# Experimental Testing of a Thermoacoustic Thermal Management System

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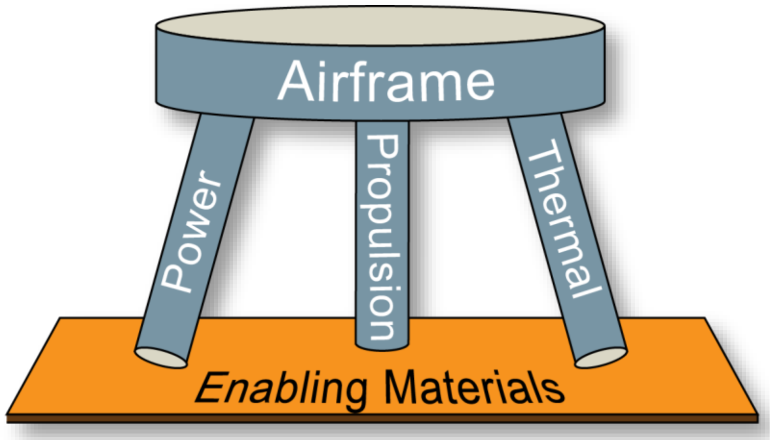
# Agenda

- Electric Aircraft Thermal Management Need
- High and Low Exegetic Sources
- Basics of Thermo-Acoustic Engine and Heat Pump
- Sage Modeling Software
  - Sage:  How Software Works
  - Sage:  Solving and Optimizing
- Instrumentation
- Test Campaign
  - 5 m Duct Transitions
- Heat Pump Temperature Distribution – 0.2 m Duct
- Heat Pump Temperature Distribution – 5 m Duct 90° Elbow
- Heat Pump Temperature Distribution – 5 m Smooth Duct
- Heat Pump Temperature Distribution – 10 m Duct
- Conclusion
- Current and Ongoing Testing
- Acknowledgements

# Electric Aircraft Thermal Management Need

| Thermal Management Technology | Disadvantage |
|---|---|
| Ram air HX | Adds weight, aircraft drag, displaces fuel capacity |
| Convective skin cooling HX | Adds weight, drag, and requires liquid pumping losses |
| Sinking heat into fuel | Limited thermal capacity due to coking and volume |
| Sinking heat into lubricating oil | Limited thermal capacity, Low delta T adds HX mass |
| Active cooling | Reduces propulsive efficiency, Adds weight and maintenance |
| Phase change cooling | Limited thermal capacity, Adds weight |
| Heat Pipe, Pumped Multiphase | Does not increase Exergy which impacts mass and efficiency |

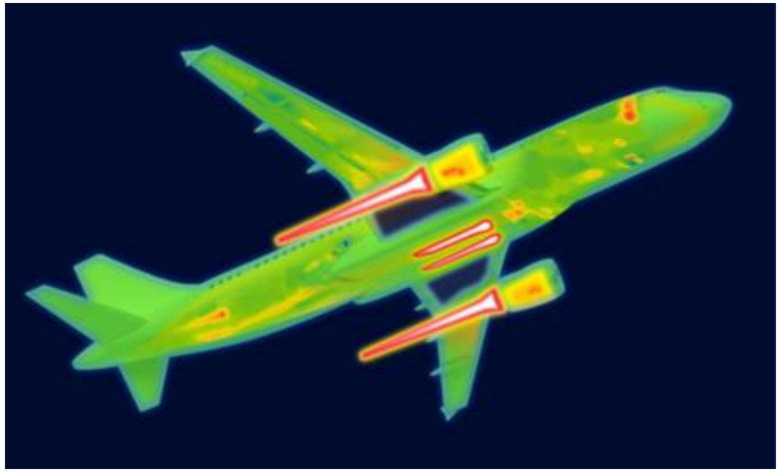
**(Dyson, 2020)**




**Preferred technology** :

- improves fuel efficiency,
- reduces emissions,
- removes heat from:
  - small core engines, more electric composite aircraft, and high-power electric propulsion systems
- reduces vehicle mass
- reduces thermal signature for military

