Design of a Test Rig to Simulate Flow Through a Ribbed Cooling Passage

Todd Beirne, Rob Bellonio, Susan Brewton, Avery Dunigan, Jeff Hodges, Scott Walsh, Al Wilder
Advisor: Dr. Karen Thole
Graduate Assistant: Evan Sewall
Mechanical Engineering Dept.
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This design builds on thermo-fluids principles and previous research

Background and Motivation for Design

Review of Existing Test Rigs

Overview of Final Rig Design
The Brayton Cycle remains the basis for the modern gas turbine engine.

The material melting points limit the rotor inlet temperature and engine performance.

Average inlet temperature: 3000°F
Melting point of metal: ~2400°F
The drive to increase inlet temperatures leads to innovative blade design

Improved materials
External film cooling
Internal cooling channels

Internal channels have ribs that create complex flow and enhance cooling

Two problems with ribs:
- Flow behavior difficult to model
- Lack of detail limits prediction ability
We want to create a large-scale environment that simulates the flow

Our clients include researchers, the government, and the engine industry
This design builds on thermo-fluids principles and previous research

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Overview of Final Rig Design

The arrangement of the ribs in the channel can be defined with several parameters

Aspect Ratio = H:L

Re = \frac{D_L V}{\nu}

\alpha

P
Han studied the heat transfer and friction in channels with two opposite rib-roughened walls

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Test Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>P/e</td>
<td>10&gt;P/e&gt;40</td>
</tr>
<tr>
<td>e/Dh</td>
<td>0.021 &gt; e/Dh &gt; 0.063</td>
</tr>
<tr>
<td>alpha</td>
<td>90</td>
</tr>
<tr>
<td>Re</td>
<td>7K &gt; Re &gt; 90K</td>
</tr>
<tr>
<td>Entrance L</td>
<td>20Dh</td>
</tr>
<tr>
<td>Test L</td>
<td>20Dh</td>
</tr>
</tbody>
</table>

Focus: The effect of entrance conditions on the heat transfer coefficient
Features: Constant wall heat flux
Unheated Ribs

Watanabe and Takahashi simulated and measured a fully developed ribbed channel flow

Focus: Flow and heat transfer measurements
Features: Constant heat flux on bottom wall only
Top wall held adiabatic

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Test Values</th>
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<tbody>
<tr>
<td>Aspect Ratio</td>
<td>2:1</td>
</tr>
<tr>
<td>P/e</td>
<td>10</td>
</tr>
<tr>
<td>e/Dh</td>
<td>0.10</td>
</tr>
<tr>
<td>alpha</td>
<td>90</td>
</tr>
<tr>
<td>Re</td>
<td>100,000</td>
</tr>
<tr>
<td>Entrance L</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Test L</td>
<td>0.55 m</td>
</tr>
</tbody>
</table>

[Han, 1984]
[Watanabe and Takahashi, 2002]
Past research provides some guidance for the parameters of our test stand

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Past Research Parameters</th>
<th>Virginia Tech Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio</td>
<td>0.5-1</td>
<td>1:1</td>
</tr>
<tr>
<td>P/e</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>e/Dh</td>
<td>0.021-0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>alpha</td>
<td>30, 45, 60, 90</td>
<td>90</td>
</tr>
<tr>
<td>Re</td>
<td>240 -100K</td>
<td>10K-100K</td>
</tr>
<tr>
<td>Entrance Length</td>
<td>0-20Dh</td>
<td>10Dh</td>
</tr>
<tr>
<td>Test Section Length</td>
<td>7-20Dh</td>
<td>15Dh</td>
</tr>
<tr>
<td>Average Temp. Difference</td>
<td>15-30C</td>
<td>10-15C</td>
</tr>
</tbody>
</table>

This design builds on thermo-fluids principles and previous research

- Background and Motivation for Design
- Review of Existing Test Rigs
- Overview of Final Rig Design
Our design allows the study of flow and thermal patterns in a ribbed channel

The size of the fan must overcome the pressure losses through the system
Two main options exist to determine the flow rate of the air in the channel:

- **Venturi Tube**
  - 10% permanent pressure loss
  - High cost ($900)

- **Orifice Plate**
  - 44% permanent pressure loss
  - Low cost ($250)

A circuit diagram helps to visualize system losses.

\[
\Delta P_{\text{total}} = \rho \sum k_i \frac{V_i^2}{2} + \rho \sum f_i \frac{L_i}{D_i} \frac{V_i^2}{2} + \sum \Delta P_{\text{other}}
\]
Review of the literature suggests a friction factor for 2-wall ribbed channels

\[ f = \frac{Hf_s + Wf_r}{H + W} \]

