THERMODYNAMIC ENGINEERING
RESEARCH AND APPLICATIONS LAB

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Numerical Modelling of Thermoacoustic Stirling Engines & Refrigerators

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Presentation Outline

- **Introduction to thermoacoustic devices & modelling strategies**
- **Literature review**
  - Review of modelling strategies
- **Standing-wave thermoacoustic Stirling engine**
  - Numerical model overview
- **Travelling-wave thermoacoustic Stirling refrigerator**
  - Numerical model overview
- **Results**
  - Standing-wave TASE: DeltaEC & Sage Validation
  - Standing-wave TASE: DeltaEC vs Sage
  - Travelling-wave TASR: DeltaEC vs Sage
- **Summary**
  - Conclusions about DeltaEC and Sage software
  - Conclusions about numerical modelling tools

Introduction To Thermoacoustic Devices

Thermoacoustic Device Components:

- Resonator Tube
- Thermoacoustic Core
- Pressure Wave Source

Thermoacoustic Devices:

- Standing-wave & Travelling-wave
- Engine & Refrigerator

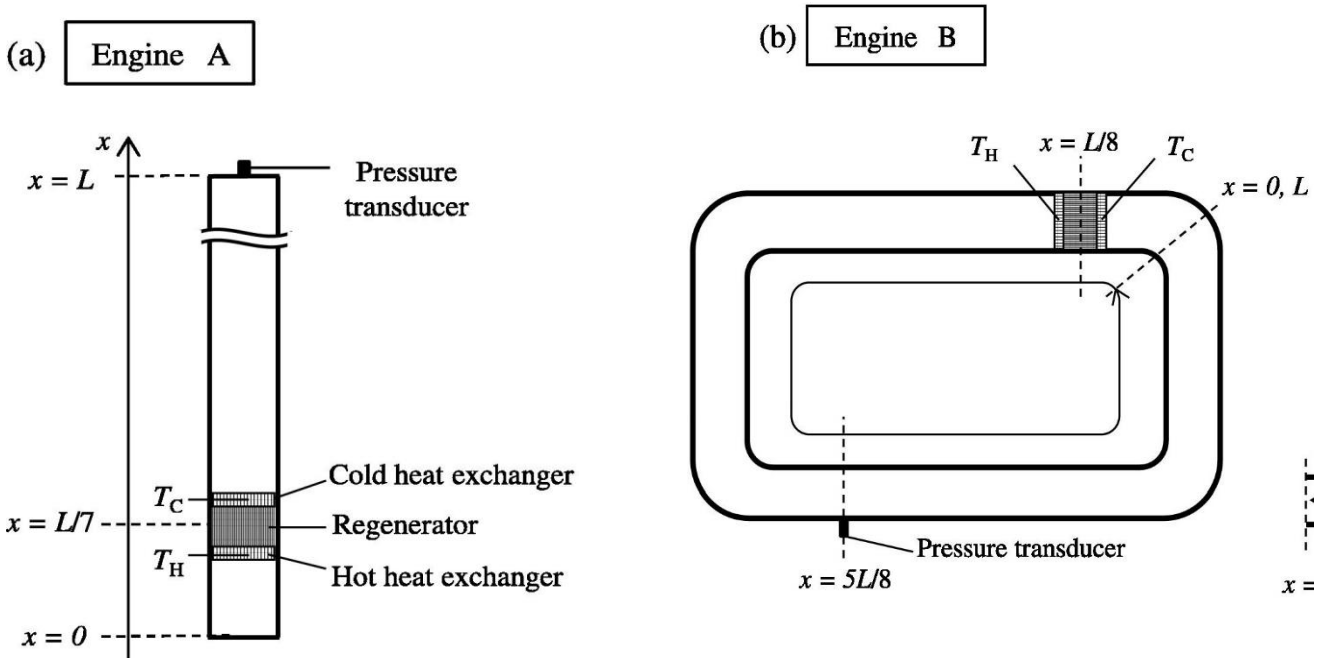

Figure 1

Figure 1. Thermoacoustic machines adapted from Tsuda and Ueda (2017, p. 63); (a) Standing-wave, (b) Travelling-wave

Introduction To Modelling Strategies

Modelling Methods:

- Analytical
  - Mathematical equations
  - Analytic functions for solutions
- **Advantages:**
  - Quick parametric study
  - Simplified
  - No modelling software
- **Disadvantages:**
  - Low accuracy
  - Singular variable focus
  - Equations become complex

SERC. (2023, 23rd January 2023). Analytical Models. https://serc.carleton.edu/introgeo/mathstatmodels/Analytical.html

Introduction To Modelling Strategies

Modelling Methods:

- Numerical
  - Incremental method
  - Graphs/tables of solutions
- **Advantages:**
  - Accurate predictions
  - Multiple variable analysis
  - Visual format for results
- **Disadvantages:**
  - Increased computational time
  - Software required