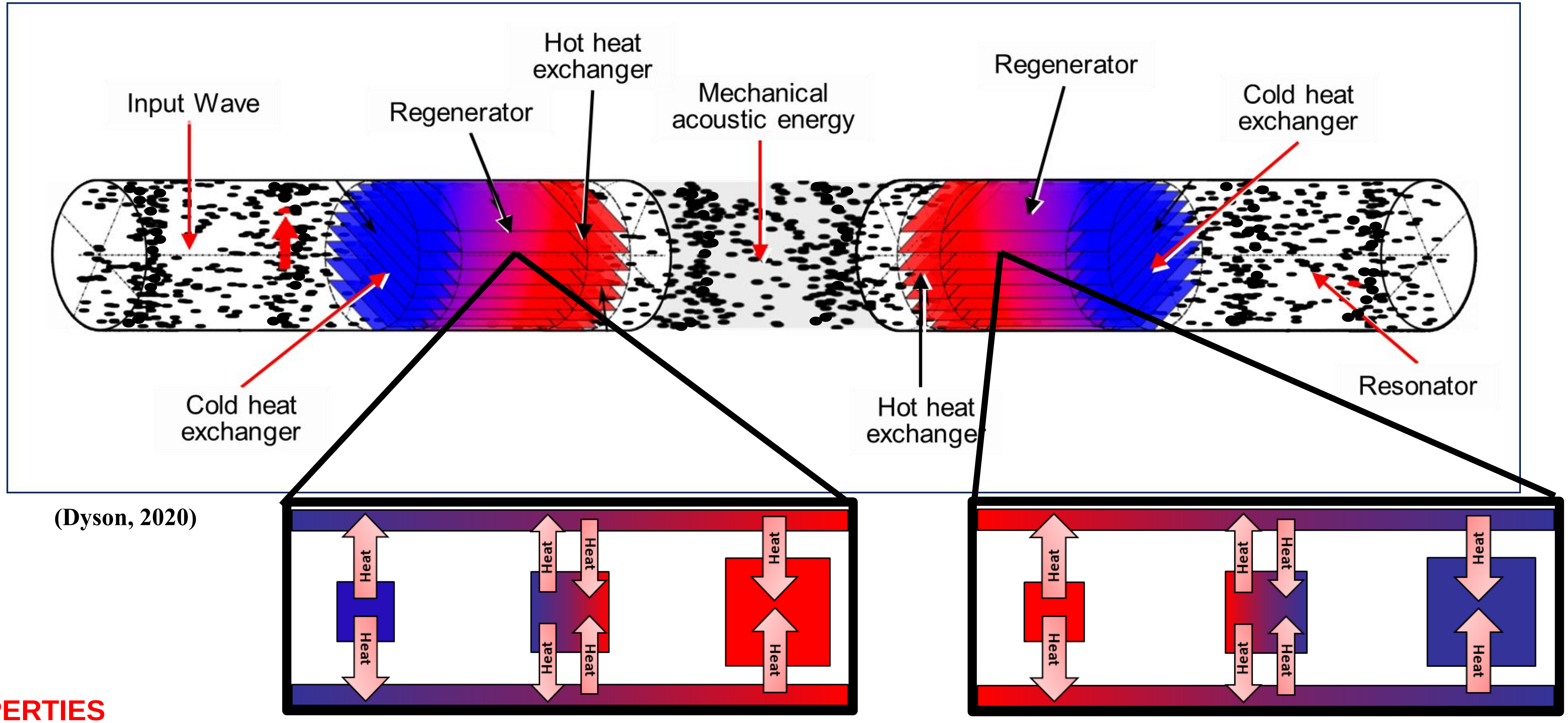
# High and Low Exegetic Sources



(Dyson, 2020)

| Beneficial Uses of Higher Exergy Waste Heat from Powertrain | | |
|---|---|---|
| **Sink Location** | Sink Temperature (°C) | Benefit |
| **Engine Core** | 600 | Recuperates engine and powertrain heat for efficiency |
| **Engine By-pass** | 100 | Increases thrust with P-51 effect |
| **Outer Mold Line** | 200 | De-icing, Anti-icing, Turbulent Boundary Layer Mgmt |
| **Auxiliary Power Unit** | 400 | Provides electrical power from waste heat |
| **Cabin** | 40 | Provides cabin heating without bleed air from turbine |
| **Battery** | 20 | Maintains batteries above freezing |
| **Oil Coolant Loop** | 100 | Smaller heat exchanger required due to higher temp. |
| **Ram Air** | 100 | Smaller heat exchanger required due to higher temp. |

# Basics of Thermo-Acoustic Engine and Heat Pump




(Dyson, 2020)

**KEY PROPERTIES**

**Can be used for thermal energy conversion:**

- **From heat to mechanical power**
- **From mechanical power to cooling**
- **From heat engine to heat pump when used in double configuration shown**

# Sage Modeling Software

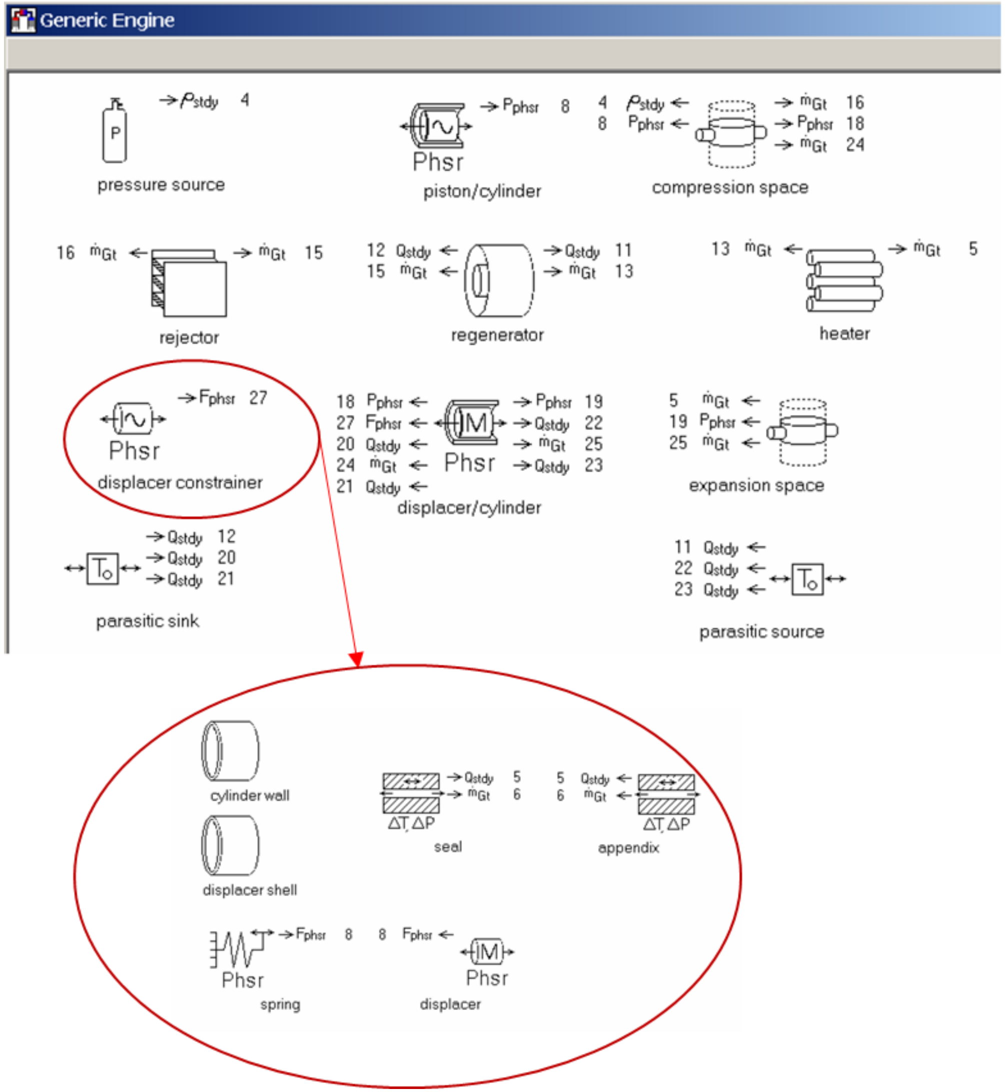
- Sage is a one-dimensional object-oriented software package used for modeling and optimizing Stirling converters
  - Sage is the successor to Globally-Implicit Stirling Cycle Simulation (GLIMPS) and GLIMPS Optimization (GLOP) software created by Gedeon Associates
  - Sage is a Delphi application running under Microsoft written in Pascal (Delphi Language)