[Han 1984]

\[ f_r = \frac{2}{\left[0.95(P_e)^{0.53} - 2.5\ln \left(\frac{2e}{D_e} - 2.5 - 2.5\ln \left(\frac{2W}{H + W}\right)\right)\right]^2} \]

[Han 1984]

The system characteristic curve was used to select the fan
Air flow can be controlled through a variety of options

- **Damper**: Low cost, but will change system curve
- **Inlet Guide Vanes**: Low cost, but low resolution of control
- **Motor Speed Control**: High cost, but highest resolution of control

Several components following the fan cool the air and create uniform flow

Flow direction: Back to fan
Air from the fan passes through a diffuser to prepare flow for conditioning

3–Dimensional diffusion to shorten length
7° diffusion to avoid flow separation

Vendor: Spiral Manufacturing Co., Inc., Minneapolis, MN

A heat exchanger is required to remove thermal energy added by the test section and the blower

Test Section
\[ T_s = \frac{q}{\rho QC_p} + T_i \]

Blower
\[ T_s = \frac{q}{\rho QC_p} + T_i \]

Heat Exchanger
\[ q = \rho QC_p(T_s - T_i) \]
Heat exchanger reduces incoming air temperature to room temperature

Performance Requirements

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat Load, q</strong></td>
<td>1100 - 3600 W</td>
</tr>
<tr>
<td><strong>Air Flow, Q</strong></td>
<td>0.047 – 0.36 m³/s</td>
</tr>
<tr>
<td><strong>Face Velocity, V</strong></td>
<td>0.20 – 1.6 m/s</td>
</tr>
<tr>
<td><strong>Entering Air Temp</strong></td>
<td>30 - 39 °C</td>
</tr>
<tr>
<td><strong>Exiting Air Temp</strong></td>
<td>20 °C</td>
</tr>
<tr>
<td><strong>Water Flow, Q</strong></td>
<td>2 GPM</td>
</tr>
<tr>
<td><strong>Entering Water Temp</strong></td>
<td>16 °C</td>
</tr>
<tr>
<td><strong>Exiting Water Temp</strong></td>
<td>24 °C</td>
</tr>
</tbody>
</table>

Vendor – Super Radiator Coils: Richmond, VA

Liquid cooled – Tap water
Limited fouling with water at 2 GPM

Honeycomb and screens straighten the air flow to establish a uniform velocity profile

Modular design uses:
- Various types of screens
- Optional turbulence grid
- Multiple number of screens
Nozzle contracts flow creating a uniform velocity profile at the entrance plane

3-D contraction
Contraction Ratio = 10:1

The test section provides access for flow and heat transfer measurements

Flow direction: Back to fan
Length:
- 15 cm
- 15 cm
- 1.5 m
- 2.25 m
ANSYS provided the necessary analysis to validate the rib design

The final rib design provided a uniform heat flux
Insulation helps keep the heat flux inside the test section

The heat transfer testing depends on a uniform heat flux on the channel walls
Estimating surface heat transfer is essential for accurate power supply design

Heat flux is dependent on the convection coefficient and temperature difference

\[ q'' = h(T_s - T_m) \]

Convection coefficient is based on Nusselt number for turbulent flow in a smooth pipe

\[ Nu = 0.023 \left( \frac{Re}{D} \right)^{4/5} \Pr^{0.4} \]

Hydraulic diameter and thermal conductivity influence heat transfer

\[ h = \frac{k \times Nu}{D_h} \]

Heat fluxes in test section are estimated to be larger than for smooth pipe

Previous research indicates that ribbed surfaces create higher Nusselt numbers
The amount of power needed for each heated surface will be different.

Higher Reynolds numbers increase heat transfer. Ribbed wall requires a majority of power.

The heater strips are connected in series to create the proper resistance.

\[ R_t = \frac{1}{\frac{1}{\text{strip}} \times 8 \text{ strips}} = 8 \Omega \]

\[ R_t = \frac{1}{8 \times \left( \frac{1}{1 \Omega} \right)} = 0.125 \Omega \]
Sufficient power must be produced to heat the test section surfaces

Commercial DC power supplies are available but are too costly

Homemade power supplies are difficult to make for the high power requirements

Variable transformers are relatively cheap and provide a high levels of power

A rectifying circuit provides direct current to the heating elements
The Unistrut system provides a strong and adaptable structural support for the test rig.

In summary, our rig design will help researchers better understand flow inside turbine blades.

Questions?

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