Preliminary Experimental Design of a Gas Turbine Compressor Stator Heat Exchanger

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Preliminary Experimental Design of a Gas Turbine Compressor Stator Heat Exchanger

A National Center for Sustainable Transportation Research Report

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Nomenclature

T  Temperature
T₀  Initial temperature
P  Pressure
P₀  Initial pressure
Nₙ  Number of stages
γ  Specific heat ratio
Q  Heat transferred
M  Mass
cₚ  Specific heat capacity
h  Average convective heat transfer coefficient
Aₚ  Surface area of heat transfer
ΔT  Difference in temperature
1. Introduction

1.1 Background

Gas turbines are commonly used in aircraft applications due to their high power to weight ratios [1]. Demand is ever increasing for gas turbines which are more efficient and produce fewer emissions, without compromising safety and reliability. Typical simple cycle gas turbines have efficiencies between 21 and 45 percent [2]. This is due to two substantial losses of energy: the back work necessary to operate the compressor, and the heat lost from the exhaust [3].

Gas turbines are composed of five main sections, operating based on the principles of the Brayton Cycle [4]. Air is drawn into the gas turbine through the air inlet. In the case of a turbofan engine, a large fan is driven in the inlet region to draw air into and around the compressor [2]. The air then enters the compressor, which increases its temperature and pressure [1]. Next, the pressurized air is mixed with fuel in the combustion chamber and the mixture combusts [2]. The hot exhaust gas enters a turbine, where it is expanded to provide thrust and to do work [1]. Exhaust is expelled out the back of the turbine. Figure 1 shows a simplified diagram of a gas turbine, showing each of these sections.

![Figure 1. Sections of a simple cycle gas turbine (Brayton Cycle)](image)

The work herein relates to the compressor section. Axial compressors, the most common type of compressor in gas turbines, accelerate the inlet air with spinning rotors [2]. The air is pushed onto stationary stator vanes, which diffuse the air, converting the velocity into pressure [2]. A set of a rotor and a stator is called a stage, and this process is repeated across multiple stages in a typical axial compressor. Equation 1 demonstrates the relationship between pressure and temperature in a compressor. Figure 2 shows the changing velocity and pressure as a result of this compression.
This work is related to the Fuel-Integrated Energy Recuperative Aeroderivative (FIERA) project at the Energy Research Laboratory. One of the main goals of the FIERA project, outlined in the FIERA Project Proposal [3], is to research the effectiveness of heat extraction at various stages of compression, as shown in Figure 3. Previous work on FIERA, performed by researcher Steven Wong, shows that compressor based heat exchangers could yield as much as a 6.08% improvement in overall efficiency [5].

Back work to operate the compressor typically accounts for over 50 percent of the work done by the turbine [6]. This research investigates a method of extracting heat from the compressor to decrease the back work, transferring this heat to the fuel flowing through the interior of the hollow compressor stators. The back work is decreased by increasing the combustion air density for compression. As shown in step 1 of Figure 3, heat is exchanged between the hot air flowing across the stators and the fuel flowing within the stators. In present-day applications, cooling the compressor is far less common than cooling the turbine components. Thermal degradation is not as significant a concern in the compressor as it is in the turbine, which operates at a much higher temperature [7]. As a result, much less research has been done in the past regarding the use of compressor heat exchangers and hollow compressor stators.

\[
T = \frac{T_0}{N_s} \left[ \left( \frac{P}{P_0} \right)^{\frac{y-1}{y}} - 1 \right] + T_0
\]

Equation 1 [2]
1.2 Objectives of Present Work

The goal of this project is to analyze the thermodynamic and heat transfer properties of a heat exchanger system within the compressor section of a gas turbine. This involves three major tasks: preliminary design and simulation of a compressor stator, fabrication of the stator, and development of experimental processes and controls.
2. Methods and Results

2.1 Design

The stator is 160 mm in length, with a 41 mm chord and an aspect ratio of 3.9, shown in Figure 4. These dimensions are similar to that of an early stage compressor stator in a General Electric CF6 turbofan gas turbine [8]. Given that this stator is hollow, a wall thickness of 0.76 mm was chosen, which correlates to standard gauge 22 sheet metal. This gauge is thin enough to allow substantial fluid flow, yet strong enough to not plastically deform under pressure loads up to 84 kPa, simulated using Finite Element Analysis (FEA) and discussed in further detail in section 2.2.