- A Sage model instance contains generic Stirling and crycooler components from three main model classes
  - Three main model classes: the stirling-cycle model class, the pulse-tube model class and the low-T cooler model class

- Sage does the following (Quotes are from Sage Website):
  - "Allows a user to create a custom engineering model by graphically selecting component parts from a palette, dropping them into a window and connected them together as required."
  - "Manages the interconnected system of components so the user can easily change data inputs, solve the underlying equations of the system and view the results."
  - "Supports interactive system-wide optimization of an arbitrary set of input variables subject to an arbitrary number of constraints (nonlinear equality or inequality) with an arbitrary objective function to be minimized or maximized."

# Sage : How Software Works

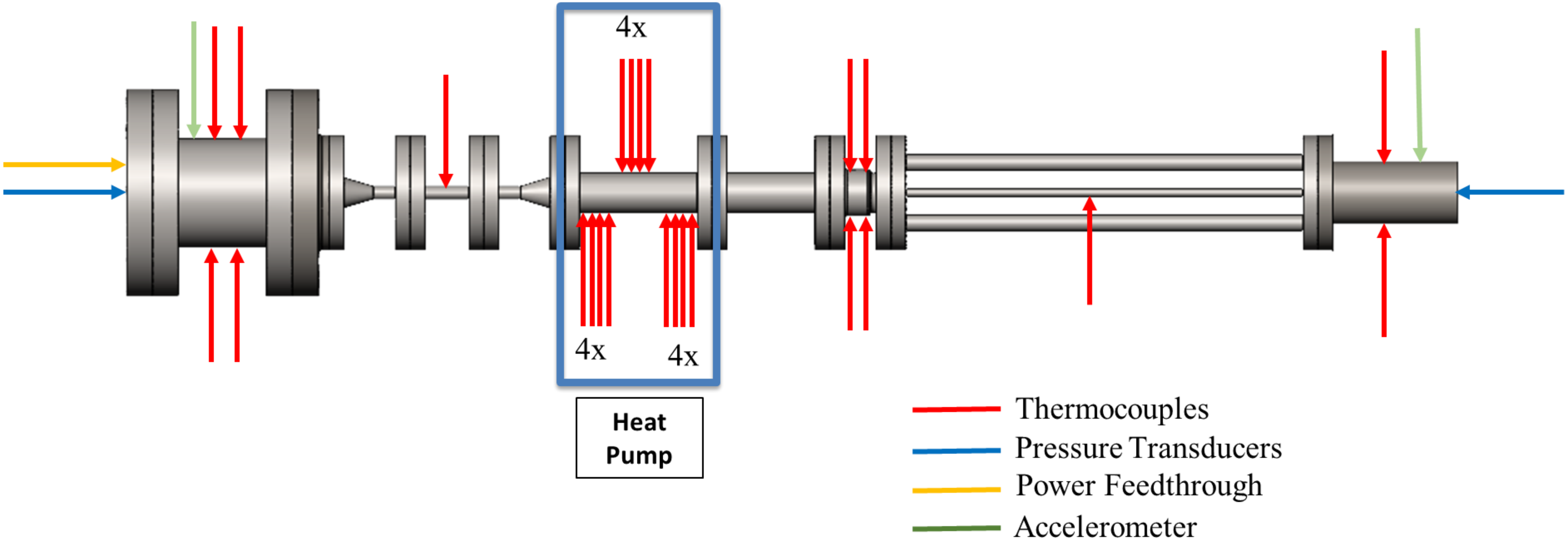
- Components within the Sage library are built upon hierarchal layers
- At the root level, components are represented as a physical part with underlying sub-systems
- Numbered arrows represent boundary connectors across which the components transfer information
  - Labels on arrows represent what type of data is being transferred between components
  - In general, boundary connections transfer forces, pressures, heat flow, or mass flow



