Lightweight Recuperator for FTT’s Advanced Engine Concept

Design and fabrication of a recuperator demonstrator

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Overview

• Introduction
• Heat Exchangers
• Waste Heat Recovery Recuperator
• Demonstrator Build
• Conclusions
Introduction

- **Objectives:**
  - Design a lightweight recuperator applicable to FTT’s Advanced Engine Concept
  - Perform a mock build of a recuperator demonstrator

- **What is heat transfer?**
  - The process of heat exchange between two fluids operating under different temperatures
  - A device that implements this process is a heat exchanger

- **What is a recuperator?**
  - Waste heat recovery heat exchanger
  - Utilizes the hot turbine exit gases to heat a portion of cooler compressor discharge air and returns it to the combustor
  - Reduces heat losses and therefore increases efficiency
Heat Exchangers

• Note the temperature differentials between the fluids. The parallel flow heat exchanger has excellent heat transfer in the entry but quickly diminishes downstream.
• Heat transfer in the counter flow scheme is maximized along the entire length of the heat exchanger and provides consistent heat transfer per unit length.
• These differences are due to the fact that there is a continuous supply of “fresh” fluid entering in opposite ends of the heat exchanger.
Heat Exchanger: Effectiveness @ Cr = 1

Where \( C_{\text{min}} / C_{\text{max}} \) are functions of fluid properties and mass flow rate.

To achieve the same effectiveness as a counter flow heat exchanger, the sizing of the cross flow and parallel flow heat exchangers would have to increase.

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By increasing $A$, it will increase the effectiveness and size of the recuperator.
• **Past Studies**
  – Analysis of a 90% effective Vick recuperator
  – An optimized 90% effective recuperator based off the pattern below
    • Too large and heavy for aerospace applications
    • 33.6” x 33.6” x 16” and weighed over 1100 lbs

• **Present Work**
  – Redesigned for 50% effectiveness
    • 10.75” x 10.75” x 4.70”
    • Weighing about 40 lbs without manifolding

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Recuperator

• **How does it work?**
  – Withdraws compressor discharge air and is flowed counter to the turbine exhaust gases drawn in from the other side

• **Past Studies:**
  – Vick’s 90% effective recuperator designed for a 3 kW, 2:1 pressure ratio microturbine
  – Flat plate, counter flow design
    • 60 panels, 0.25 mm thick, spanning 65 mm total

• **New Design for the Advanced Engine Concept**
  – Designed for 10:1 pressure ratio between channels
  – Internal structure must be robust while maximizing surface area
  – New array consisting of circular and “+” shaped channels
This redesigned high density recuperator utilizes “+” shaped hot flow channels to maximize heat transfer to the cold flow tubes while offering structural rigidity.

The Vick recuperator, below, offers improved effectiveness in a small package but the flat plate design would deform under the 10:1 pressure ratio.
Recuperator Design

- Developed a spreadsheet that incorporated laminar flow theory into a 1-D heat transfer analysis for a counter flow heat exchanger

- **Inputs:**
  - Temperature
    - Turbine Exhaust
    - Compressor Discharge
  - Pressure
    - Turbine Exhaust
    - Compressor Discharge
  - Mass flow rate
  - Axial Length
  - Geometric Parameters
    - Wall thickness
    - Cold flow cross-sectional area

- **Outputs:**
  - Thermal Efficiency (Effectiveness)
  - Cold air and hot gas exit temperature
  - Pressure Loss
  - Cold air and hot gas exit pressure
  - Discretized Sections
    - $Re, f, HTC, FP-Ps, M, P/P$
  - Minimum number of required channels
  - Surface Areas
  - Volume
  - Mass and Weight
Recuperator: Design Parameters

- Key relationships
  - \( q_{\text{convection}} = hA\Delta T \)
  - \( q_{\text{conduction}} = \frac{kA}{t} \Delta T \)
  - \( q_{\text{overall}} = UA\Delta T_{lm} \)
  - \( T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \)
  - \( NTU = \frac{UA}{\dot{m}C_P} \)
  - \( UA = \frac{1}{\frac{1}{h_cA_c} + \frac{1}{k_wA_w} + \frac{1}{h_hA_h}} \)
  - \( Re_D = \frac{\rho UD}{\mu} = \frac{4\dot{m}}{\pi D \mu} \)
  - \( Nu = \frac{h_D}{k} = 4.36 \) for constant heating
  - \( \varepsilon = \frac{T_{c,0} - T_{c,i}}{T_{h,i} - T_{c,i}} \)
Designing the Recuperator

Effectiveness

NTU

Design point: NTU = 1, \( \varepsilon = 0.50 \)

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1-D Heat Transfer Prediction

Initial Conditions and Inputs

- Hot gas inlet
- Cold Air Inlet
- ΔT, ΔP
- ΔT, ΔP
- ΔT, ΔP
- ΔT, ΔP

Hot Gas Outlet

- P/P
- HX Sizing

Post Processing

Compute Re, f, HTC, FP-Ps, M, and P/P for each stage

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The resulting code gives temperature data, as well as other information, for each section from inlet to outlet.

Efficiency:
• 57%

Pressure Drop:
• 2% P/P through both channels

Thermal Resistances:
• 43% from the hot gas to the wall
• 56.3% from the cold gas to the wall
• 0.7% Conductive resistance through the wall
Demonstrator Build

- **Demonstrator Part**
  - For the feasibility and thermal performance tests, only a small portion was needed for the build
  - Consisted of 12 x 82 cold flow channels

- **Base Material**
  - Acrylic based polymer

- **Process**
  - Fabricated using FTT’s SLA printer
  - Feasibility test for Direct Metal Laser Sintering (DMLS) which would be used to build the actual part
  - A process that prints thin layers of plastic with wax to support the internal structure
  - Wax must be drained once the build is complete

- **Pros/Cons**
  - SLA is much more cost effective than DMLS for an experimental part
  - Provide clues for underlying problems with the part geometry
  - Acrylic has a low melting temperature
  - Reduced temperature range for testing

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SLA Fabrication: Results

• By inspection:
  – Internal geometry in the recuperator section was maintained
  – Wax was not able to drain from the small channels
  – Deformations in the manifolding resulting from capillary action
  – Collapse of the hot gas channels
  – Not enough internal supports to maintain the geometry
Results

Solutions:

• Added extra material for handling purposes
• Added external and internal ribs to support the rectangular channels
• Modified the manifolds to allow for easy removal of wax material
• Solvents may be used to aid in the removal of excess wax
Results

• The 2nd trial showed much improvement
  – Added supports prevented collapsing
  – Modified manifolds enabled the residual wax to drain properly

• Areas for improvement
  – Selected material is inherently weak and may not handle the pressures
  – Difficult to completely remove the residual wax.
Future Work

• Thermal Performance Testing
  – Increase hole size to maintain better tolerances
  – Increase wall thickness to improve strength

• Performance and Weight Optimization

• Determine efficient manifolding scheme to the Advanced Engine Concept

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Conclusion

- Learned the pros and cons of various heat exchanger designs
- Outlined the important concepts and design procedures for a lightweight recuperator
- SLA Model
  - Learned the capabilities of the machine
  - Addressed the problem areas for future projects
  - DMLS is feasible, the part must be properly supported to prevent the part from deforming
- More design work and testing needed

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