SERC. (2023, 23rd January 2023). Numerical Models.
https://serc.carleton.edu/introgeo/mathstatmodels/Numerical.html

Literature Review: Modelling Strategies

Existing Literature:

- Scarce use of analytical models in existing papers
- Frequent use of DeltaEC (Bi et al., 2017; Rotundo et al., 2007; Swift et al., 2012; Tijani et al., 2002)
- Scarce use of Sage (Wang et al., 2020)
- No comparison of DeltaEC & Sage

Standing-wave TASE: Numerical Model

- Models based off experimental prototype by Swift (1992)
- No Needle valve/Tank
- Experimental data used for validation

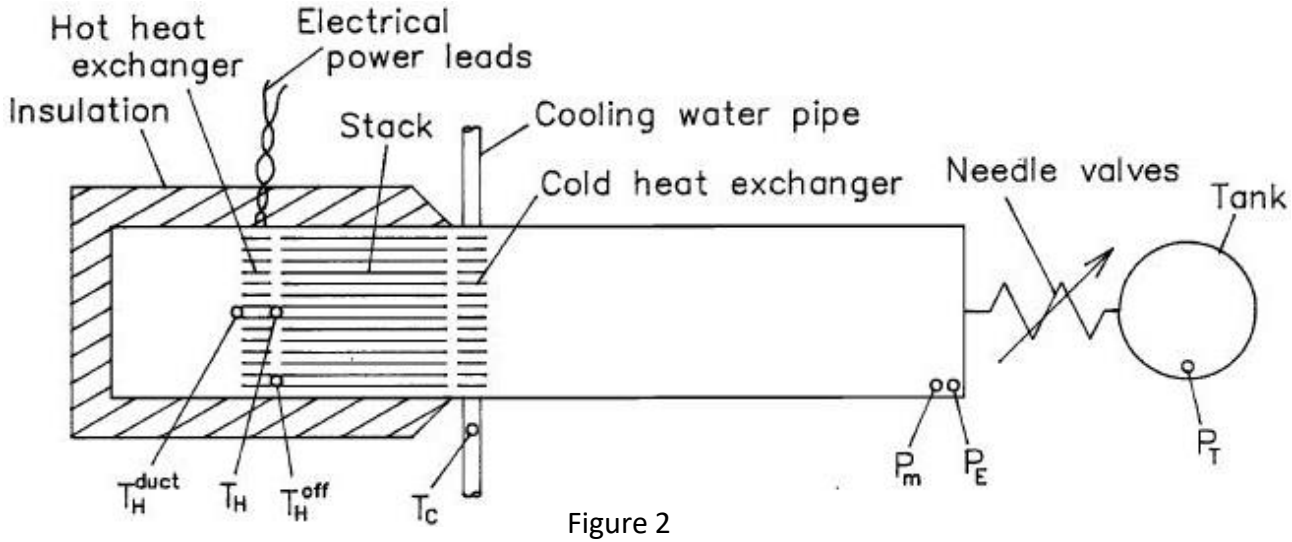

Figure 2

Experimental Apparatus

Figure 2. Experimental apparatus schematic adapted from Swift (1992, p. 1553)

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Travelling-wave TASR: Numerical Model

- Models based off design by Wang et al. (2020)
- No experimental prototype
- Paper results used for validation

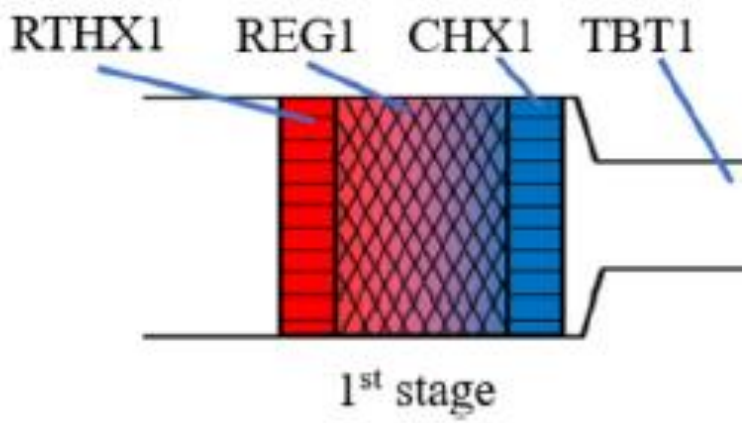

Figure 3

Single-Stage TWTASR Schematic

Figure 3. Single-Stage travelling-wave thermoacoustic refrigerator schematic adapted from Wang et al. (2020, p. 92)

Results: Standing-wave TASE DeltaEC Validation

- **Pressure amplitude:**
  - Increases with heat input & mean pressure
  - Deviation is greater for higher mean pressures
- **Temperature difference & Frequency:**
  - Not affected by heat input
  - Decrease with mean pressure
  - Deviation is significant for lower mean pressures