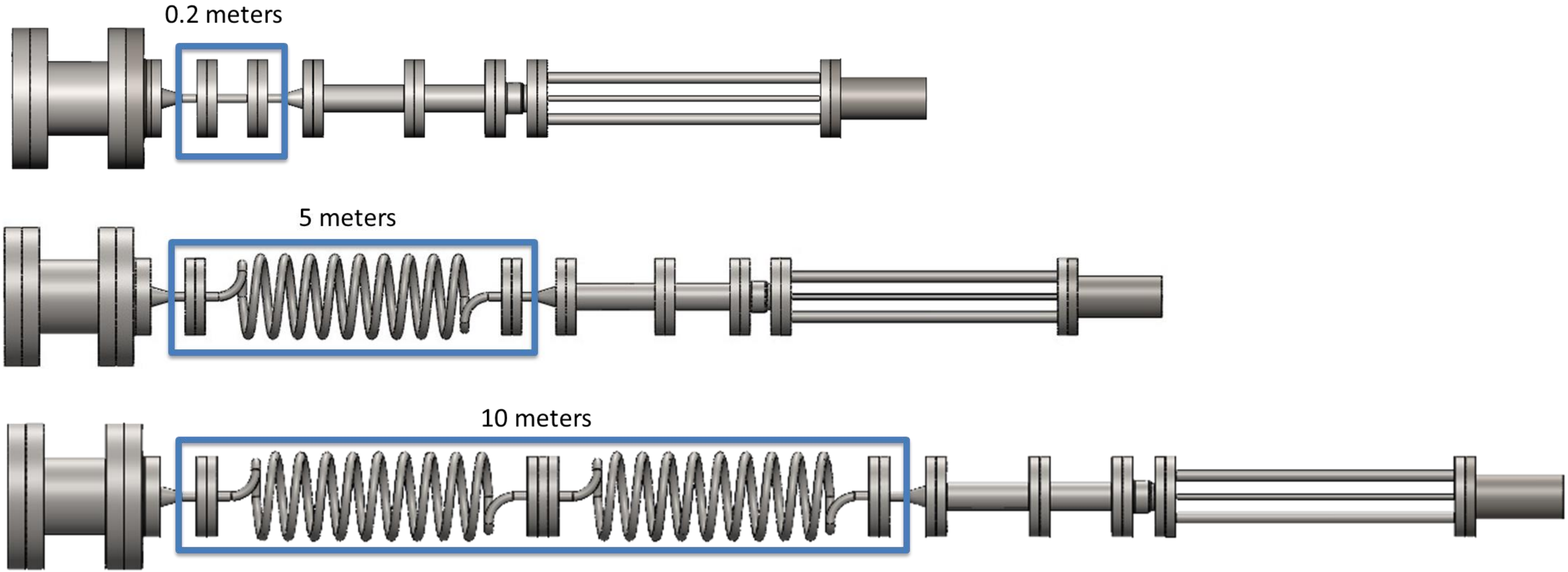
# Sage : Solving and Optimizing

- Solving
  - Simultaneously and implicitly solves for periodic solution on all space and time notes of its computational grid.
  - Third order model: Uses nodal analysis or control volumes to solve governing 1D equations
  - Performed by a non-linear solver
    - ✓ Non linear solver performs its duties by solving a sequence of linear approximations to the model equations, basically performing Newton's Method
    - ✓ The coefficients of the linearized equations result from numerical partial derivatives taken with respect to the equation's implicit variables
    - ✓ Equations where implicit variables $(\rho, \rho u A, \rho e)$ are determined are Conservation of Continuity, Momentum, and Energy
- Optimizing
  - A nonlinear optimizer employs a variation of Powell's sequential quadratic-programming method (*M.J.D. Powell ,A Fast Algorithm for Nonlinearly Constrained Optimization Calculations*)
  - Optimization in Sage GUI is performed by:
    - ✓ A set of independent optimized variables
    - ✓ Arbitrary of inequality/equality constraints to be satisfied
    - ✓ Objective function to be minimized or maximized

