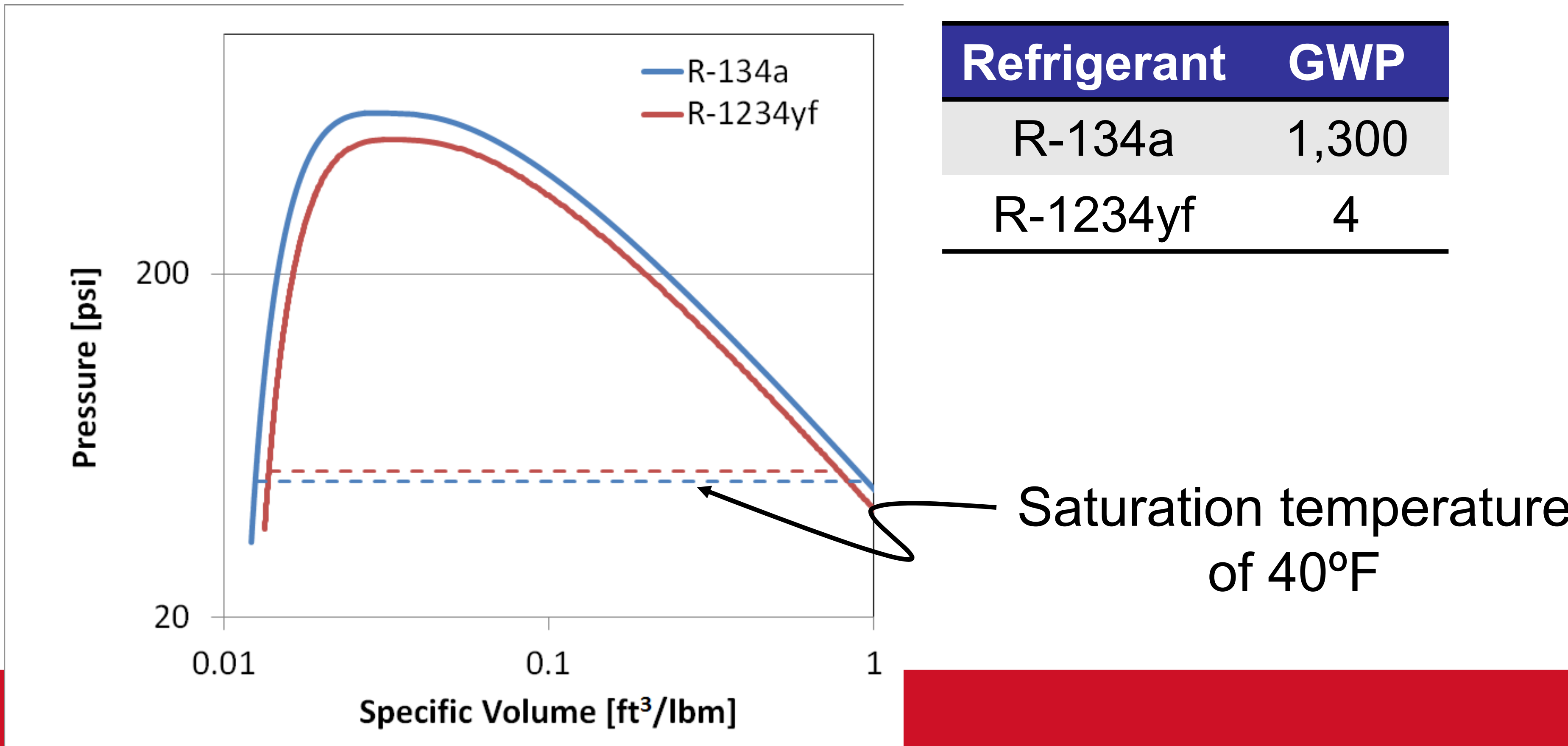
Figure 10b:
Isentropic efficiency
with R-32

Summary of R-410A Compared to R-32

- When R-32 is “dropped in” to a R-410A compressor, the model predicts it will:
  - Achieve slightly higher capacities despite a reduction in mass flow rate
  - Require slightly more power input
  - Experience significantly higher discharge temperatures
  - Increase sensitivity to geometric parameters