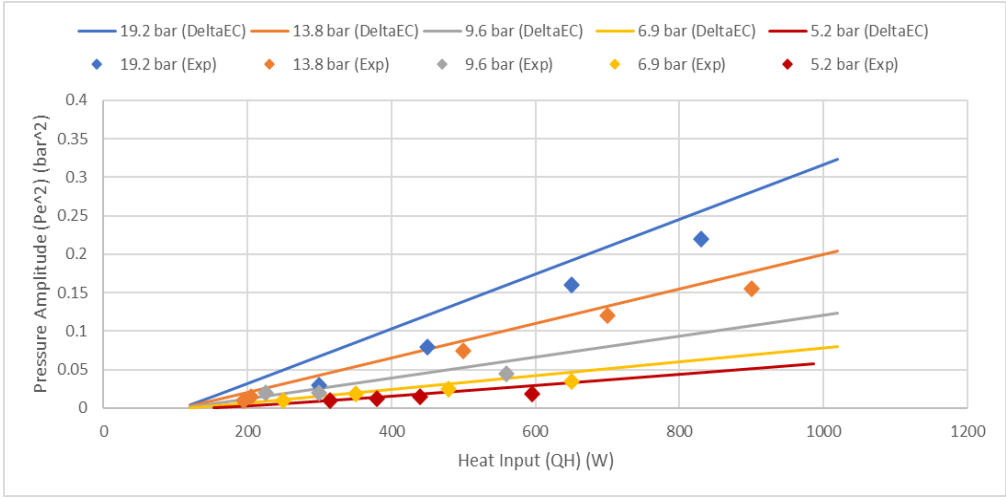

Figure 4(a)

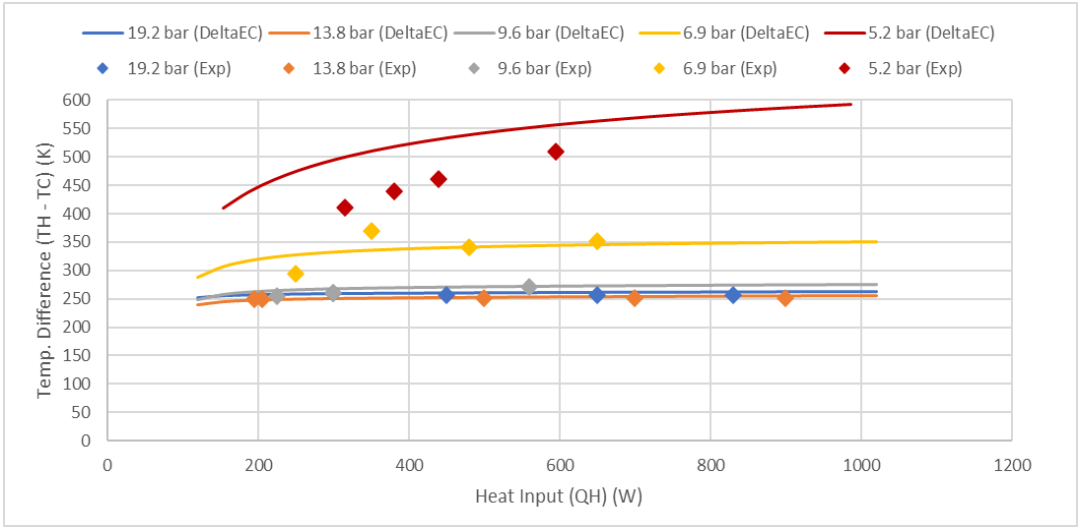

Figure 4(b)

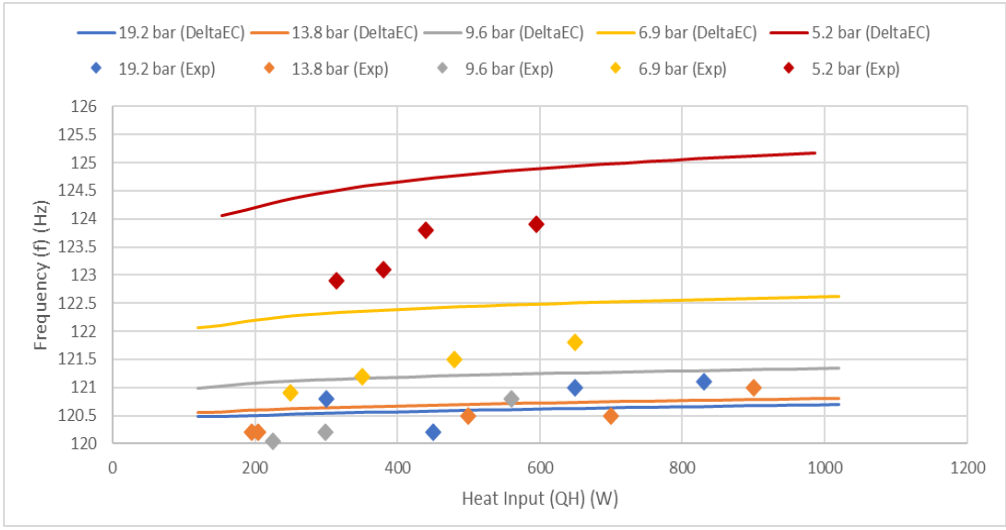

Figure 4(c)