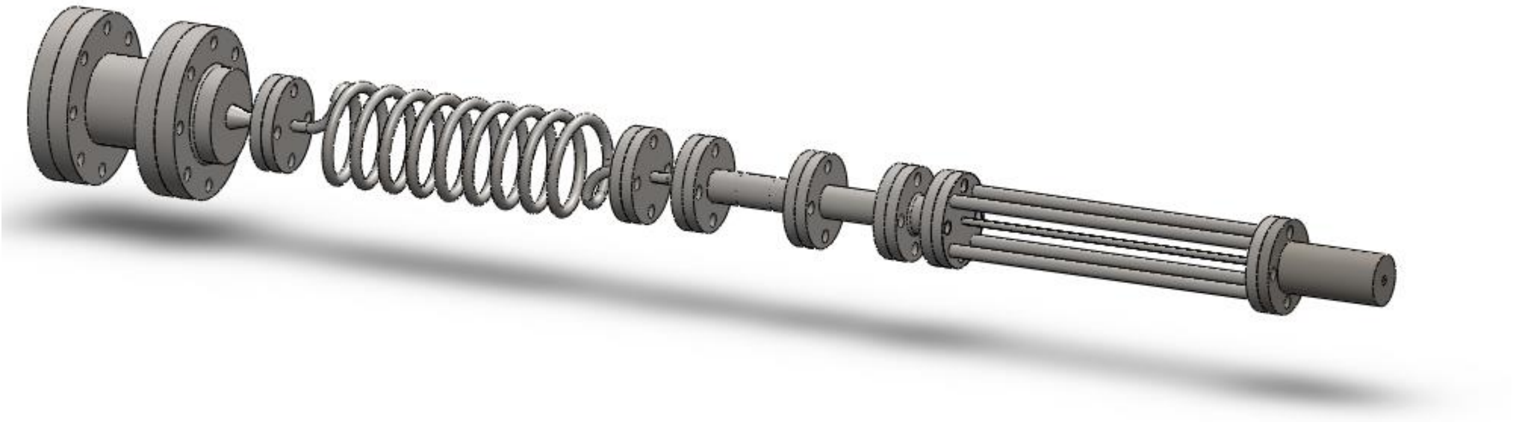
# Instrumentation

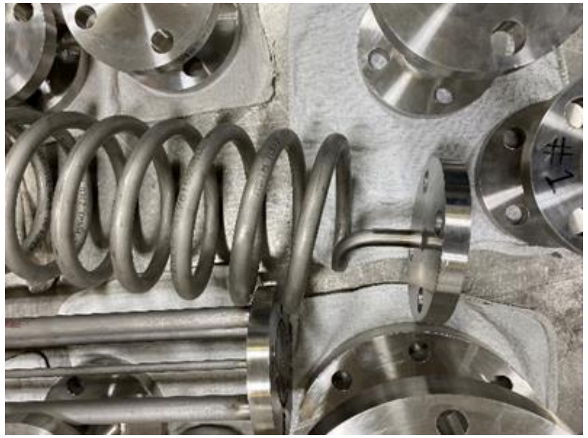


# Test Campaign

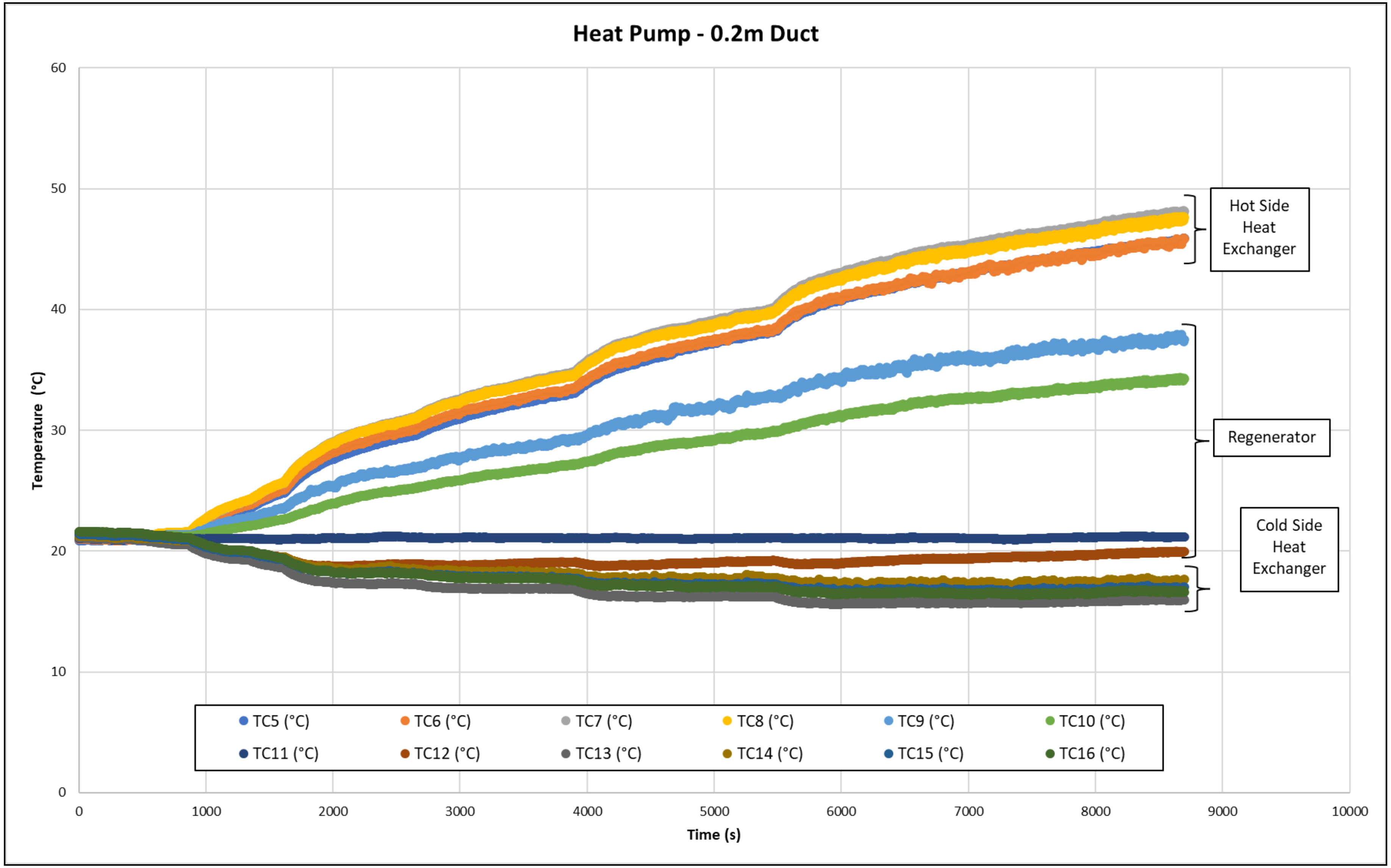


# 5m Duct Transitions



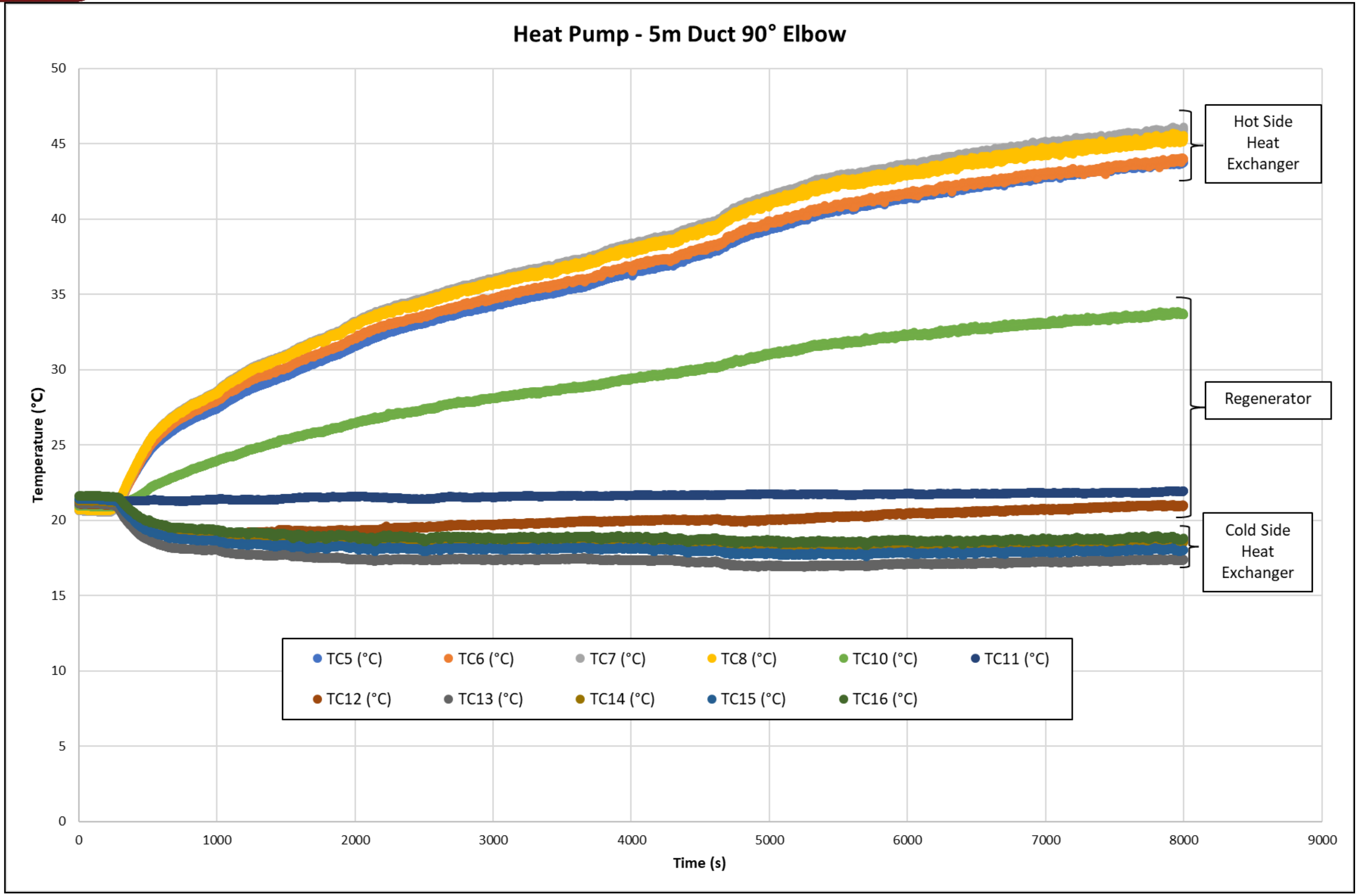


