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NASA
National Aeronautics
and Space Administration

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1978

TWO-DIMENSIONAL COLD-AIR CASCADE STUDY OF A FILM-COOLED TURBINE STATOR BLADE

V - COMPARISON OF EXPERIMENTAL AND ANALYTICAL AERODYNAMIC RESULTS FOR BLADE WITH 12 ROWS OF 0.038-CENTIMETER- (0.015-IN.-) DIAMETER COOLANT HOLES HAVING STREAMWISE EJECTION ANGLES

by Herman W. Prust, Jr.

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SUMMARY

Experimentally determined changes in aerodynamic efficiency for a full-film-cooled stator blade with 12 spanwise rows of coolant holes were compared with predicted efficiency changes based on two published analytical methods. This is the second of two such comparisons. One of the analytical methods was used as published; the other was modified for certain cases of coolant ejection from the blade suction surface.

Efficiency results were compared for 23 cases of coolant discharge, including ejection from each of the 12 single rows and from various combinations of rows as well as full film cooling. The experimental efficiency changes were predicted reasonably well by both methods. For all cases of coolant ejection, covering coolant fractions from 0 to about 9 percent, the difference between experimental and predicted changes was no greater than about 1 percent for either method.

The largest differences between experimental and predicted results occur for multirow ejection when part of the coolant is being ejected from an area on the blade surface that has lower static pressures than those at the blade exit. For these cases, the as-published method predicts low, and the modified method high. An example is full film cooling in which 3 of the 12 coolant rows have blade surface pressures that are lower than those at the blade exit. For this case, over the range of tested coolant fractions, the as-published method predicts efficiency changes as much as 1 percent lower than experimental, and the modified method predicts efficiency changes as much as 3/4 percent higher than experimental.

For 16 cases of single- and multirow ejection from areas on the blade surface with higher static pressures than at the blade exit, both methods predict the experimental changes very well. That is, the difference between the experimental and predicted results is no more than about 1/2 percent for either method.

INTRODUCTION

Different methods of ejecting coolant air from the turbine blade surface are known to have significantly different effects on turbine aerodynamic efficiency. Extensive research programs are, therefore, in progress at the Lewis Research Center, and elsewhere, to investigate both analytically and experimentally the effect of various coolant ejection schemes (refs. 1 to 17). As examples, references 1 and 2 present two simple analyses for predicting the effect of different coolant schemes on turbine aerodynamic efficiency. References 3 to 6 report the results of an experimental investigation of the effect of stator blade transpiration cooling on turbine performance. And references 7 to 11 report the results of an experimental investigation of the effect of stator blade trailing-edge ejection on turbine performance. Reference 12, which summarizes the results of the stator blade transpiration and trailing-edge ejection investigations, shows trailing-edge ejection to be more efficient aerodynamically than transpiration ejection.

Currently, a program is in progress at Lewis to study the effects of full film cooling on turbine aerodynamic efficiency. One phase of the program is the development of analytical procedures to satisfactorily predict these effects. As part of the effort to develop such methods, experimental results from three tests of full-film-cooled stator blades are being compared with results predicted by the analytical methods of references 1 and 2. These two published analyses are the same in several basic respects. For instance, both assume one-dimensional, constant-pressure mixing of the coolant and primary flows. However, they differ in other respects, such as the assumed mixing location of the coolant and primary flows.

The objectives of comparing experimental efficiencies with efficiencies predicted by these two methods are to determine the accuracy of the prediction methods and, if needed, to improve their accuracy by adding empirical corrections. The experimental results for the three blades used in the comparisons are reported in references 13 to 16. The first blade tested (refs. 13 and 14) had 12 spanwise rows of coolant holes with ejection angles in a streamwise direction. The second blade tested (ref. 15) had the same number of coolant rows, the same coolant row locations, and the same coolant hole spacing and angles but only half the coolant hole diameter of the first blade tested. The third blade tested (ref. 16) had 45 spanwise rows of holes and was tested with seven different coolant hole ejection angles, the orientations being either streamwise, spanwise, or compound.

