Interaction between Struts and Swirl Flow in Gas Turbine Exhaust Diffusers

Roman Z. PIETRASCH    Joerg R. SEUME
Turbomachinery Laboratory, University of Hannover, Appelstr. 9, D-31678 Hannover, Germany
E-mail: "surname"@ifs.uni-hannover.de

The increasing use of gas turbines in combined cycle power plants together with the high amount of kinetic energy in modern gas turbine exhaust flows focuses attention on the design of gas turbine diffusers as the connecting part between the Brayton/Joule and the Rankine parts of the combined cycle. A scale model of a typical gas turbine exhaust diffuser is investigated experimentally. The test rig consists of a radial type, variable swirl generator which provides the exhaust flow corresponding to different gas turbine operating conditions. Static pressure measurements are carried out along the outer diffuser walls and along the hub of the annular part and along the centerline of the conical diffuser. Velocity distributions at several axial positions in the annular and conical diffuser have been measured using a Laser Doppler Velocimeter (LDV). Pressure recovery coefficients and velocity profiles are depicted as a function of diffuser length for several combinations of swirl strength, tip flow and strut geometries. The diffuser without struts achieved a higher pressure recovery than the diffuser with struts at all swirl angle settings. The diffuser with cylindrical struts achieved a higher pressure recovery than the diffuser with profiled struts at all swirl angle settings. Inlet flows with swirl angles over 18° affected the pressure recovery negatively for all strut configurations.

Keywords: gas turbine exhaust diffuser, swirl, struts, pressure recovery coefficient.


Introduction

Sovran and Klomp[1] offered diffuser performance charts for ideal diffuser. Under real operating conditions the losses in the diffuser do not allow the ideal pressure recovery coefficient to be reached. The cause of the losses may be for example friction and flow separation on walls and internals, like struts, or blockage effects of the boundary layer.

Lippert[2] investigated the combination of an annular diffuser with 8 struts and an upstream turbine and obtained similar results. Only for the configuration without struts and with swirl-free inlet flow the pressure recovery was the same as in the design point.

Thayer[3] carried out an early investigation of the influence of struts on annular diffusers. The investigations showed an insignificant decrease of the diffuser efficiency for swirl angles up to 20°. Higher swirl angles resulted in an rapid decrease of efficiency. He drew the conclusion that the flow is still attached at the struts at lower swirl angles and separates at higher incidence.


The investigations of Senoo et al.[5] regards systematically several struts positions and chord length of struts. The investigations were carried out at different Reynolds numbers and swirl angles between 0° and 24°. He concluded that the losses are low for swirl angles of up to 20°.

A scale model of a typical gas turbine exhaust diffuser (annular followed by conical) was investigated experimentally and numerically by Fleige[6]. Four swirl angles and three strut configurations (none, 5 symmetrically profiled struts, and 5 struts with circular cross-section) were investigated. The diffuser without struts achieved the highest pressure recovery at all swirl angles investigated. Inlet swirl higher than 8° is found to adversely influence the pressure recovery of the diffuser. For swirl angles higher than 10°, cylindrical struts were found to yield better diffuser performance than profiled struts.

Test Facility

The test rig[6] of an approximately 1/10 scale model of a typical gas turbine exhaust diffuser was used to
investigate the effects of the interaction between swirl flow and struts. Fig. 1 shows a cross sectional view of the test rig. The test rig uses a swirl generator to simulate the exhaust flow of a turbine, which then passes through an annular and a conical diffuser. The turbine exhaust flow is modeled using a radial type swirl generator (a) followed by a transition piece which directs the flow from the radial into the axial direction. Immediately downstream of this turn, the modeled tip leakage flow (b) can be injected. Tip leakage air is supplied by a 5 kW variable speed radial blower. The swirl angles of main and tip flow can be varied independently in the range of \( \pm 45^\circ \) and \( \pm 22^\circ \), respectively, from the axial direction. The main flow swirl generator (a) and the tip leakage flow generator (b) are followed by a short cylindrical part in order to allow measurements of the diffuser inlet conditions. The first part of the diffuser is an annular diffuser (c) with a constant diameter inner hub and an area ratio of 1.85. A conical diffuser (d) is connected to the annular diffuser. The area ratio of the conical diffuser is 2.25 based on the full cross sectional area at the inlet as inlet area or 2.9 based on the annular cross section as inlet. The diffuser parts can easily be separated by moving the inlet and annular diffuser upstream on a linear traverse (e). This allows an easy and fast installation of new strut configurations on the hub.

The exit of the conical diffuser section is attached to a settling chamber. The flow is sucked from the inlet through the diffusers by a fan with a 37 kW, variable speed electrical motor. A maximum flow rate of 8 m\(^3\)/s is adjustable. For the presented investigations the flow rate is 5.5 m\(^3\)/s, corresponding to a mean axial velocity at the diffuser inlet of 46 m/s. The Reynolds number of the model based on the hydraulic inlet diameter and the mean axial velocity at the inlet section is approx. 6*10\(^5\) whereas typical Reynolds numbers defined in the same way for real exhaust diffusers are in the range of 5*10\(^6\).

Expanding Fleige’s work, the diffuser test rig was altered to allow the annular diffuser’s hub with the mounted struts to be turned. This allows an investigation of the circumferential variation of the flow. This design enables measurements at various points in between two neighbouring struts without traversing the measuring system circumferentially. The hub holds 5 equally mounted struts. The angle between two struts is 72°. As 0° and 72° are blocked through the struts themselves, measurements start at 6° and end at 66 degrees. In between, the hub is turned manually by 6° and locked at the desired position. Cylindrical struts are mounted at an axial distance of 230 mm after the inlet of the annular diffuser and 110 mm ahead of the end of the hub. The distance of the profiled struts leading edge to the inlet is 135 mm and the trailing edge is 102.5 mm ahead of the hub end.

**Instrumentation**

The instrumentation includes 97 static wall pressures on the whole outer cone and 88 on the inner cylinder of the annular part. In the conical part of the diffuser static pressure is measured using a centerline probe with 20 wall taps. Velocities and turbulence quantities are measured using a 2D-LDV. Optical access is provided by Perspex windows of 1.5 mm thickness in the outer cone at 7 axial positions (Fig. 1, No.1 to 7). All static pressure measurements are obtained using "classic" U-type manometers and multi manometers filled with colored water.

The LDV in use is a commercially available DANTEC fibre-optical laser-doppler-velocimeter. It is operating in the backward scatter mode. The lens used focuses the measuring volume approx. 160 mm in front of the probe lens. It has a length of 1.06 mm and a diameter of

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**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>( A )</td>
<td>cross-sectional area (mm(^2))</td>
</tr>
<tr>
<td>( AR )</td>
<td>area ratio</td>
</tr>
<tr>
<td>( B )</td>
<td>relative obstruction</td>
</tr>
<tr>
<td>( c )</td>
<td>absolute velocity (m/s)</td>
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<tr>
<td>( c_p )</td>
<td>pressure recovery coefficient</td>
</tr>
<tr>
<td>( L )</td>
<td>diffuser length (mm)</td>
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<td>( p )</td>
<td>pressure (Pa)</td>
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<tr>
<td>( Re )</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>( r )</td>
<td>radius (mm)</td>
</tr>
<tr>
<td>( z )</td>
<td>axial position (mm)</td>
</tr>
</tbody>
</table>

**Superscripts**

- \( ° \) degree
- \( * \) total
- \( ~ \) averaged value

**Subscripts**

- \( \text{dyn} \) dynamic
- \( i \) ideal
- \( tg \) tangential direction
- \( 1 \) position 1
- \( 2 \) position 2