Figure 4. Standing-wave TASE DeltaEC Results; (a) pressure amplitude against heat input, (b) Temperature difference against heat input (c) operating frequency against heat input

Results: Standing-wave TASE Sage Validation

- **Pressure Amplitude:**
  - Deviation increases with mean pressure
  - Predicts lower amplitudes for higher mean pressures
- **Temperature Difference & Frequency:**
  - Deviation is greater at lower mean pressures
  - Overpredicts frequency

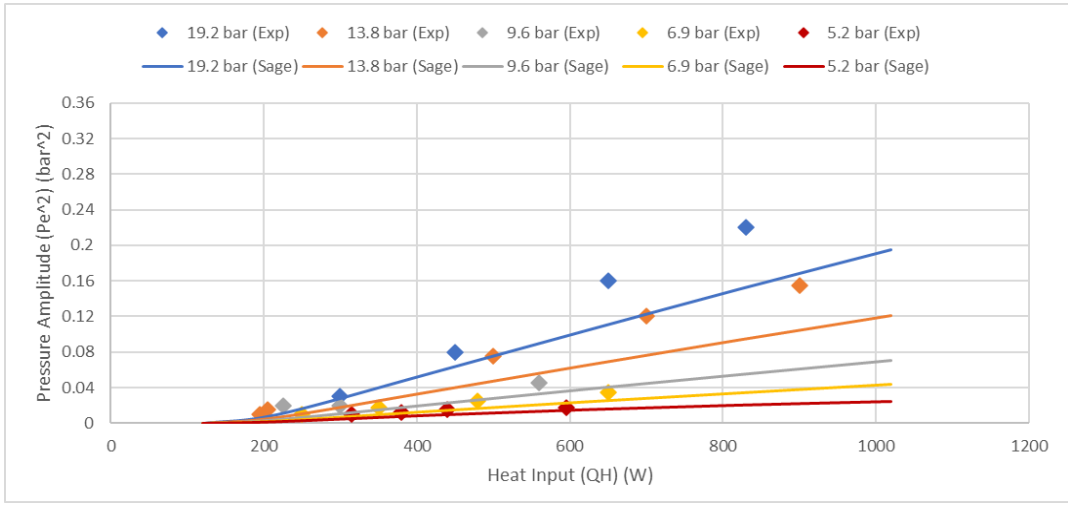

Figure 5(a)

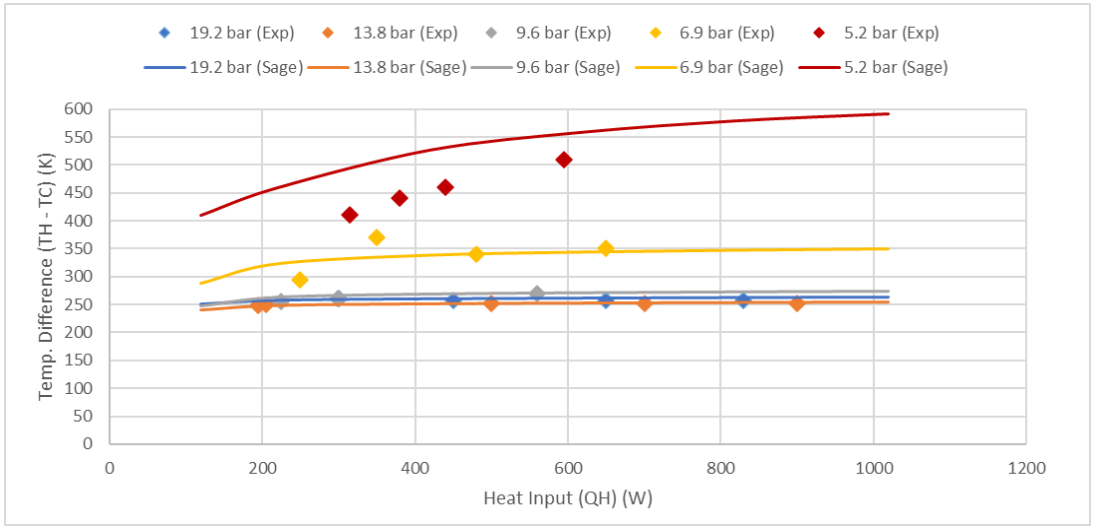

Figure 5(b)