The investigation comparing the experimental and predicted efficiency results for the first blade tested has been completed, and the results are reported in reference 18. For coolant ejection from areas on the blade surface with higher static pressures than at the blade exit, the methods of references 1 and 2 were used as published since the results for these cases show that both methods predict the experimental results quite well. For cases of ejection from areas on the blade surface with lower pressures than at the blade exit, the method of reference 1 was used as published, but the method of reference 2 was modified by an empirical correction to fit the data better. The results of this comparison show that both the method of reference 1 as published and the method of reference 2 as modified are pessimistic, but that the modified method of reference 2 gives better agreement.

This report presents a comparison of experimental efficiencies for the second stator blade tested (ref. 15) with efficiencies predicted by the analytical methods used in reference 18 (i.e., the method of ref. 1 as published and the method of ref. 2 as modified).

The experimental data were obtained from tests conducted in a two-dimensional cascade with the temperatures of the primary and coolant air near ambient. The tested, nominal, ideal, primary-air critical velocity ratio was 0.65. Separate tests were made for ejection from each coolant row and from various combinations of coolant rows, including full film cooling. The tested range of coolant- to primary-air mass flow ratio (coolant fraction) was 0 to about 9 percent.

The experimental and predicted results of the subject investigation are compared in terms of the fractional change in primary efficiency relative to the efficiency of the noncooled solid blade. Primary efficiency is defined as the ratio of the actual kinetic energy of the total flow (primary plus coolant) to the ideal kinetic energy of the primary flow only. Predicted results are compared with experimental results for all cases of single-row and multirow coolant ejection reported in reference 15.

SYMBOLS

D	coolant hole diameter, cm; in.
L	coolant hole length, cm; in.
L_{pr}	pressure-surface length from leading edge to trailing edge (fig. 2), cm; in.
L_s	suction-surface length from leading edge to trailing edge (fig. 2), cm; in.
p	absolute static pressure, N/cm^2; psia
p'	absolute total pressure, N/cm^2; psia
V	absolute velocity, m/sec; ft/sec
w	mass flow rate, kg/sec; lbm/sec
x	local position along blade surface from leading edge (fig. 2); cm; in.
y	coolant fraction, w_c/w_p
β	angle between coolant hole axis and local blade surface tangent in plane parallel to blade end-wall surface, deg

η_o	blade-row efficiency with no coolant flow
η_p	primary efficiency, ratio of actual kinetic energy of total flow to ideal kinetic energy of primary flow only
η_{th}	thermodynamic efficiency, ratio of actual kinetic energy of total flow to ideal kinetic energy of total flow

Subscripts:

c	coolant flow
cr	conditions at Mach 1
id	ideal quantity corresponding to isentropic process
m	blade exit station, where flow conditions of coolant and primary flows are assumed to be uniform (fully mixed)
p	primary flow
t	total flow, primary plus coolant
0	station at blade row inlet

DESCRIPTION OF TEST BLADE

The test blade with its spanwise rows of coolant holes and their numbering system is shown in figure 1. The blade is hollow, untwisted, and of constant cross section. The blade profile corresponds to the mean-section profile of the stator blade of reference 19, in which the reference blade is described in detail. Significant dimensions of the blade are as follows: span, 10.16 centimeters (4.0 in.); chord, 5.74 centimeters (2.26 in.); pitch, 4.14 centimeters (1.63 in.).

Table I lists the location of each coolant row and the geometry of the coolant holes. (The symbols used in table I are explained by fig. 1(c).) All symbols are defined in the section SYMBOLS. The axes of all coolant holes are parallel to the planes of the blade end walls. The diameter and spanwise pitch of the coolant holes in all rows are 0.038 centimeter (0.015 in.) and 0.144 centimeter (0.045 in.), respectively.

