Natural Cooling Thermal Analysis of the High Pressure Rotor of an Aero-Engine: a Preliminary Study

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ABSTRACT
A preliminary study on the shutdown cooling process of the high pressure rotor of a gas turbine is launched in this paper. A simplified 2D model, with relatively small computational power requirements, is applied to evaluate the asymmetric temperature distribution during the shutdown process. The results show a slight increase in metal temperatures and later a gradual decrease in temperatures due to “heat soak” effect. It is observed that the maximum asymmetric temperature difference occurs at the 6th stage compressor disk.

In order to validate the CFD solutions presented in this work, a vertical placed HPT casing model was run following the same process as for the large model. The solution was then compared with experimental results. The comparison demonstrates reasonable agreement, with the CFD results being approximately 20K cooler than the experimental results after 1 hour.

INTRODUCTION
Due to the slower cooling of the top half and a relatively faster cooling of the bottom half, gas turbines can suffer from differential thermal expansion during the cooling process after shutdown, known as thermal bow. Attempts to start a gas turbine in this bowed condition can lead to rotor-to-stator contact, trigger further heating, and subsequently further bow, which can result in severe damage to the engine. Thus, it is very important to understand the shutdown phenomena as it has significant influence on the safety of turbine components.

Gabriel M. et al. [1, 2] presented a 2D numerical procedure for the assessment of the thermal regime during natural cooling. The concept of the cooling calculation is to replace the steam gross buoyancy during the gland steam ingestion phase by an equivalent fluid conductivity, which gives the same thermal effect on the metal parts.

After engine shutdown, temperature and pressures of fluid trapped in gas turbine rises due to heat received from metal, after the engine is turned off. This effect is dominant on temperature distribution for few minutes/hours after the engine is turned off. Vishno V. R. et al. [2] utilized a 2D axisymmetric thermal model to predict the overall temperature distribution of the gas turbine components. Several analytical studies are carried out to understand the various effects including the heat soak effect. Susanne S. et al. [3] presented a discussion of heat soak effect for various gas turbine engine shutdown scenarios, compared with experimental data and discussed how the temperatures at the shutdown point can be used to approximately determine a suitable shutdown procedure in order to control the bearing soak back peak.

3D transient conjugate heat transfer (CHT) is normally required to simulate the buoyant convection flow inside and outside the gas turbine. Evan O. S. et al. [4] utilised a technique using a combination of 3D CHT computational fluid dynamics (CFD) and finite element analysis (FEA). The results indicate that the geometries of gas turbine design do have an appreciable effect on the onset time, severity, and duration, as well as the axial distribution of the shaft thermal bow. Debabrata M. et al. [5] introduced an exemplary physics-based cool-down prediction methodology capable of accurately capturing the rotor cool-down process. The methodology involves development of a full 3D rotor casing thermal model integrated CHT FE model and validated with measured field data.

HIGH PRESSURE ROTOR MODEL
To gain an understanding of the temperature distribution of the high pressure rotor, without requiring fully detailed
gas turbine models, a simple 2D cross section model of the high pressure rotor is considered, as shown in Figure 1. Two-stage high pressure turbine (HPT) drives the axial ten-stage compressor. The flow area inside the rotor is also considered to simulate the air trapped in the high pressure rotor. This analogue represents the important features of the rotor, such as disks and shafts, while remaining computationally cheap.

**Figure 1 High pressure rotor model**

The 2D planar FEM model was developed to perform the transient thermal analysis after shutdown. The model was meshed using commercial software ICEM. Some details of the geometry has been simplified to ease the mesh generation and to reduce grid size. A close up view of the mesh at the fluid-solid interface is shown in Figure 2.

**Figure 2 Close-up of mesh at fluid-solid interface**

The key details of the mesh are shown in Table 1. In this study, the fluid and solid are solved simultaneously in the commercial CFD package, FLUENT. The turbulence model used for this study is standard K-epsilon, being a standard, versatile turbulence model. The enhanced wall treatment was used, resulting in the solver y+ value shown in Table 1. Full buoyancy effect option is enabled to simulate the buoyancy convection inside the rotor.

<table>
<thead>
<tr>
<th>Table 1-Mesh details</th>
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<tbody>
<tr>
<td>Number of Solid Elements</td>
</tr>
<tr>
<td>Number of Fluid Elements</td>
</tr>
<tr>
<td>Total Elements</td>
</tr>
<tr>
<td>Number of Nodes</td>
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<td>y+</td>
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A mission cycle transient thermal analysis is performed before starting of transient shutdown study. The mission cycle transient result will be the starting point of shutdown analysis. The temperature trapped in the rotor is assumed to be uniform at the bleed temperature.

