IMPROVING AERODYNAMICS OF THE INTERCOOLER FLOW PATH FOR THE DEVELOPMENT OF HIGH EFFICIENCY GAS TURBINES

FINAL REPORT

A.K. Agrawal
S.R. Gollahalli
A. Tinneti
Y. Gao

Gas Turbine Systems Laboratory
School of Aerospace and Mechanical Engineering
University of Oklahoma
Norman, OK 73019

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The thermodynamic analyses of gas turbine cycles with modifications such as intercooling, recuperating, and reheating have shown that intercooling is important to achieving high efficiency gas turbines (Cook and Nourse, 1993; Wikes et al., 1993; Cohn, A., 1993). Intercooling in gas turbines entails cooling of air between the low pressure (LP) and high pressure (HP) compressor sections. Lower air temperature reduces the volume flow rate in the HP compressor and hence, the compression work. A major benefit of intercooling is the lower air temperature at the HP compressor discharge, which allows for more effective cooling of the hot gas flow path. Although the concept of gas turbine intercooling can be found in basic text books, its implementation in gas turbines has received considerable attention only in recent years (Shepard et al., 1995; Davidson et al. 1996).

In an intercooler system, the air exiting the LP compressor must be decelerated to provide the necessary residence time in the heat exchanger. The cooler air must subsequently be accelerated towards the inlet of the HP compressor. The flow nonuniformities inevitably introduced by the heat exchanger, if not isolated, could lead to rotating stall in the compressors and thereby, reduce the overall system performance and efficiency. Also, the pressure losses in the intercooler flow path adversely affect the system efficiency and hence, must be minimized. Thus, the primary objective of this research is to maximize the benefits of gas turbine intercooling by isolating, minimizing, or eliminating nonuniformities in the flow streams of the compressors, and through reduction in the stagnation pressure loss in the intercooler flow path.

Figure 1 shows the schematic of the on-axis intercooler system concept developed in this project. This configuration uses a water-cooled shell-and-tube heat exchanger of annular cross-section, with air flowing axially inside finned tubes. The arrangement is typical of multi-stage centrifugal compressors and it differs from the Navy's ICR design (Shepard et al., 1994), wherein the space constraints led to a compact plate and fin heat exchanger with airflow normal to the turbine axis. The diffuser upstream of the heat exchanger not only augments the frontal area for the heat exchanger but also improves the overall efficiency by recovering static pressure at the LP compressor discharge. The diffuser consists of a moderately diffusing prediffuser and a dump or sudden expansion; a design typical of combustor-diffusers used in gas turbines (Klein, 1995). The contraction is needed to accelerate the airflow to the HP compressor after the cooling has taken place. A compact, contoured wall design was used to reduce the overall length. Note that all of the flow passages are annular in cross-section. The flow passages in Figure 1 could also be used for applications requiring an off-axis heat exchanger. In this case, interconnecting passages must be placed at the outer periphery of the diffuser and contraction sections to, respectively, collect the LP compressor air for cooling and to return the cooler air to the HP compressor.

The goal of the experimental work was to obtain quantitative data in approximately one-fourth scale model of the intercooler flow path in a typical industrial gas turbine (see Figure 2). The annulus height at the test-section inlet was 0.0524m to allow a reasonable measurement accuracy. The overall diffuser area ratio and length were, respectively, 5.4 and 0.533m. The length of the heat exchanger and contraction was, respectively, 0.508m and 0.457m. Overall, the test-section was 1.5m long with the maximum casing diameter of 0.838m. The diffuser and contraction casing and hub were made of, respectively, clear plexiglas and hard mahogany wood with precisely machined surfaces exposed to the flow. The heat exchanger was fabricated with two steel plates rolled into annular cylindrical shells. The intercooler flow resistance was simulated by a header plate with a hole pattern punched out to represent the tube layout. Approximately 250 pressure taps were provided on the hub and casing, and 20 probe access ports were drilled on the casing at four circumferential locations. Airflow through the test model was provided by an open circuit windtunnel shown schematically in Figure 3. Flow measurements were obtained from wall pressure taps, and radial traverses of a five-hole probe and a cross-film anemometer. The voltage signals from pressure sensors and hot-film sensors were acquired on a computer using low and high speed data acquisition boards and accompanying software.