Modeled Refrigerants: R-134a and R-1234yf

- R-1234yf has lower GWP than R-134a with similar thermodynamic properties



Refrigerant	GWP
R-134a	1,300
R-1234yf	4

Modeled Operating Conditions

Conditions:

- 40ºF (4°C) evaporating
- 15ºF (8°C) superheat
- Pressure ratio of 2.5

6.7% difference

Refrigerant	p_{evap} [psia]	p_{cond} [psia]	Δp [psia]	T_{cond} [ºF]
R-134a	49.8	124.2	74.4	92.7
R-1234yf	53.1	132.5	79.4	96.4

Refrigerant	p_{evap} [kPa]	p_{cond} [kPa]	Δp [kPa]	T_{cond} [ºC]
R-134a	343	856	513	33.7
R-1234yf	366	914	548	35.8

Capacity (5 ton unit)

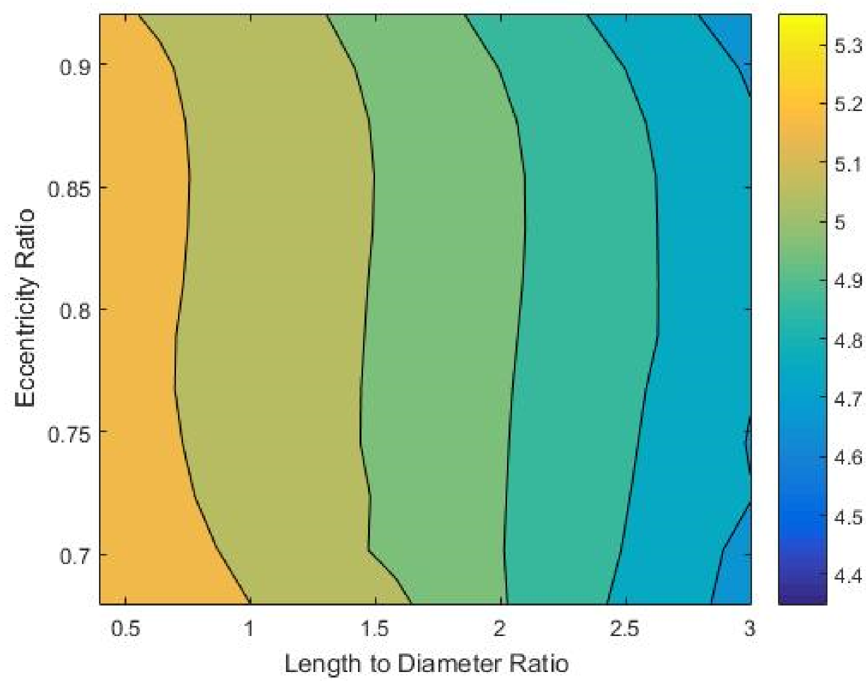


Figure 11a:
Capacity
with R-134a [tons]