DESCRIPTION OF EXPERIMENTAL TESTS

In the experimental investigations of reference 15, separate tests were first made with coolant ejection from each of the 12 single rows of coolant holes. Next, the effects of multirow coolant ejection from the suction and pressure surfaces were individually determined. In the multirow tests, the combinations of rows considered were the two rows nearest the leading edge, the three rows nearest the leading edge, etc., until all six rows on each separate surface were included. Finally, tests were conducted to determine the effect on stator blade performance of full film cooling from all 12 coolant rows. The multirow test configurations are listed in table II.

DISCUSSION AND DEFINITION OF PRIMARY EFFICIENCY

A number of efficiency expressions are commonly used to describe the performance of high-temperature, air-cooled turbines. For cold aerodynamic tests without internal blade inserts, actual hot-engine heat transfer and pressure drop processes are not duplicated. The selection of an efficiency definition therefore becomes arbitrary. The major parameter studied in the subject aerodynamic investigations was the effect of ejected coolant on the kinetic energy output of the combined flow (primary plus coolant). This effect is well shown by the efficiency expression termed "primary efficiency." Therefore, the results of this investigation were computed and reported in terms of primary efficiency. Primary efficiency relates the actual energy of the total flow to the ideal energy of only the primary flow and is expressed as

$$\eta_p = \frac{w_t V_{t,m}^2}{w_p V_{p,id,m}^2} \tag{1}$$

Thermodynamic efficiency is the same as primary efficiency except that the ideal energy of the coolant flow is included in the denominator.

$$\eta_{th} = \frac{w_t V_{t,m}^2}{w_p V_{p,id,m}^2 + w_c V_{c,id,m}^2} \tag{2}$$

The state condition of equal inlet total pressure of the coolant and primary flows $p'_{p,0} = p'_c$ is a significant state condition for comparing primary efficiency results since it is representative of the first turbine stage of a gas turbine engine. At this condition for cold-air tests with equal inlet total temperature of the coolant and primary flows, the ideal specific energies of the coolant and primary flows are equal. As indicated previously, the change in primary efficiency relative to the efficiency of the uncooled blade represents that part of the output kinetic energy contributed by, or charged to, the coolant. Therefore, when the ideal specific energies of the coolant and primary flows are equal, the percentage of change in primary efficiency per percentage of coolant flow effectively represents the efficiency of the coolant flow. It thus provides a useful measure for evaluating various coolant schemes for the same or different blades.

ANALYTICAL METHODS

The predicted results of this report are based on the analytical methods of references 1 and 2, called methods 1 and 2, respectively, hereinafter. Method 1 was used as published. Method 2 was modified from the analysis of reference 2 as described in reference 18 for coolant ejection from the diffusion region of the blade surface. The expansion and diffusion regions of the blade surface are defined, as shown in figure 2, as the areas on the blade surface where the local static pressure is higher or lower, respectively, than the blade-exit static pressure.

For convenience to the reader and to indicate the differences between the two methods, they are described briefly here. Detailed descriptions of the methods are presented in references 1, 2, and 18.

The methods are alike in two basic respects. They both assume (1) that the coolant and primary flow are mixed one-dimensionally at constant static pressure and (2) that only the component of coolant flow momentum that is parallel to the main-stream flow at the coolant hole exit contributes to the useful blade row output.

In other respects, the methods differ. Method 1 employs the same analytical procedure for coolant ejection from both the expansion and diffusion regions of the blade surface; method 2 uses a different analytical procedure for ejection from each region. Briefly, method 1 mixes the individual coolant flow and a portion of the main-stream flow sequentially at each ejection location along the blade suction and pressure surfaces; it then mixes the resultant flow with the remainder of the main-stream flow at the blade row exit. In contrast, for coolant ejection from the expansion region, method 2 expands the individual coolant flows from the ejection location to the blade exit and then mixes the coolant flow with the total main-stream flow. For coolant ejection from the diffusion region, method 2 assumes that the component of coolant flow momentum that is parallel to the main-stream flow at the ejection location is maintained at the blade row exit, where the coolant flow mixes with the primary flow. This procedure for ejection from the diffusion region neglects the compression energy required to raise the pressure of the coolant from the lower pressure at the ejection location to the higher pressure at the blade exit. For this reason, method 2 predicts higher energy output than method 1 for coolant ejection in this region. Although neglecting the required coolant compression work appears physically incorrect, the results of reference 18 show that method 2 gives better agreement with experimental results. The reason for the anomaly is not understood.