The static pressure distribution along the hub and casing of the diffuser are shown in Figure 4. The pressure increased in the prediffuser and reached a peak value (Cp=0.4) at the prediffuser exit. Subsequently, the pressure remained nearly constant suggesting no recovery in the dump. Details of the diffuser flow field are depicted in Figure 5 deduced from 5-hole pressure probe measurements. Evidently, the recirculation occupied about half of the flow area in the dump. The flow attached towards the tail end, at an axial distance of 12 times the annulus height at the test-section inlet, where a uniform exit velocity profile was achieved. Experiments at different operating conditions revealed that the diffuser flow was neither affected by the intercooler or by the part-load operation.

Pressure coefficients along the hub and casing of the contraction are shown in Figure 6. The pressure coefficient of about -1.0 at the exit plane indicates that the change in the static pressure was caused mainly by flow acceleration and not by the stagnation pressure loss. Pressure traverses revealed stagnation pressure loss of only 2 to 3% of the exit dynamic head. Details of the flow field in the contraction are depicted in Figure 7 by velocity vectors deduced from cross-film probe measurements. Overall, the results indicate that the contraction performed as desired; a distorted inlet flow was accelerated to an exit flow with uniform pressure and axial velocity profiles. The flow acceleration was accomplished with only a minor loss in the stagnation pressure. The inlet flow conditions did not have a noticeable effect on flow distribution at the passage exit.

An aerodynamic optimization procedure employing computational fluid dynamics was developed to help in the design of annular flow passages with contoured walls. The optimization aimed to align the mean flow with the geometric centerline of the flow passage. Together with a weighting function which enabled the geometric constraints to be maintained, the deviations among the geometric centerline and three physical centerlines served as guide or objective function for the optimization. The flow solver for the calculations was validated using experimental data obtained in the intercooler system. Figure 8 shows the geometric and computed physical centerlines in the diffuser. The large deviations of geometric and physical centerlines suggest the inability of the mean flow to align with the passage geometry and thereby, indicates a lack of aerodynamic design in the dump region. Extensive computations revealed that this situation could not be reversed by reshaping walls of the dump. In contraction, the geometric and physical centerlines matched closely with each other (see Figure 9) thereby, producing an aerodynamic design.

In summary, this unique project has produced a conceptual design of the intercooler flow path, obtained experimental data to help in the design of the prototype, and developed CFD based optimization techniques to design annular flow passages. The main conclusion are listed below.

- The intercooler flow nonuniformities were generally isolated from the upstream and downstream compressor sections in the proposed design. Although the present concept was intended for an on-axis water-cooled intercooler, it could also be adapted to an off-axis, air-cooled intercooler with only minor modifications.
- The flow passages incurred a loss of about 1.0 percent of the intercooler stagnation pressure (or 0.5 dynamic head at the LP compressor discharge). This loss should be added to the stagnation pressure loss in the heat exchanger. An off-axis intercooler will incur additional losses in the interconnecting passages.

- Majority of the static pressure recovery occurred in the prediffuser. Most of the stagnation pressure loss occurred in the dump. The stagnation pressure loss in the contraction was negligible.
- The present design required a long dump to produce a uniform diffuser exit flow, crucial for high effectiveness of the intercooler.
- An effective optimization technique was developed to design the prediffuser, contraction, and other annular flow passages used in gas turbine systems.

The primary challenge of the intercooler design is to achieve the desired characteristics; minimum flow nonuniformities and minimum stagnation pressure loss, within a short length. The proposed concept satisfies most of the design requirements. The main improvement will be to reduce length of the dump region without compromising on uniformity of the diffuser exit flow. Because the wall reshaping was found to be inadequate for this purpose, we suggest the following:

- Splitter plates and/or guidevane should be considered to redistribute the flow and to enhance mixing in the dump. These flow elements should be placed towards the end of the prediffuser to avoid adverse effects on pressure recovery in the prediffuser. The future work should be conducted to develop strategies to effectively design these flow elements.
- The prototype is likely to require struts to support the casing load on the hub. These struts when placed at the end of the prediffuser will enhance mixing in the dump. The future work should be conducted to characterize the 3D effects of the support struts.
- Boundary layer suction at the casing wall may be effective in minimizing or eliminating flow separation in the dump. The future work should be conducted to evaluate this approach.

Finally, experiments are recommended to determine effects of inlet flow conditions including the swirl on flow characteristics of the diffuser and contraction passages.