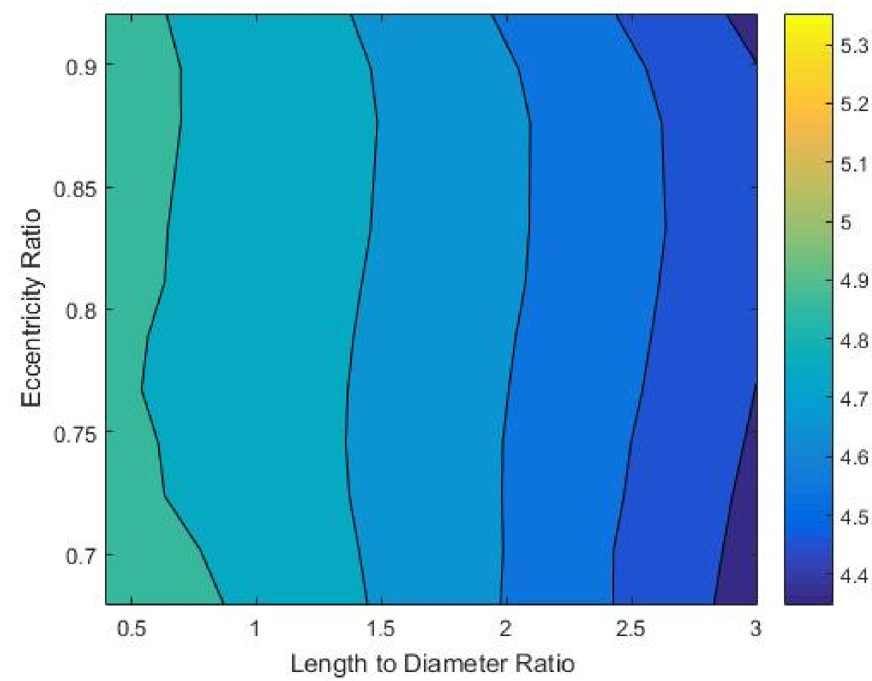


Figure 11b:
Capacity
with R-1234yf [tons]