RESULTS AND DISCUSSION

A comparison of experimental and predicted changes in aerodynamic efficiency caused by coolant ejection from a full-film-cooled stator blade with 12 spanwise rows of coolant holes is presented. The comparison includes efficiency changes caused by ejecting coolant from each of the 12 rows and from various combinations of coolant rows, including full-film cooling. The results of a similar study for another full-film-cooled stator blade are reported in reference 18. The subject stator blade has the same number of coolant rows, the same coolant row locations, and the same coolant hole spacing and ejection angles as the other blade, but the coolant hole diameters are 0.038 centimeter (0.015 in.) - one-half that of the other blade.

The experimental results for the subject blade, published in reference 15, were obtained from tests in a two-dimensional cascade at a nominal, primary-air, ideal, critical velocity ratio of 0.65, with the coolant and primary-air temperatures essentially equal to the ambient temperature. The predicted results were based on the two published analytical methods of references 1 and 2, called methods 1 and 2, respectively. Method 1 was used as published. Method 2 was modified from reference 2 as described in the section ANALYTICAL METHODS for coolant ejection from the diffusion region of the blade surface. The expansion and diffusion regions of the blade surface are defined as the areas on the blade surface where the local static pressure is higher or lower, respectively, than the blade-exit static pressure.

Comparative experimental and predicted results are given in terms of the percentage of change in primary efficiency relative to the efficiency of the solid uncooled blade. Primary efficiency is defined as the ratio of the actual kinetic energy of the total flow (primary plus coolant) to the ideal energy of the primary flow only. The results are compared for tested coolant fractions from 0 to about 9 percent. In comparing the results, the condition of equal total pressure of the coolant and primary flows is significant since it is representative of the first turbine stage of a gas turbine engine.

The comparative results are presented in three parts. The first part concerns single- and multirow ejection from the expansion region of the blade suction and pressure surfaces; the second part covers single-row ejection from the diffusion region of the blade suction surface; and the third part presents multirow ejection from the suction surface and also from all 12 rows (full film cooling).

Coolant Ejection from Expansion Region of Blade Surface

Single-row results. - The experimental and predicted changes in primary efficiency relative to the efficiency of an uncooled blade $\Delta\eta_p/\eta_0$ as a function of coolant fraction y for the nine test cases of single-row ejection from the expansion region of the blade surface are shown in figure 3. The two analytical methods give almost the same results for ejection from any given row, the efficiency changes for method 1 being slightly less than those for method 2 in some cases.

The agreement between experimental and predicted results for both methods shown in figure 3 is considered very good. For all cases of single-row ejection from the expansion region, over the range of tested coolant fractions, the largest difference between experimental and predicted results is less than 1/2 percent; and when $p'_{p,0} = p'_c$, the largest difference is less than 1/4 percent.

Multirow-results. - Figure 4 presents the experimental and predicted efficiency changes for the seven test cases of multirow ejection from the coolant rows in the expansion region of the blade surface. The agreement between these experimental and predicted results is about as good as that for single-row ejection (fig. 3). That is, for both methods, over the range of coolant fractions, the largest difference between experimental and predicted results is only slightly more than 1/2 percent; and when $p'_{p,0} = p'_c$, the largest difference is no greater than 1/4 percent.

