Project No. E-16-648
Project Director: Howard McMahon
Sponsor: Rolls-Royce, Inc.; Atlanta, GA

Type Agreement: Letter of 11/25/81
Award Period: From 11/25/81 To 12/31/81
Sponsor Amount: $4,399
Cost Sharing: N/A

Title: Effect of Tip Radius on the Discharge Coefficient of a Flat Plate/Endwall Nozzle

ADMINISTRATIVE DATA
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Defense Priority Rating: N/A
Security Classification: N/A

RESTRICTIONS
See Attached N/A Supplemental Information Sheet for Additional Requirements.
Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.
Equipment: Title vests with N/A

COMMENTS:

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Date 2/5/82

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Effective Termination Date: 12/31/81

Clearance of Accounting Charges: 

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice and Closing Document
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Assigned to: AE (School/Laboratory)

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FORM OCA 10:781
EFFECT OF TIP RADIUS
ON THE
DISCHARGE COEFFICIENT
OF A
FLAT PLATE/ENDORWALL NOZZLE

FINAL REPORT
TO
ROLLS-ROYCE INC.
CONTRACT E-16-648

B. R. Daniel and H. M. McMahon

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

January 22, 1982
INTRODUCTION

New compressor blades in the Rolls-Royce RB 211 engine have tips with square edges. However, during engine overhaul it is customary to polish the blades that have been removed from the engine before these blades are installed again. During this polishing process, the sharp edge of the blade tip is slightly rounded.

The question has arisen as to whether this very small amount of rounding (to a corner radius of approximately 0.008" to 0.012") can have a significant effect on the discharge coefficient of the flow through the blade-tip clearance and hence affect the performance of the engine.

In order to assess the sensitivity of a flow to such a small charge in geometry, tests were conducted to determine the discharge coefficient for a simple two-dimensional flow past a flat plate having a sharp edge which simulates the unpolished blade. These results were compared with the discharge coefficients for two similar flat plates which were subjected to one and two polishing cycles, respectively. The discharge coefficients also were evaluated as a function of gap size and pressure ratio. This report presents the procedure used and the results obtained from this two-dimensional test program.

TEST ARTICLE AND PROCEDURES

To minimize positioning errors the blades (i.e., the flat plates) were designed to fit into a slot in the chamber section and to be positioned flush against the top plate (See Figure 1). The gap simulating the blade clearance is a machined recess in the top plate. Three top plates with gap heights of 0.020", 0.030" and 0.040" were used. Measuring equipment considerations led to the selection of a gap width of 4.0". Since it was expected that the effect of the edge ablation on the discharge coefficient would be very small, an accuracy and repeatability of ± 1.0% of the discharge coefficient value was set as a goal. Considering the gap dimensions, an error in blade position of 0.001" would lead to a 2.5-5 0% error in area and hence in mass flow. Detailed fabrication drawings, RR-1 through RR-8, have been submitted to Rolls-Royce*.

*The machining work on the test articles was done by Mr. Dewey Ransom of the Aerospace Engineering Machine Shop.
The blades were made of titanium and were 0.049" thick. Three blades were used:

Blade #1 - Reference blade, square edges
Blade #2 - Same as reference blade, except put through one polishing operation
Blade #3 - Same as reference blade, except put through two polishing operations.

The polished blades were supplied by Rolls-Royce.

Air for the test was provided by the 500 cubic foot, 125 psig air supply in the Aerospace Engineering Laboratory. A schematic of the flow system is shown in Figure 2. Photographs of the test set-up are included as Figure 3 and 4.

The airflow rate was measured using a Fischer and Porter Rotameter (Tube No. 5-35-600/CD-10-1085) which has a tube 600 mm long graduated to read flows from 3.0 to 12.0 lbm/min at 220 psig and 70°F. The actual metering pressure (20-60 psig) was read using a 12" diameter Heise Gauge indicating 0-250 psig with 0.25 psi graduations. The metering temperature was read with a thermocouple and displayed on a digital Doric, Type K readout which has a compensated cold junction.

Five pressure ratios (i.e., the ratio of the pressure in the stilling chamber, \( p_c \), to the ambient pressure \( p_a \)) were used: 1.2, 1.4, 1.6, 1.8, and 2.0. The ambient pressure was read on a 4" diameter Aneroid Barometer having 0.02" Hg. graduations.

The chamber temperature was measured with a thermocouple and read on a second channel of the Doric digital readout. As was expected, the metering temperature and the chamber temperature agreed within ± 1°F so that only the latter temperature was read and recorded.