Capacity per Unit Mass Flow

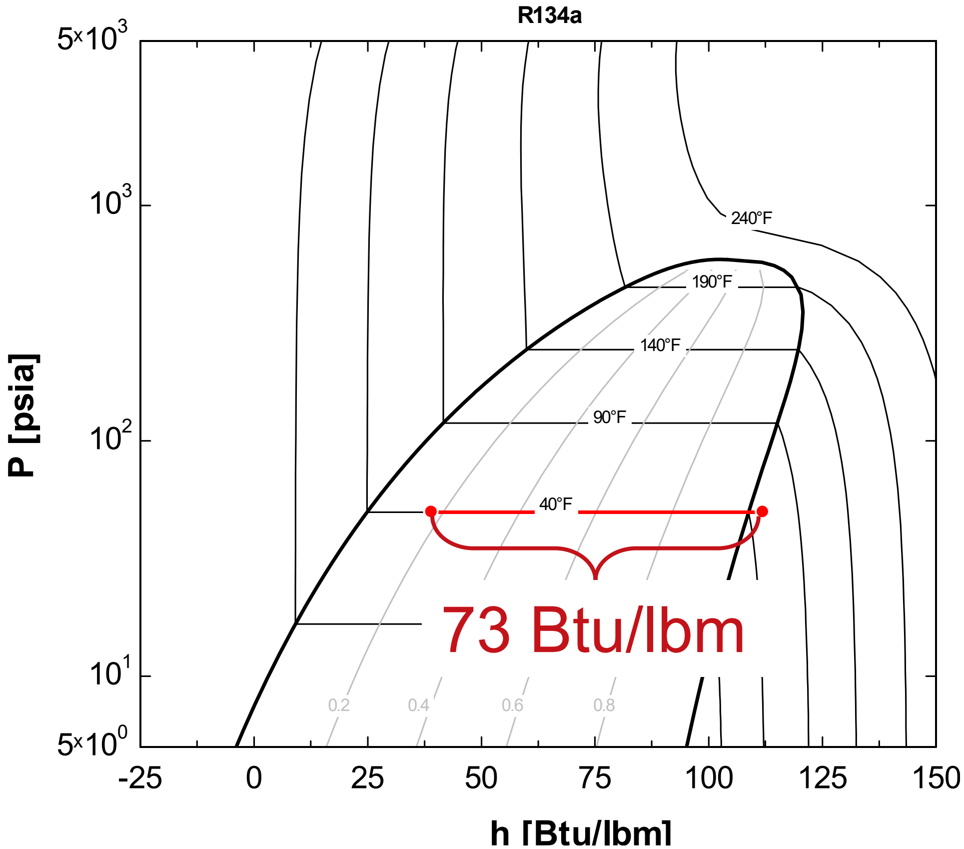


Figure 3a:
P-h for R-134a

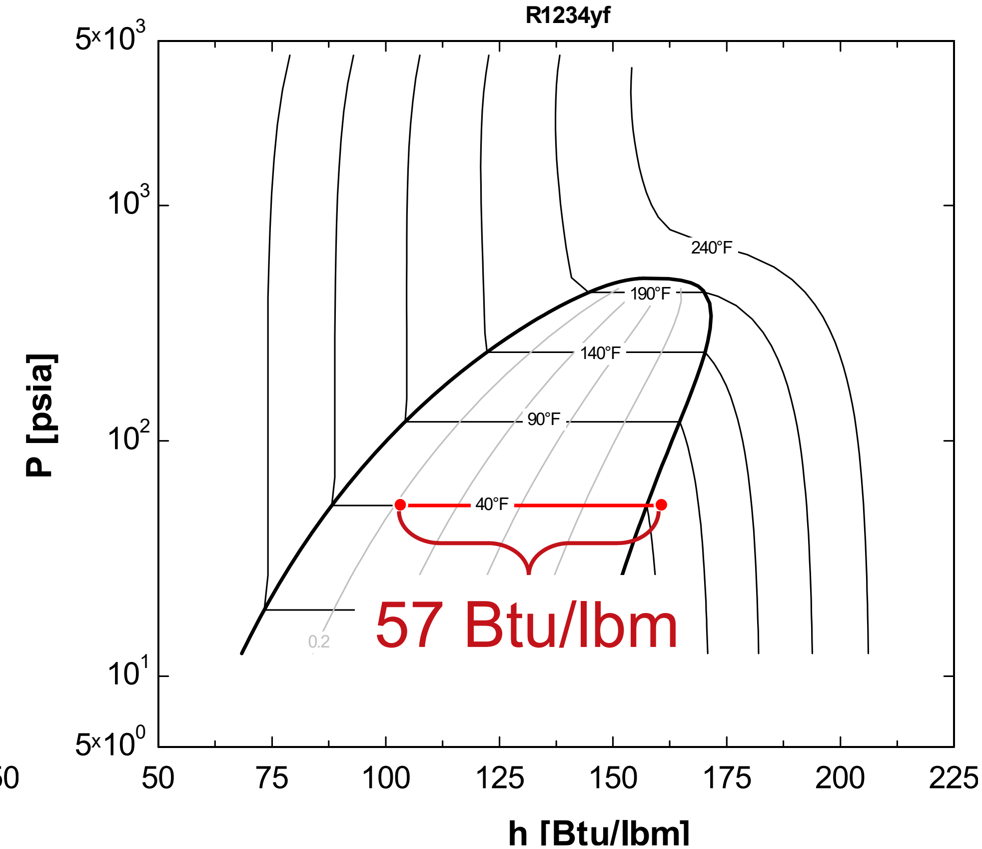


Figure 3b:
P-h for R-1234yf

Mass Flow Rate