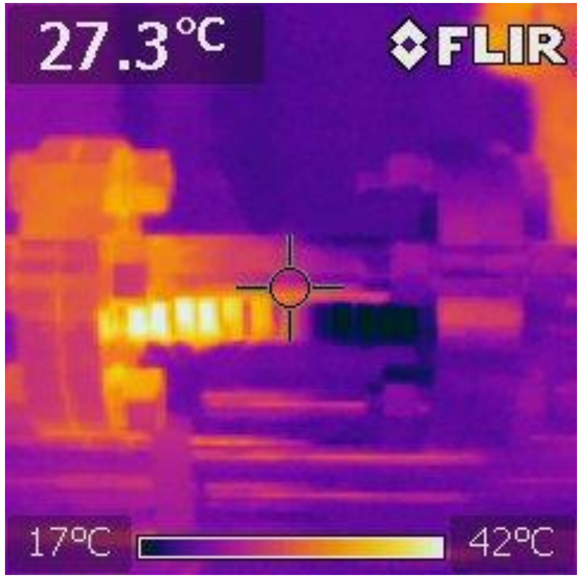
# Heat Pump Temperature Distribution – 0.2m Duct

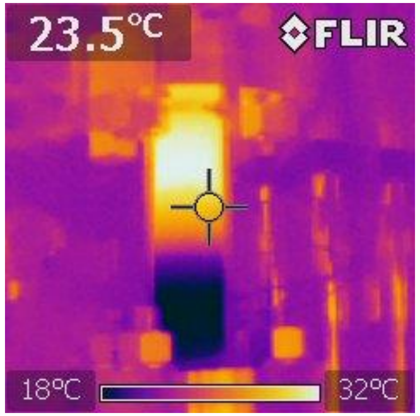



| Maximum Temperature (°C) | Minimum Temperature (°C) | Δ Temperature (°C) |
|---|---|---|
| 48.14 | 15.93 | 32.22 |