### DATA ANALYSIS

A computer program was written to evaluate the discharge coefficient, \( C_D \), from the measured mass flows, pressures, and temperatures where

\[
C_D = \frac{\text{actual mass flow}}{\text{ideal (isentropic) mass flow}} = \frac{\dot{m}_{\text{act}}}{\dot{m}_{\text{ideal}}} \tag{1}
\]

The value of \( \dot{m}_{\text{act}} \) was determined by correcting the rotameter reading (\( \dot{m}_{\text{std}} \)) to account for the actual metering conditions. If the density of the meter float (steel) is much greater than the density of the fluid (air), the required expression is
\[
\dot{m}_{\text{act}} = \dot{m}_{\text{std}} \sqrt{\frac{p_r}{p_{\text{std}}} \cdot \frac{T_{\text{std}}}{T_r}} \tag{2}
\]

Where \( \dot{m}_{\text{act}} \) = actual mass flow rate

\( \dot{m}_{\text{std}} \) = mass flow rate as read from meter scale

\( p_{\text{std}} = 220 \text{ psig} + p_a \)

\( p_a \) = ambient pressure

\( T_{\text{std}} = 70^\circ \text{F} + 460 \)

\( p_r \) = metering pressure used (psia)

\( T_r \) = metering temperature, here taken to be the temperature in the stilling chamber, \( T_C \).

Under the assumptions that the flow is isentropic and that the velocity in the stilling chamber is negligible compared to the velocity in the slot, then

\[
\dot{m}_{\text{ideal}} = A p_c \left\{ \frac{2 g}{R T_c} \left[ \frac{\Delta p}{p_c} \left( 1 - \frac{3}{2 \gamma} \frac{\Delta p}{p_c} \right) \right] \right\}^{1/2} \tag{3}
\]

or, when choked (i.e., \( p_a < (0.528) (p_c) \))

\[
\dot{m}_{\text{ideal}} = A p_c \left\{ \frac{g \gamma}{R T_c} \cdot \left( \frac{2}{\gamma+1} \right) \frac{\gamma+1}{\gamma-1} \right\}^{1/2} \tag{4}
\]

where \( \dot{m}_{\text{ideal}} \) = ideal (isentropic) mass flow rate

\( A \) = slot area

\( p_c \) = chamber pressure

\( \Delta p \) = \( p_c - p_a \)

\( p_a \) = ambient pressure

\( T_c \) = chamber temperature

\( R \) = gas constant for air

\( \gamma \) = ratio of specific heats

\( g \) = acceleration due to gravity

The first equation for \( \dot{m}_{\text{ideal}} \) is an approximation to the exact expression valid when \( \Delta p/p_c \) is small, which is satisfied for these tests.

In calculating the discharge coefficient, the mass flow ratio in Equation 1 is independent of temperature if the metering temperature and the chamber temperature are
the same (as was the case here) since the resulting temperature ratio is unity. However, the
two temperatures have been input in the computer program so that the values of \( m_{act} \) and
\( m_{ideal} \) (which are output in addition to \( C_D \)) will be precise.

RESULTS AND DISCUSSION

A summary of the 17 test runs made during this study is shown in Table 1 and the
values of the discharge coefficients for each of the three gap sizes are presented in Figures
5, 6, and 7 as a function of pressure ratio and blade edge condition.

It is seen that the repeatability of the data is good, most results being contained within
a scatter band of \( \pm 1\% \) as was set as an initial goal. Repeatability here means testing one
blade and then completely removing it and testing one or more other blades before the
subject blade is re-installed for a repeatability check.

At all pressure ratios and gap sizes, the effect of the edge rounding is to increase the
discharge coefficient by a significant amount which is much larger than the data scatter in
the individual tests. This increase in discharge coefficient is in the range of 10-14\% for
moderate pressure ratios.

Over most of the pressure ratios tested, the change in discharge coefficient between
one polishing and two polishes is small or negligible compared to the change in the discharge
coefficient between the reference (square) blade and one polishing. For the smallest
pressure ratio (1.2) and the smaller gap sizes (0.020" and 0.030") the second polishing
decreases the discharge coefficient relative to its value after the first polishing.

These two-dimensional tests indicate that the small amount of edge rounding due to
polishing may significantly increase the discharge coefficient of a compressor blade as
compared with the value for a square-tip blade. Also, most of the increase occurs as a
result of one polishing, with the second polishing in general leading to much smaller charges
in discharge coefficient.
Table 1

SUMMARY OF TEST RUNS

<table>
<thead>
<tr>
<th>BLADE</th>
<th>GAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.020</td>
</tr>
<tr>
<td>1</td>
<td>4*,5*,16</td>
</tr>
<tr>
<td>2</td>
<td>6, 17</td>
</tr>
<tr>
<td>3</td>
<td>3, 7</td>
</tr>
</tbody>
</table>

*Runs not plotted:

4, 5  - Blade probably not in proper position since it was installed without removing chamber top.
Figure 1 Sketch of Test Article with Components disassembled.
Figure 2  Schematic of Flow System
Figure 3  Photograph of Test Set-Up
Figure 5 Discharge Coefficient vs Pressure Ratio
Gap = 0.020"
Figure 6  Discharge Coefficient vs Pressure Ratio
Gap = 0.030"
Figure 7  Discharge Coefficient vs Pressure Ratio
Gap = 0.040"