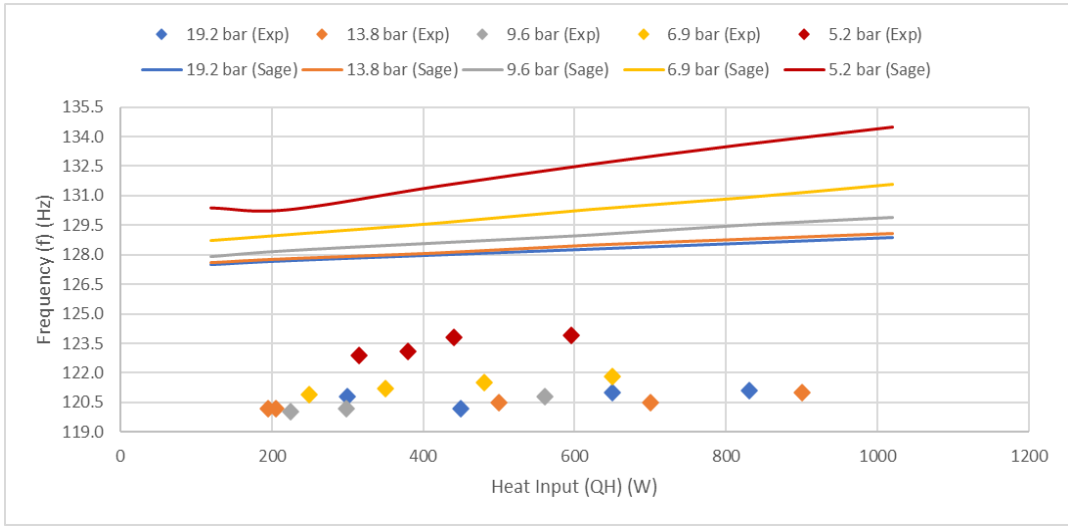

Figure 5(c)

Figure 5. Standing-wave TASE Sage Results; (a) pressure amplitude against heat input, (b) Temperature difference against heat input (c) operating frequency against heat input

Results: *Standing-wave TASE DeltaEC vs Sage*

- **Pressure Amplitude:**
  - DeltaEC predicts higher amplitudes
  - Deviation increases with higher mean pressures
- **Frequency:**
  - Sage predicts higher values
  - Different distribution of energy/losses

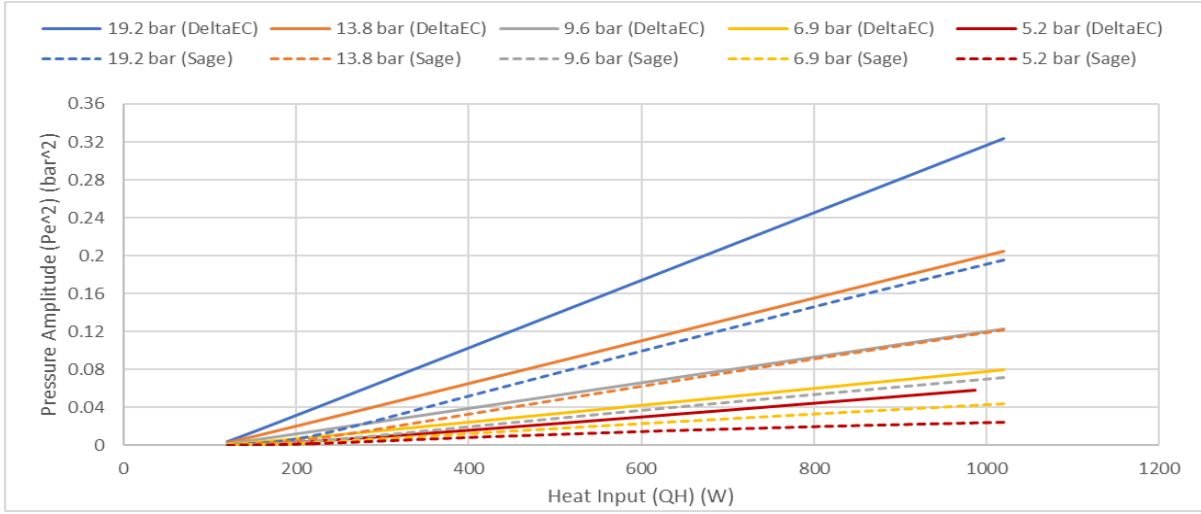

Figure 6(a)