$$\dot{m} = \eta_v \left(\frac{\dot{V}_{ideal}}{v_{in}} \right)$$

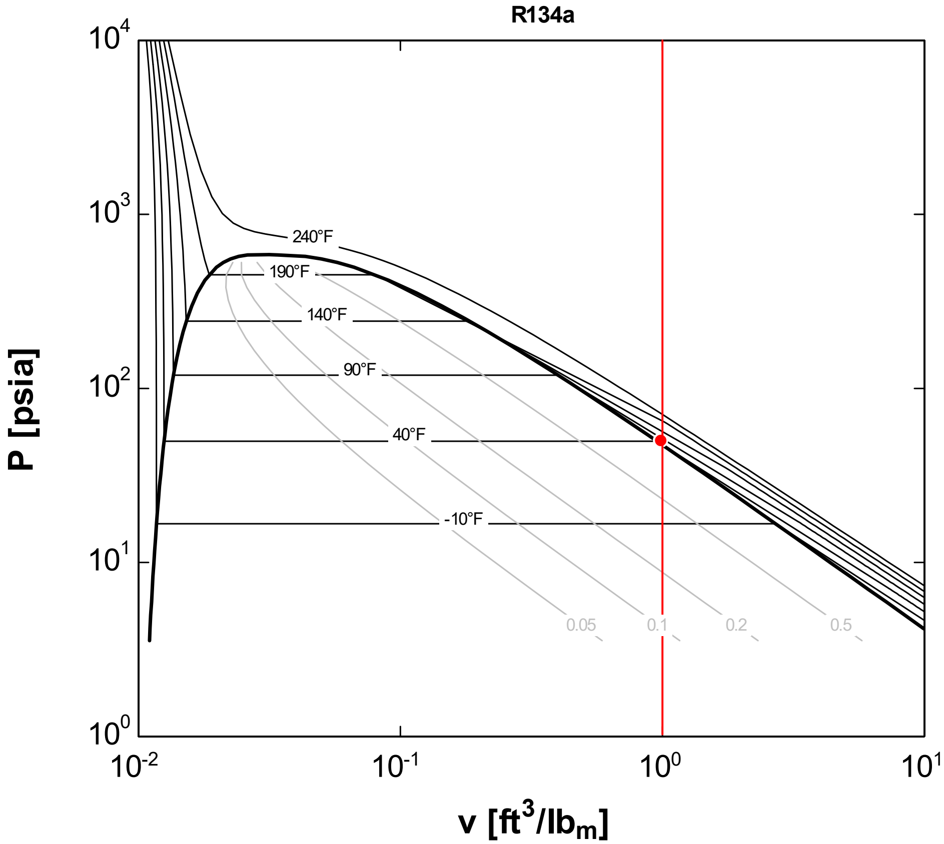


Figure 5a:
P-v for R-134a

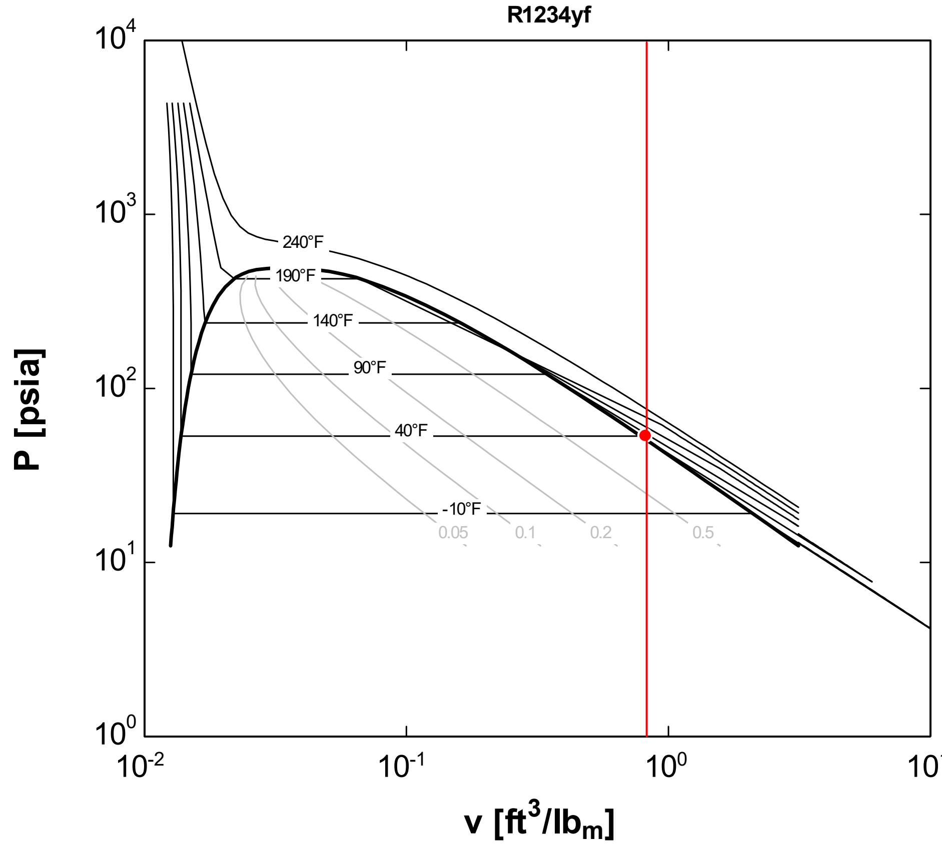


Figure 5b:
P-v for R-1234yf

Volumetric Efficiency (5 ton unit)

