Design of a Heat Exchanger for Intense Cooling of Inlet Bleed Air at High Mach Numbers

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Heat Exchanger Solution

- HX using cryogenic fuel one possible way to cool bleed air
- Original designed by NASA Glenn Research Center for a Proof-of-Concept test
- Radial heat exchanger uses LH$_2$ as working fluid
  - Radial HX only for POC test
  - 3-D printed
- Liquefy and/or Cool Bleed Air at High Temperature and Low Pressure
- Design feasibility and efficiency is unknown

Fig 1. Original Heat Exchanger Design$^4$
Original HX Design

- LH2 moves inward against bleed air flow, making 7 passes
- Tubes positioned at 45° relative to air flow

Fig 2. Side View of 36° Slice Showing Air and LH2 Paths

Fig 3. Top View of Original HX Showing 45° Tube Angle
Approach

• Assess performance of Original Design & Improve it
  • Design of flight HX and vehicle trade study outside the scope of this study
• Method: Computational Fluid Dynamics
  • Tools:
    • SolidWorks Flow Simulation
    • ANSYS Fluent
  • Performance Metrics:
    • Average Air Outlet Temperature
    • Heat Transfer Rate from Air
    • Heat Exchanger Efficiency
    • Number of Elements that reach Liquefaction Temperature

\[
\dot{Q}_h = \dot{m}_h c_{p,h} (T_{h,\text{in}} - T_{h,\text{out}})
\]

\[
\eta = \frac{\dot{Q}_{\text{actual}}}{\dot{Q}_{\max}}
\]
Twisted Tube Cross-Sections
TwistP1, Brick Velocity and Temperature Contours

Straight Brick

TwistP1 Brick

Straight Brick

TwistP1 Brick

**Velocity Contour**
- 66.64
- 62.72
- 58.80
- 54.88
- 50.96
- 47.04
- 43.12
- 39.20
- 35.28
- 31.36
- 27.44
- 23.52
- 19.60
- 15.68
- 11.76
- 7.84
- 3.92
- 0.00

**Temperature Contour**
- 300.00
- 283.73
- 267.46
- 251.19
- 234.92
- 218.65
- 202.38
- 186.11
- 169.84
- 153.56
- 137.29
- 121.02
- 104.75
- 88.48
- 72.21
- 55.94
- 39.67
- 23.40

[m s\(^{-1}\)]

[K]
TwistP1, Leaf Velocity and Temperature Contours
COMPARISON METRICS
Average Outlet Temperature for Each Configuration

\[ \dot{Q}_h = \dot{m}_h c_{p,h}(T_{h,in} - T_{h,out}) \]
Heat Transfer Rate for Each Configuration

\[ \dot{Q}_h = \dot{m}_h c_{p,h}(T_{h,in} - T_{h,out}) \]
Efficiency for Each Configuration

Calculated $\eta$: If 100% Air Cooled to 64.5K: $Q_{\text{max}} = 4,040\text{W}$

Absolute $\eta$: If 100% Air Cooled to 20K: $Q_{\text{max}} = 4,800\text{W}$
Histogram: Percent of Elements per Temperature

15 Degrees

45 Degrees

75 Degrees

Brick
Histogram Percent of Elements per Temperature

Leaf

TwistP1

TwistP2
Key Findings

1. Configuration TwistP1 (Pitch = 52mm) provides best HX performance based on 1) Air Outlet Temperature, 2) Heat Transfer Rate of Tube Walls, 3) Percent Element Below Tliq

2. Straight Angled Tube Configurations (including Original Design) perform worse according to (1-3) than twisted designs

3. According to (3), Leaf performs nearly as well as TwistP1 and better than TwistP2, and may be the more practical configuration in terms of ease of fabrication
Future Work

- Two-phase flow simulation
  - Determine appropriate hydrogen flow rate
- Fabrication techniques (3-D Printing Preferred)
  - Structural analysis
- Design of compact on-board HX
  - Parametric study of other geometry variables (tube size, spacing, etc.)
  - Trade between HX weight and bleed duct weight
  - System analysis to study overall vehicle benefit
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References