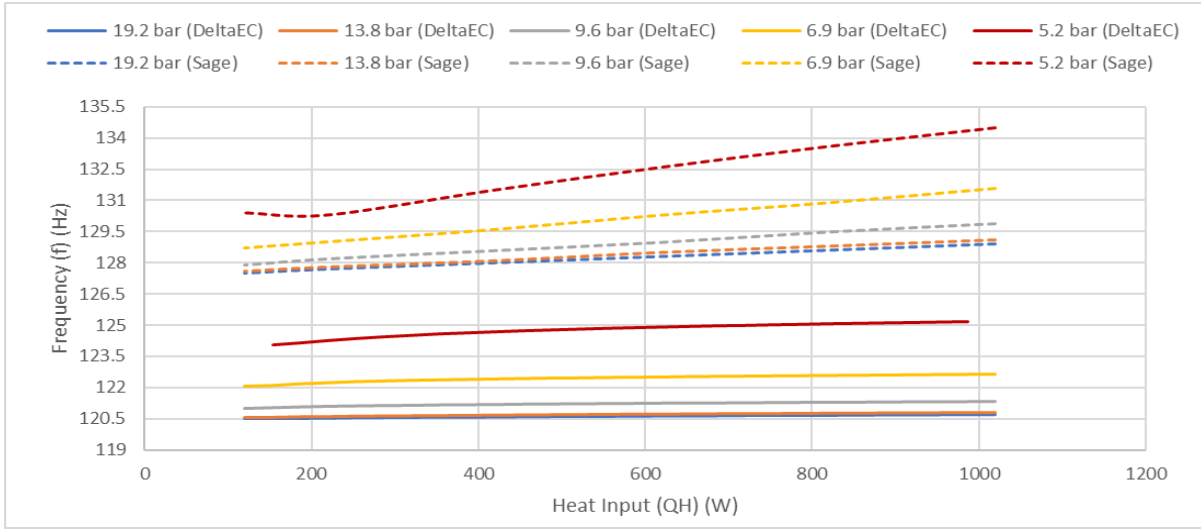

Figure 6(b)

Figure 6. Standing-wave TASE DeltaEC & Sage Results; (a) pressure amplitude against heat input, (b) operating frequency against heat input

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Results: Standing-wave TASE DeltaEC vs Sage

- Phase unchanged by heat input & mean pressure
- Anomaly for 6.9 bar (DeltaEC)
- Phase close to 90 degrees
- Phase directions opposite

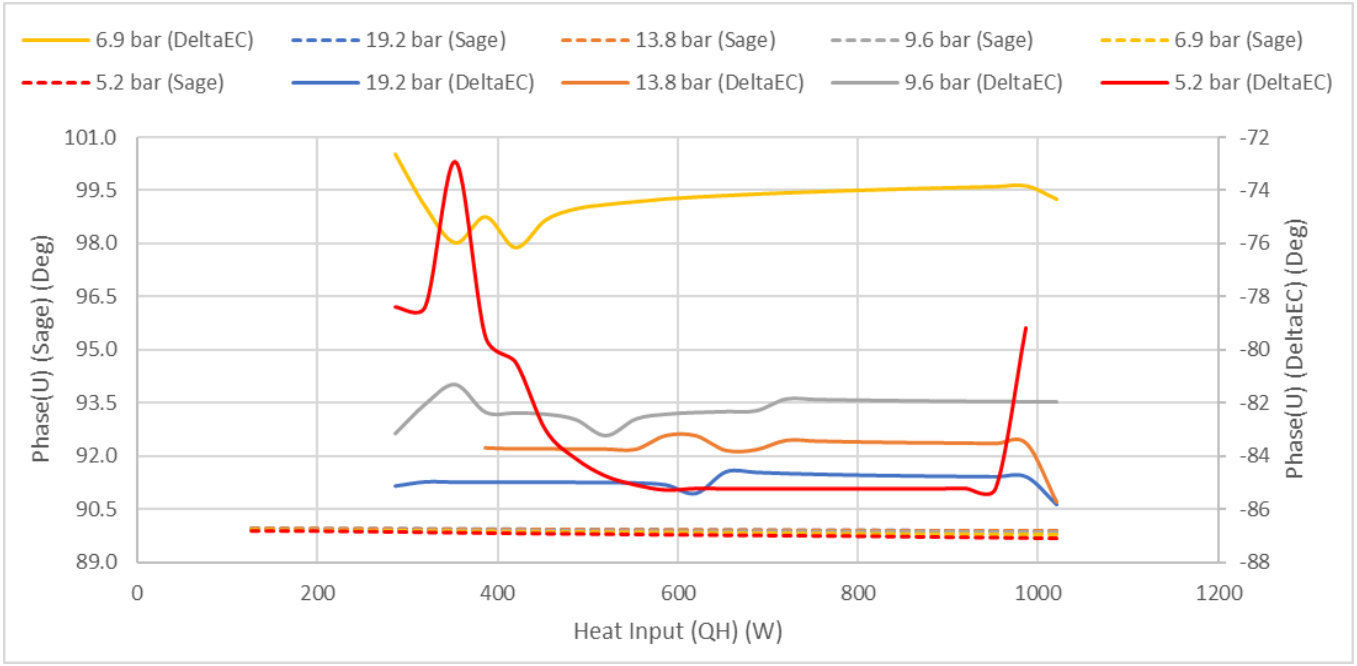

Figure 7. Phase of the volume velocity (Cold End) against heat input

Results: Travelling-wave TASR DeltaEC Vs Sage

- **Length of Regenerator:**
  - Cooling Power & COP decreases, Utilisation rate increases with length
  - Sage shows less drastic change in COP
  - Sage predicts smaller Utilisation rate values