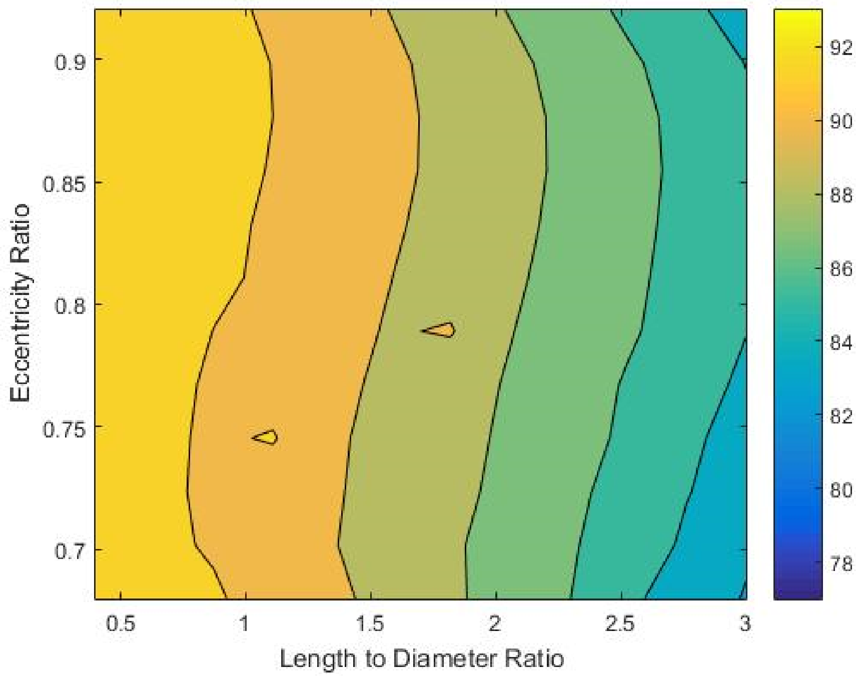


Figure 11a:
Volumetric efficiency
with R-134a [%]

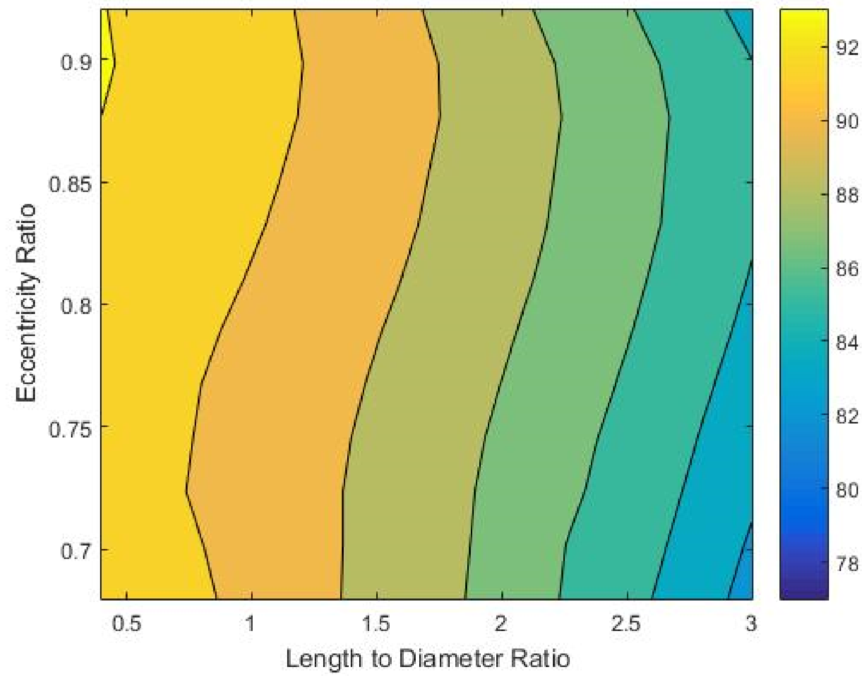


Figure 11b:
Volumetric efficiency
with R-1234yf [%]

Discharge Temperature (5 ton unit)