Single-Row Coolant Ejection from Diffusion Region of Blade Surface

The results for the three test cases of single-row ejection from the diffusion region of the blade surfaces are shown in figure 5. For these cases, the agreement is quite good for both methods, the efficiency changes predicted by method 2 being generally greater than experimental and the efficiency changes for method 1 being generally less than experimental. For the three cases, over the range of tested coolant fractions, the predicted efficiency changes are no more than 1/4 percent greater than the experimental changes for method 2, and no more than 1/4 percent less than the experimental changes for method 1. These same maximum differences were obtained when $p'_{p,0} = p'_c$. As described in the section ANALYTICAL METHODS, method 2 predicts larger efficiency changes than method 1 for ejection from the diffusion region because method 2 neglects the compression work required to raise the static pressure of the coolant from the lower pressure at the discharge location on the blade surface to the higher pressure at the blade exit.

Multirow Coolant Ejection from Suction Surface and Coolant Ejection from All Twelve Rows of Coolant Holes

The experimental and predicted efficiency changes for the three test cases of multirow ejection from both the expansion and diffusion regions of the blade suction surface are shown in figure 6. The results are compared for four-, five-, and six-row ejection from the suction surface, with three rows in the expansion region and either one, two, or three rows in the diffusion region (fig. 2).

Both analytical methods predict the experimental efficiency changes reasonably well. However, as would be expected from the results for single-row ejection in the diffusion region, method 2 predicts larger efficiency changes than method 1. For example, for four-, five-, and six-row ejection from the suction surface, over the range of tested coolant fractions, the predicted efficiency changes are no more than about 3/4 percent greater than the experimental changes for method 2 and no more than about 1 percent less than the experimental changes for method 1. The largest difference for both methods occurs with six-row ejection. For the same three cases, when $p'_{p,0} = p'_c$, the predicted efficiency changes are no more than about 1/4 percent greater than experimental for method 2 and from about 1/4 to 1 percent less than experimental for method 1.

Figure 7 compares the results for ejection from all 12 rows on both the suction and pressure surfaces, that is, full film cooling. With full film cooling, 3 of the 12 rows are in the diffusion region of the blade surface (fig. 2). For tested coolant fractions between roughly 3 and 9 percent, the predicted efficiency changes for the two methods vary from about 1/4 to 3/4 percent greater than experimental for method 2 and from about 3/4 to 1 percent less than experimental for method 1. The differences of about 3/4 percent more than experimental for method 2 and about 1 percent less than experimental for method 1 that occur for full film cooling and six-row ejection from the suction surface (fig. 6(c)) are the maximum differences found in this study.

Referring again to figure 7 for full film cooling, when $p'_{p,0} = p'_c$, the predicted efficiency changes are about 1/4 percent greater than experimental for method 2 and about 3/4 percent less than experimental for method 1. As with the other cases of multirow ejection with partial discharge in the diffusion region, the reason for the larger efficiency change for method 2 is that method 2 neglects the compression work required with coolant ejection in the diffusion region.

CONCLUDING REMARKS

Experimental efficiency results have been compared with predicted results obtained from two analytical methods for a full-film-cooled stator blade having 12 spanwise rows of coolant holes ejecting in a streamwise direction. These experimental tests were made at a coolant to primary-air temperature ratio of 1 for coolant fractions from 0 to about 9 percent. The results for this blade indicate that either of the two prediction methods give reasonably good agreement for blades having this range of coolant fractions and angle orientation. For example, for 23 test cases of single and multirow coolant ejection, over the range of tested coolant fractions, the difference between experimental and predicted results for both methods was no greater than 1 percent for any case and less than 1/2 percent for most cases. Although the experimental and predicted results agree reasonably well for this blade, additional comparisons for different blades having different temperature ratios are necessary in order to demonstrate the general reliability of the methods.

SUMMARY OF RESULTS

Experimental results have been compared with predicted changes in aerodynamic efficiency caused by ejecting coolant from a film-cooled stator blade with 12 spanwise rows of coolant holes. The comparison includes changes in efficiency caused by ejecting coolant from each of the 12 coolant rows and from various combinations of coolant rows, including full film cooling. This is the second of two such comparisons. The subject blade had the same number of coolant rows, the same coolant row locations, and the same coolant hole spacing and ejection angles but one-half the coolant hole diameters as the first blade reported.