- **Diameter of Regenerator:**
  - Cooling Power & Utilisation Rate increases, COP decreases with length
  - Sage predicts higher COP
  - Sage predicts smaller Utilisation rate values

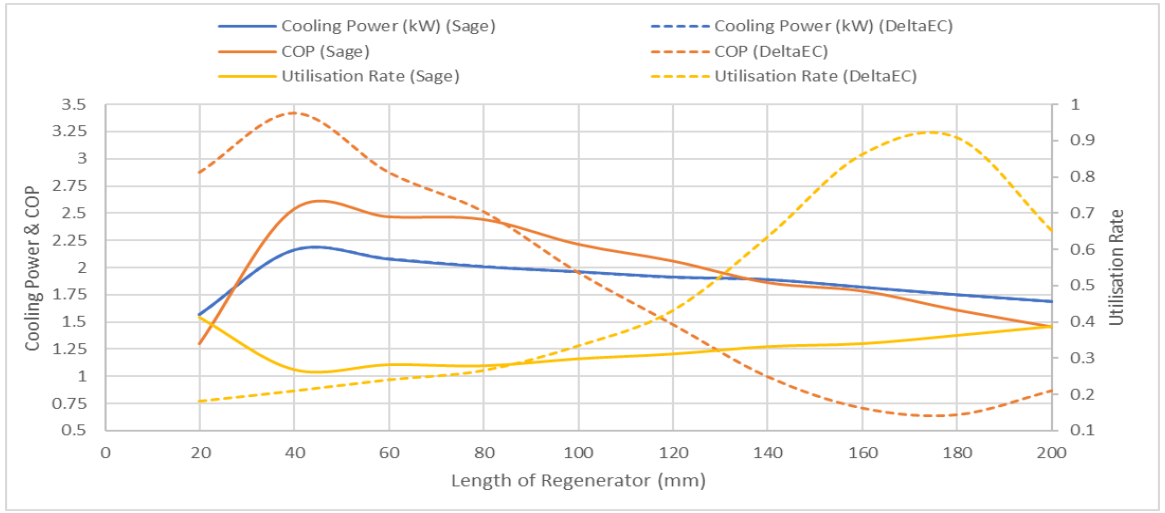

Figure 8(a)

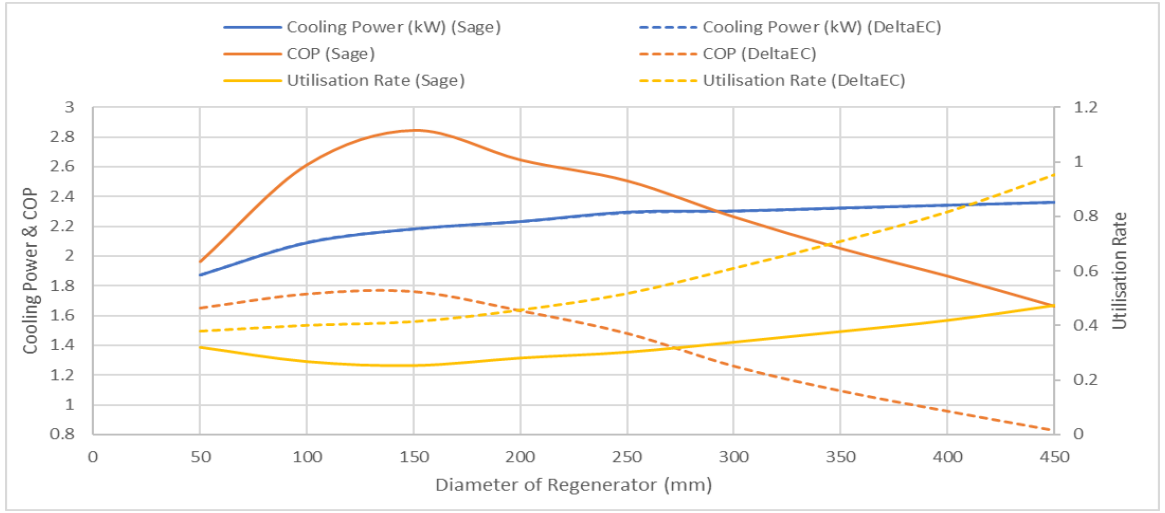

Figure 8(b)

Figure 8. Travelling-wave TASR results for DeltaEC & Sage; cooling power, COP & Utilisation Rate against regenerator (a) length, (b) Diameter