# Heat Pump Temperature Distribution – 5m Duct 90° Elbow

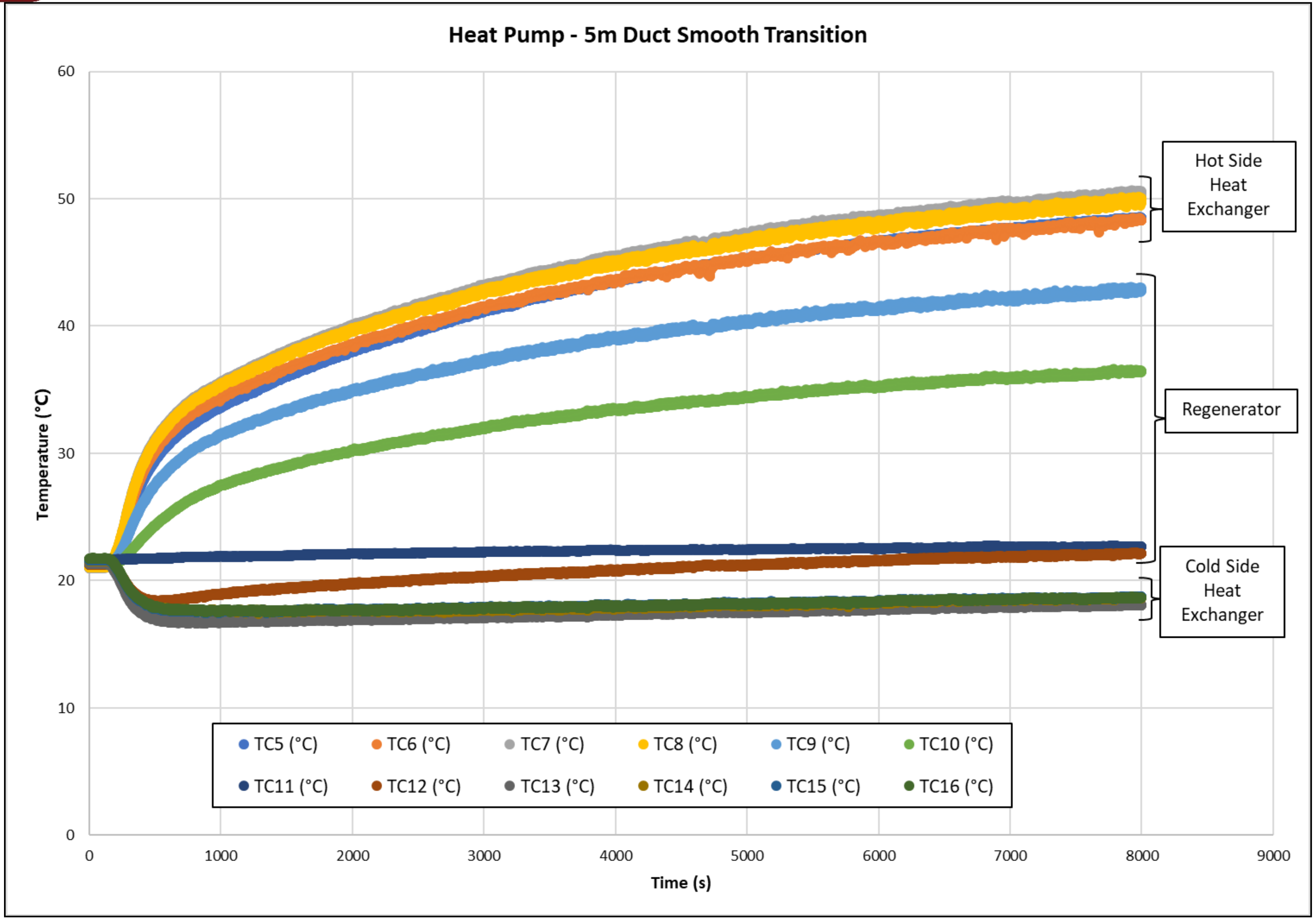


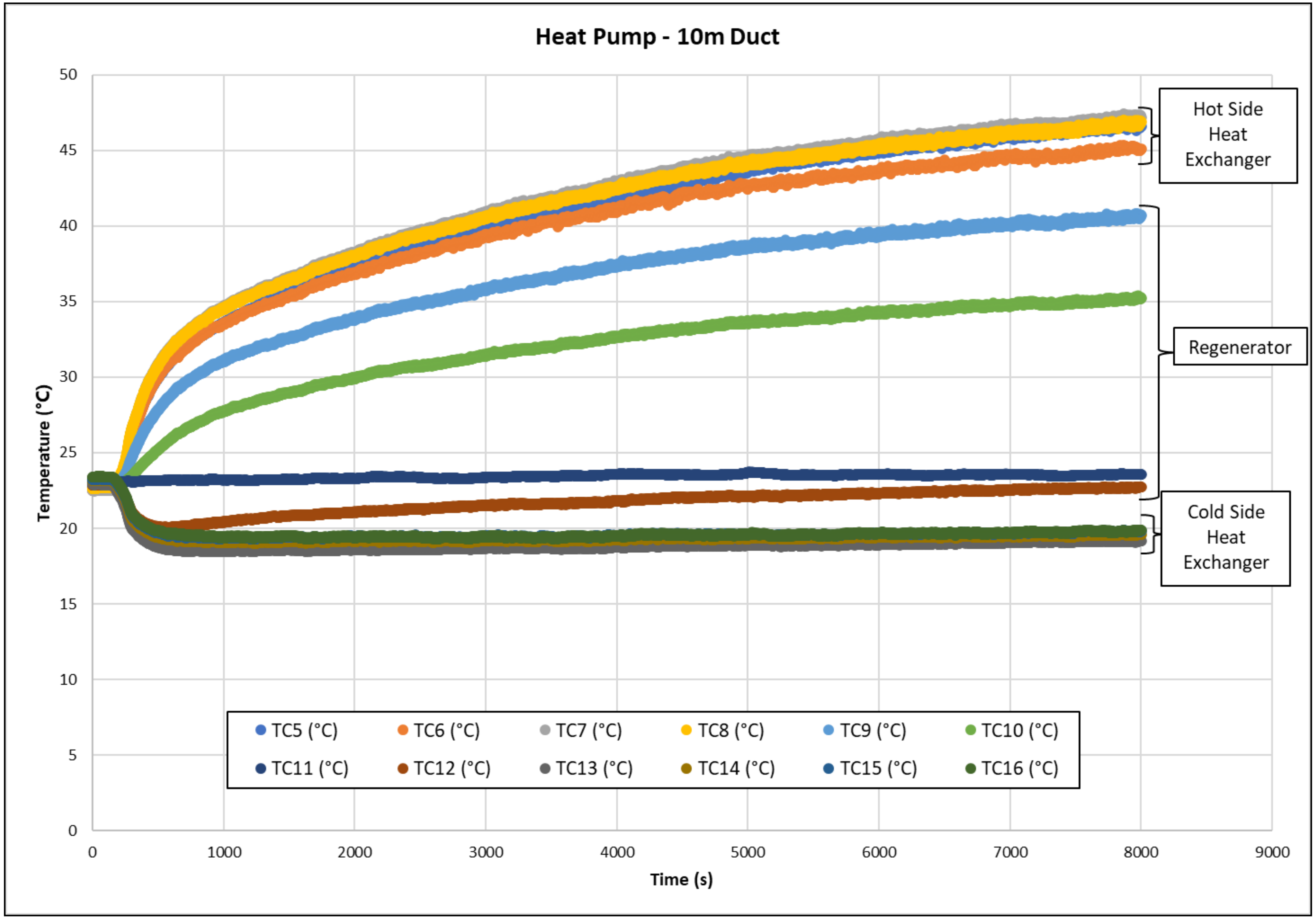

| Maximum Temperature (°C) | Minimum Temperature (°C) | Δ Temperature (°C) |
|---|---|---|
| 45.99 | 17.39 | 28.60 |