The predicted results were based on the same two analytical methods that were used in the comparison of the first blade reported. The methods are called method 1 and method 2 in this report. Method 1 was used as published. Method 2 was modified from the published procedure, as described in the comparison of the first blade reported, for cases of coolant ejection from the diffusion region of the blade surface. (The expansion and diffusion regions of the blade surface are defined as the parts of the blade surface where the local static pressure is higher or lower, respectively, than the static pressure at the blade row exit.)

The experimental results, previously published, were obtained from tests conducted in a two-dimensional cascade at a nominal, ideal, primary-air, critical velocity ratio of 0.65 with the coolant and primary-air temperatures essentially equal to ambient.

Experimental and predicted results are given in terms of the percentage of change in primary efficiency relative to the efficiency of the uncooled solid blade as a function of coolant fraction. Primary efficiency is defined as the ratio of the actual kinetic energy of the total flow (primary plus coolant) to the ideal kinetic energy of the primary flow only. The summarized results that follow give the largest differences between experimental and predicted results for the range of coolant fractions investigated.

1. The level and trends of experimental efficiency change are predicted reasonably well by both analytical methods. For example, for 23 different cases of single- and multirow ejection over a range of coolant fractions from 0 to about 9 percent, the difference between predicted and experimental results was no greater than about 1 percent for either method.

2. The maximum differences between experimental and predicted results for both methods occur for cases of multirow ejection when part of the coolant is discharged from the three rows in the diffusion region of the blade suction surface. For example, with full film cooling, the predicted efficiency changes are about 3/4 percent greater than the experimental changes for method 2 and about 1 percent less than the experimental changes for method 1. A similar comparison for ejection from all six rows on the suction surface shows results that are almost the same as for full-film cooling.

3. Method 2 predicts higher efficiencies than method 1 for coolant ejection from the diffusion region because it neglects the compression work required to raise the pressure of the coolant ejected in this region. This is indicated by results for three cases of single-row ejection in the diffusion region, for which the predicted changes are no more than 1/4 percent greater than the experimental changes for method 2 and no more than 1/4 percent less than the experimental changes for method 1.

4. For 16 cases of single- and multirow ejection from the expansion region of the blade surface, the largest difference between the experimental and predicted efficiency changes was no more than about 1/2 percent for either method.

Lewis Research Center,
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505-04.

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TABLE I. - COOLANT HOLE SPECIFICATIONS[a]

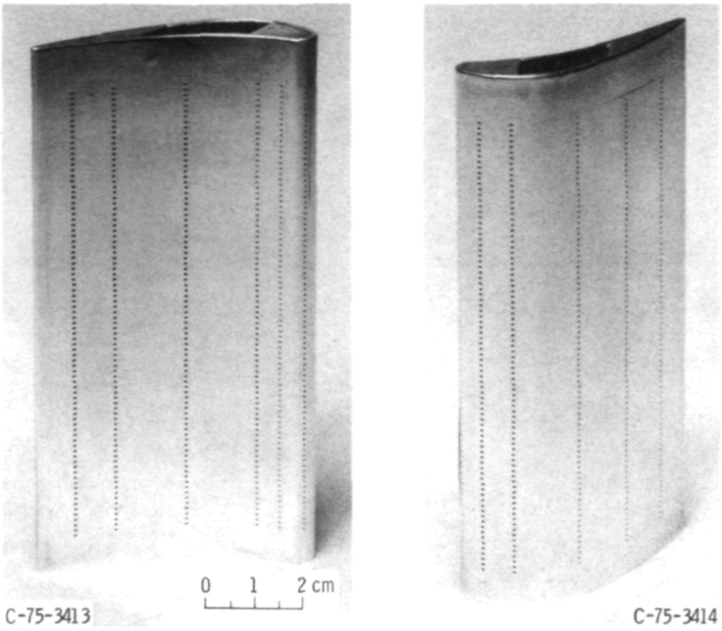
Coolant hole row	Fraction of blade surface length from leading edge to coolant row exit, x/L_{pr} or x/L_s	Angle between coolant hole axis and tangent to local blade surface in plane parallel to blade end walls, β, deg	Coolant hole length-to-diameter ratio, L/D
1	0.035	90	4.4
2	.12	34	7.4
3	.20	33	6.6
4	.45	35	↓
5	.70	33	↓
6	.85	34	↓
7	.035	90	4.4
8	.105	36	7.4
9	.20	39	9.0
10	.40	38	8.0
11	.60	38	7.6
12	.80	35	7.6

[a] Coolant hole diameter, 0.038 cm (0.015 in.); coolant hole spanwise pitch, 0.114 cm (0.045 in.).