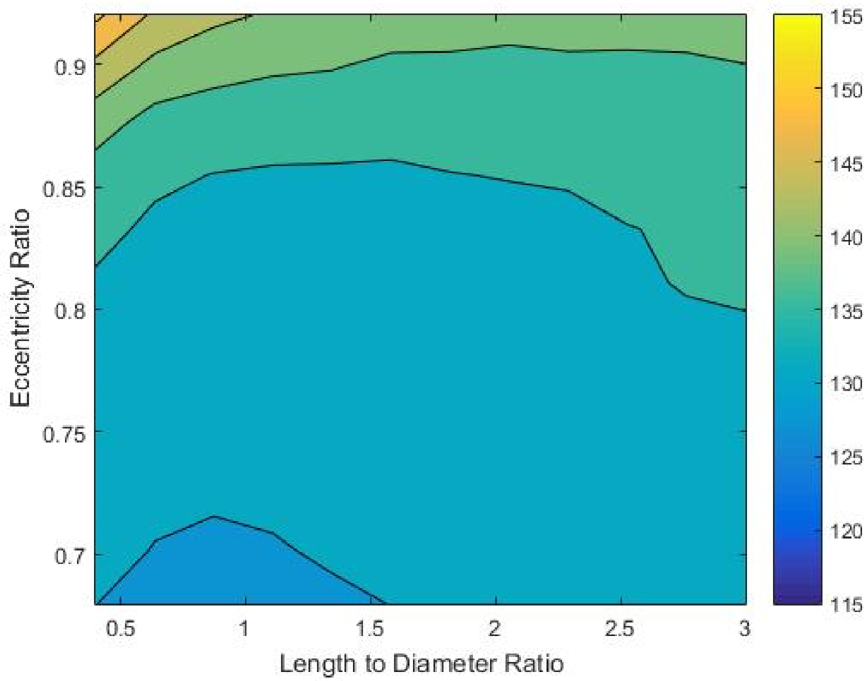


Figure 11a:
Discharge temperature with R-134a [°F]

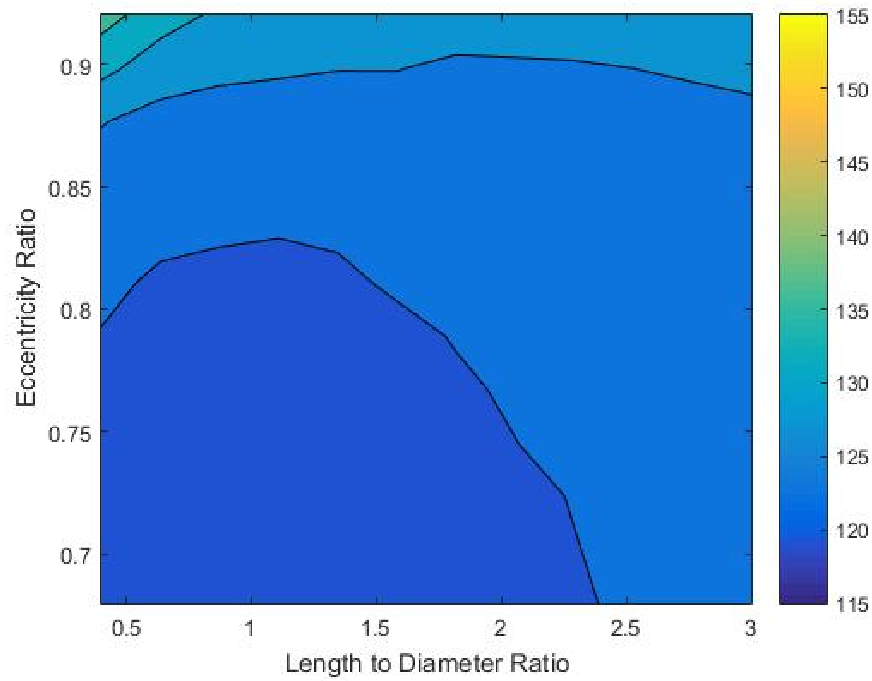


Figure 11b:
Discharge temperature with R-1234yf [°F]

Isentropic Efficiency (5 ton unit)