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Results: Travelling-wave TASR DeltaEC Vs Sage

- **Length of Regenerator:**
  - Magnitude increases with length
  - Sage predicts nearly constant positive phase
  - DeltaEC predicts negative direction

- **Diameter of Regenerator:**
  - Magnitude increases with diameter
  - Sage predicts nearly constant positive phase
  - DeltaEC predicts negative direction

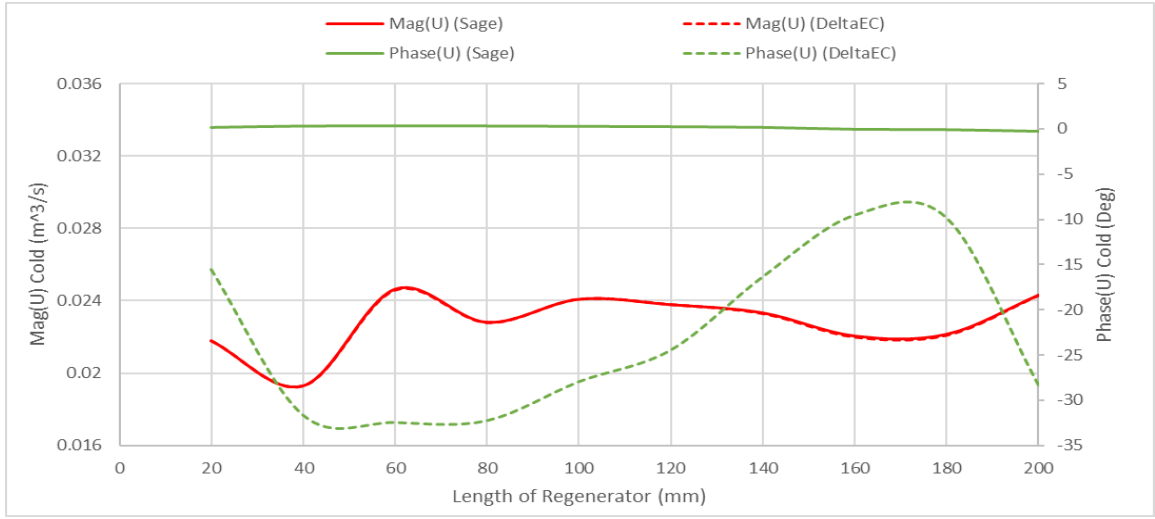

Figure 9(a)

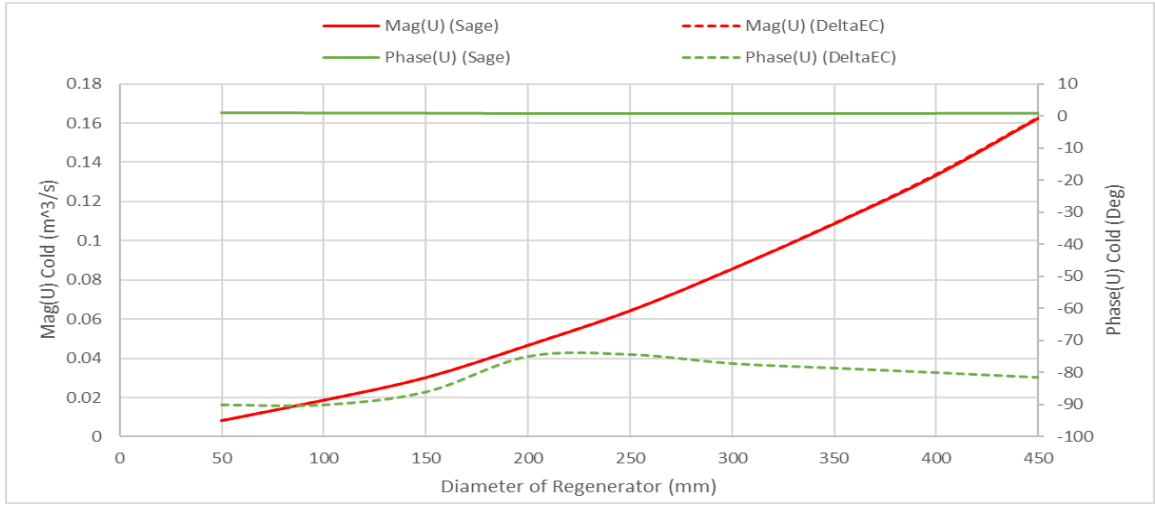

Figure 9(b)

Figure 9. Magnitude & Phase of the volume velocity (Cold End) against regenerator (a) length, (b) diameter

Summary

Conclusions:

- **DeltaEC & Sage Software:**
  - Successful models for Standing & travelling-wave
  - Different Optimal conditions

- **Numerical Modelling Tools:**
  - Analysis of complex geometries/optimisation with minimal cost
  - Future improvement in performance

Thank you!

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