In house tools are used to solve for the time-based heat transfer boundary conditions of the outer surface of the rotor for the shutdown analysis. The heat transfer of the inner surface of the rotor is automatically considered by the CFD solver. Due to the limitations with computational resources, the current heat transfer simulations do not include radiation.

**RESULTS AND DISCUSSION**

This section discusses shutdown thermal behaviour of the high pressure rotor. All the parameters like time and temperatures are kept as non-dimensional to maintain the consistency. Temperatures in this presentation are scaled with respect to the maximum temperature (close to the firing temperature) of the machine.

In Figure 3 is shown typical non-dimensional temperature distribution of the starting point of the shutdown thermal analysis. Once the machine is turned off, there is no active flow of cooling air. During this time, hot components convect heat to the air surrounding the metal and decrease the pressure, which in turn leads to lower air density. Due to buoyancy effect, this heated air, having lower density, moves up and brings heavier cold air near to hot surface at bottom half of the shaft. This leads to metal in the lower half getting cooled effectively, while metal at upper half is cooled less effectively. This establishes a gradient within the rotor, as shown in the temperature contour at time t=0.15 in Figure 4.

**Figure 3 Starting point thermal distribution**

**Figure 4 Temperature contour at time t=0.15**
During the cooling down process, the air temperature at the mean flow pass drops more quickly than that trapped in the rotor due to better ventilation. That leads to a more effective cooling of the outside of the rotor than the inside of the rotor. This establishes a reversed temperature distribution at the radial direction of the disks, as shown in the temperature contour at time $t=0.4$ in Figure 5.

Transient compressor disk rim temperatures are shown in Figure 6 (according to Figure 1). After the turbine is turned off, the temperature at point 2 and point 3 gradually rises. During shutdown, metal at compressor rim is heated due to conduction from hotter metal region. The temperature of the compressor disk rim at the upward side is always higher than that of the downward side due to natural convection. The temperature differences between the upward and downward sides are shown in Figure 7 (according to Figure 1). The asymmetric temperature differences of the compressor disk rim increase until reach a peak, and then gradually decreases as the rotor cools down.

Figure 8 shows the transient compressor disk bore temperatures (according to Figure 1). The temperature of the compressor disk bore at the upward side is always higher than that of the downward side due to natural convection. The maximum asymmetric temperature difference occurs at the 6th stage compressor disk bore (point 9) where the buoyancy effect is intense, for there is a large temperature difference between the 6th disk and the 7th disk at the initial condition.
Figure 9 shows the transient turbine disk temperatures at the rim, the centre and the bore (according to Figure 1). After shutdown of the machine, the metal temperature at disk centre and disk bore is heated due to conduction from disk rim. Hence there is a minor rise in disk centre and bore temperature during the beginning of the shutdown process. During shutdown, the main flow pass temperature drops more quickly than the air trapped inside of the rotor due to a better ventilating condition. Thus the temperature of the disk rim is cooled faster than the disk bore. Then a reversed axial temperature distribution occurs due to the better cooling of the rotor outer surface. This thermal gradient leads to compressive mechanical loading of wheel during shutdown.

VALIDATION

In order to validate the CFD solutions presented in this work, a simple vertical placed HPT casing was run following the same process as for the large model. The solution was then compared to experimental data. The comparison, shown in Figure 10, demonstrates reasonable agreement, with the CFD results being approximately 20K cooler than the experimental results after 1 hour. The difference between the CFD and experimental results is not completely unexpected as the CFD model is simplified compared with the HPT casing profile. While this may be indicative of some absolute uncertainty in the solution, the results of this study are still useful as they show the relative sensitivity of the system to certain changes. A CFD image and a test rig photo of the HPT casing is shown in Figure 11. A simple validation case of a vertical placed HPT casing gives confidence that the heat transfer mechanisms of interest are being modelled to a reasonable degree of accuracy.

CONCLUSIONS

The conductive cooling of a simplified high pressure rotor was modelled, and the temperature distribution was measured using 2D CHT CFD. The present work shows that the shutdown cool down transient behaviour for steam turbine components may be predicted by the developed methodology.

REFERENCES