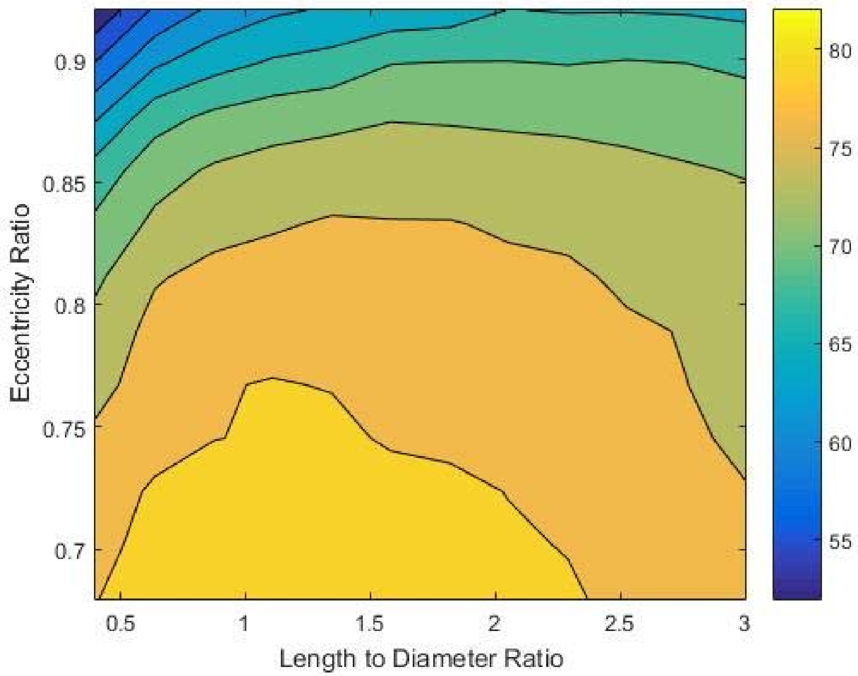


Figure 11a:
Isentropic efficiency
with R-134a [%]

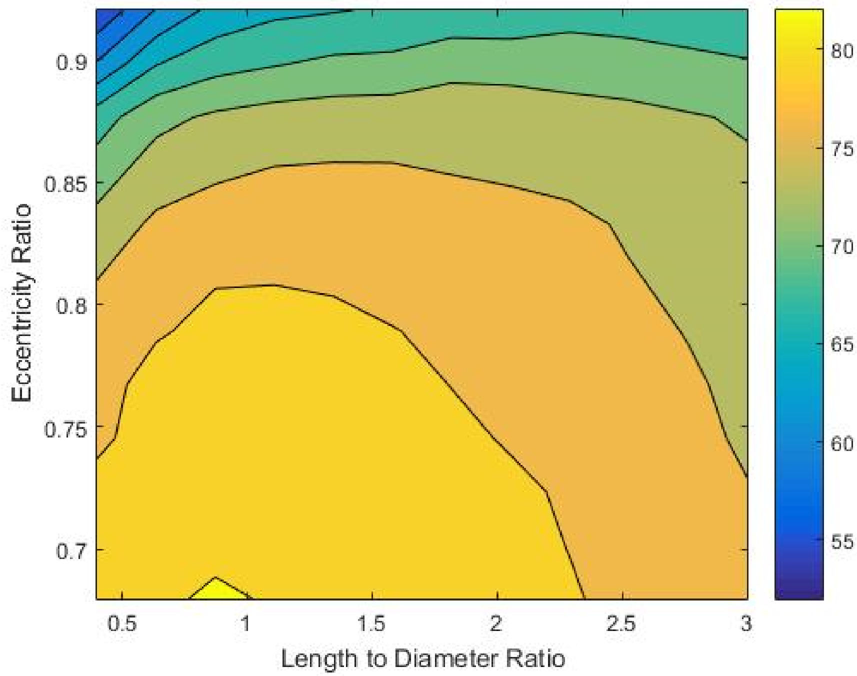


Figure 11b:
Isentropic efficiency
with R-1234yf [%]

Conclusions

- Compressor models provide cost- and time-effective method to predict “drop in” performance
  - Reveal changes in performance trends
  - Provide insight into physical reasons for trends
- Accurate results require:
  - Thermophysical properties of refrigerant and lubricant
  - Physically-based model

References

Bradshaw, C.R., Groll, E.A., 2013. A Comprehensive Model of a Novel Rotating Spool Compressor. *International Journal of Refrigeration*. 36(7), 2007 - 2013.

Questions?

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