The airfoil shape is a NACA 65 airfoil. It was chosen after consideration of three possible designs [9], compared in Figure 5. The NACA 65 airfoil was chosen for a few reasons: precedent, as many compressor stators historically use this airfoil shape [10]; suitability for use as a hollow stator due to its larger cross-sectional area; and good performance in preliminary FEA simulations.

Figure 4. Dimensions and shape of stator model (not to scale)

Figure 5. Comparison of three airfoil shapes with hollow cross-sections

2.2 Modeling and Simulations

Modeling was accomplished using SolidWorks Computer Aided Design (CAD) software. The stator profile was sketched and then extruded. A 5 mm cross-section of the model was created to reduce computational times, which was then exported as an IGS file.

Since the General Electric CF6 has a 17-stage compressor with a compression ratio of 28:1 [11], calculations were made to determine the expected changes in pressure and temperature. Assuming that the change in pressure is constant between stages, this pressure change was determined by multiplying standard atmospheric pressure by the compression multiplier, then
dividing by the number of stages. Associated temperatures for each stage were calculated using Equation 1.

This results in a change in total pressure between stages of 167 kPa, a maximum temperature of 488 °C at the 17th stage, and the change in temperature rising with respect to the stage number.

ANSYS Fluent Computational Fluid Dynamics (CFD) software was used to test some basic conditions and to validate the design. The IGS file was imported into ANSYS DesignModeler. Then, a mesh was created with 386,574 elements. A sample velocity of 260 m/s was applied on the concave portion of the stator, at an angle of attack of 20 degrees, a typical angle in gas turbine compressor design [2]. The results of this CFD study confirmed that the distribution of pressure hitting the stator is not uniform. The data from ANSYS Fluent was then imported into Microsoft Excel, which provided a polynomial line of best fit to represent the distribution of pressure. This graph is shown in Figure 6.

Returning to SolidWorks, the pressure distribution equation was used in an FEA pressure simulation. Note that this simulation only accounts for pressure, neglecting any other loads which may be transferred through the stator. The FEA results in Figure 7 show that this stator design is satisfactory given the expected pressures, with a safety factor of 1.16.

2.3 Fabrication

Materials are an important consideration. Stainless steels are an obvious choice for stators due to their high heat tolerance and high strength, and martensitic 403 grade stainless steel has been a traditional choice for compressor blades [12]. For this study, 304 grade stainless steel was chosen, since it is widely available and has suitable properties. Table 1 compares different grades of stainless steel. Various types of coatings are commonly used as well [12], though that is beyond the scope of this work.
Table 1. Stainless Steel Grades and Their Properties [13] [14]

<table>
<thead>
<tr>
<th>Material</th>
<th>Max temperature (°C)</th>
<th>Melting temperature (°C)</th>
<th>Yield strength (MPa)</th>
<th>Hardness</th>
<th>Elongation</th>
<th>Composition (approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>304 SS</td>
<td>921</td>
<td>1371</td>
<td>207</td>
<td>Rockwell B 92</td>
<td>40%</td>
<td>Cr-20 Ni-12</td>
</tr>
<tr>
<td>309 SS</td>
<td>1050</td>
<td>1371</td>
<td>207</td>
<td>Rockwell B 96.4</td>
<td>40%</td>
<td>Cr-23 Ni-13</td>
</tr>
<tr>
<td>403 SS</td>
<td>704</td>
<td>1495</td>
<td>207</td>
<td>Rockwell B 98</td>
<td>25%</td>
<td>Cr-12 Mn-1</td>
</tr>
<tr>
<td>455 SS</td>
<td>1100</td>
<td>1400</td>
<td>772</td>
<td>Rockwell B 106</td>
<td>12%</td>
<td>Cr-12 Ni-8 Cu-2</td>
</tr>
</tbody>
</table>