# Heat Pump Temperature Distribution – 5m Smooth Duct



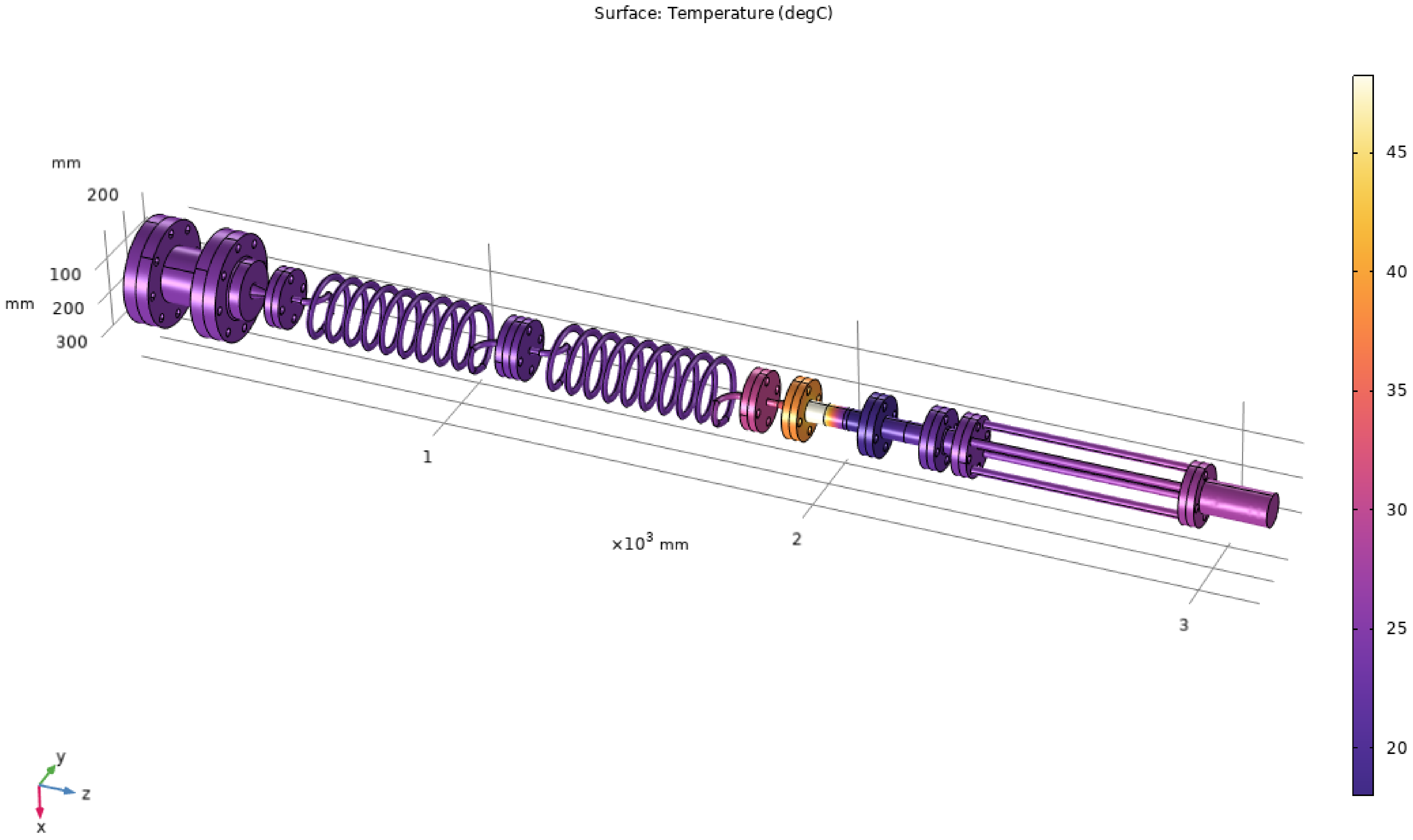

| Maximum Temperature (°C) | Minimum Temperature (°C) | Δ Temperature (°C) |
|---|---|---|
| 50.47 | 18.09 | 32.38 |

# Heat Pump Temperature Distribution – 10m Duct




| Maximum Temperature (°C) | Minimum Temperature (°C) | Δ Temperature (°C) |
|---|---|---|
| 47.21 | 19.16 | 28.04 |

# Temperature Distribution – 10 m Duct



# Conclusion

- A traveling-wave thermo-acoustic rig was designed and built at NASA GRC as a novel thermal management solution for electric aircraft.
- Experimental results show minimal acoustic power degradation between 0.2 m, 5 m, and 10 m distances.
- 90° turns in the thermoacoustic heat pump can degrade acoustic power.
- Heat Pump deltas where between 28.04 °C and 32.38 °C
- This technology can also be customed for space applications

# Current and Ongoing Testing

- Perform longer tests until steady-state is reached
- Add heat engine to amplify acoustic power
- Using Optical methods to visualize wave patterns and to further understand underlying physics

# Acknowledgments


- Don Fong, Casey Theman, Frank Lam, Frank Gaspare, and David Hausser provided an immense amount of technical and hands-on support
- Advanced Cooling Technologies (ACT) – Through a SBIR Phase III program, built a full scale thermoacoustic heat pump (TAHP) for both cooling and thermal energy delivery