Various methods of fabrication were considered:

- Investment casting is typically used for fabrication of hollow turbine components [15]. This could be an excellent option, given the proper equipment.
- Additive manufacturing is a newer method, using laser metal deposition [15]. This method looks promising and would have been the preferred fabrication method for this project. Unfortunately, the lack of access to such technology makes this option inaccessible.
- CNC milling from a solid block was also considered. This would be difficult, since the large aspect ratio of the stator makes it impossible for a small enough endmill to reach the hollow inner area.

Given the aforementioned difficulties, sheet metal fabrication was chosen. Two pieces of sheet metal were cut to size on a sheet metal shear, then deformed using a 3D printed mold. Each piece of sheet metal was pressed between two plastic molds which fit together, as shown in Figure 8. A steel reinforced epoxy, rated at sufficiently high temperature and pressure specifications, was used to bond the pieces into their final form. The finished stator is shown in Figure 9.
2.4 Experimental Design

The experimental procedure will involve flowing hot, compressed air over the stator at various angles of attack. Meanwhile, fuel will flow through the hollow stator. In initial tests, water will be used instead of fuel. Thermocouples and pressure indicators will be placed before and after the stator, on both the air and the fuel sides, to analyze changes in temperature of the air as well as the fuel. The piping and instrumentation diagram (P&ID) for this experimental setup is shown in Figure 10.

Figure 10. Piping and instrumentation diagram (P&ID) for the experimental setup
Conductive and convective heat transfer will be analyzed. Conductive heat transfer occurs through the stator, from the outer edge to the inner edge. Convective heat transfer occurs from the air to the outer edge of the stator, and from the inner edge of the stator to the fuel. Equation 2 can be used to calculate the enthalpy change of the fluid stream, and Equation 3 can be used to calculate the steady state heat transfer across the stator. Three iterations must be solved, accounting for each of the three heat transfer occurrences.

$$Q = m \ c_p \Delta T$$  \hspace{1cm} \text{Equation 2 [16]}

$$Q = h \ A_s \Delta T$$  \hspace{1cm} \text{Equation 3 [16]}

A clear experimental enclosure was built using polycarbonate sheets, shown in Figure 11a-b. The pieces were cut to size and joined with epoxy. The removable side pieces, which are used to hold the stator in place at a specified angle of attack, are made of acrylic and were cut on a CNC laser machine. Different side pieces can be switched out to test different angles of attack. Future work will involve fabrication of another enclosure of the same design, using 304 stainless steel, to be used for the actual experimentation. A CAD model is shown in Figure 11c.

![Figure 11a. Polycarbonate experimental enclosure](image1)

![Figure 11b. Laser cut removable side pieces](image2)

![Figure 11c. CAD model of the experimental enclosure](image3)
2.5 Assumptions

The proposed experiment is presumed to be quasi-isobaric. In a compressor with multiple rotors and stators, a pressure increase will occur after the air is pushed onto the stators. However, in this experiment, no practical pressure rise is expected to occur, since only one stator is used.

3. Conclusion

In an effort to increase the efficiency of existing gas turbine designs, work on the FIERA project is ongoing. As one part of this project, a new compressor stator design has been created, utilizing hollow stators to preheat the fuel using the hot air from the compressor. The design was formulated using CAD software and preliminary simulations were run using FEA and CFD. The stator was fabricated, and an experimental setup was designed. Future work will involve implementation of the experimental procedure and analysis of the results.
4. References