TABLE II. - COOLANT HOLE MULTIROW

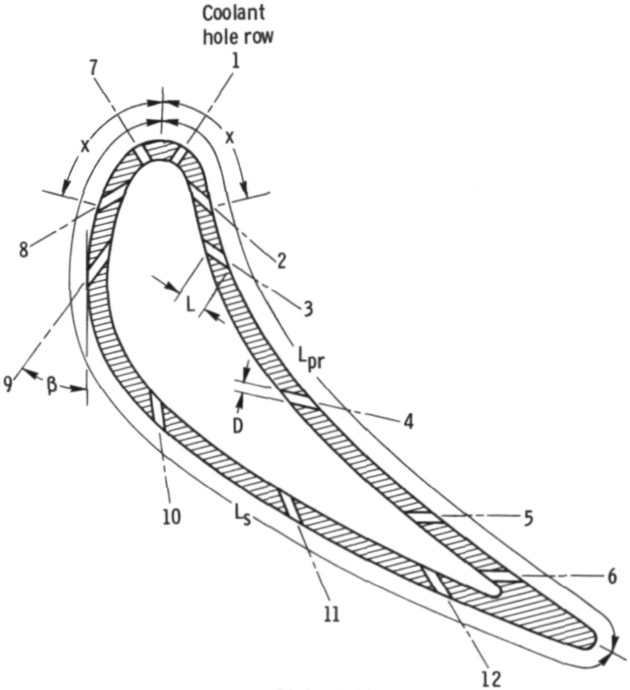
CONFIGURATIONS TESTED

Configuration	Coolant hole rows included	Region of blade surface
1	1 and 2	Pressure surface
2	1 to 3	↓
3	1 to 4	↓
4	1 to 5	↓
5	1 to 6	↓
6	7 and 8	Suction surface
7	7 to 9	↓
8	7 to 10	↓
9	7 to 11	↓
10	7 to 12	↓
11	1 to 12	Both pressure and suction surfaces



(a) Pressure surface.

(b) Suction surface.



(c) Blade profile.

Figure 1. - Film-cooled stator blade.

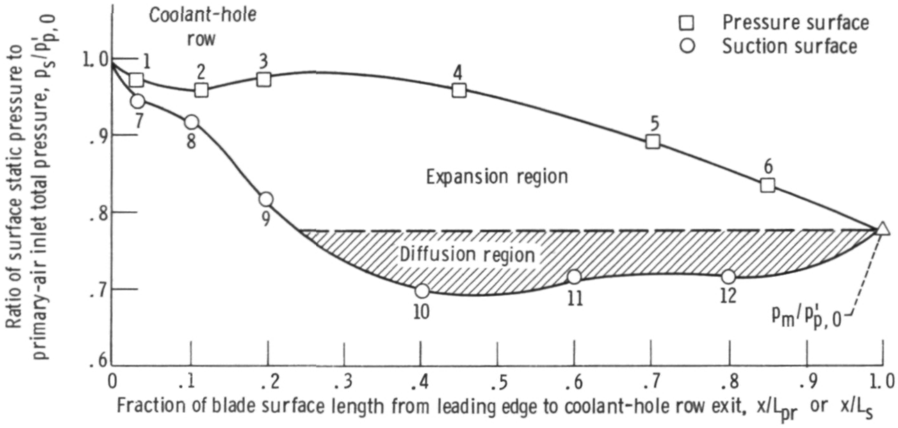
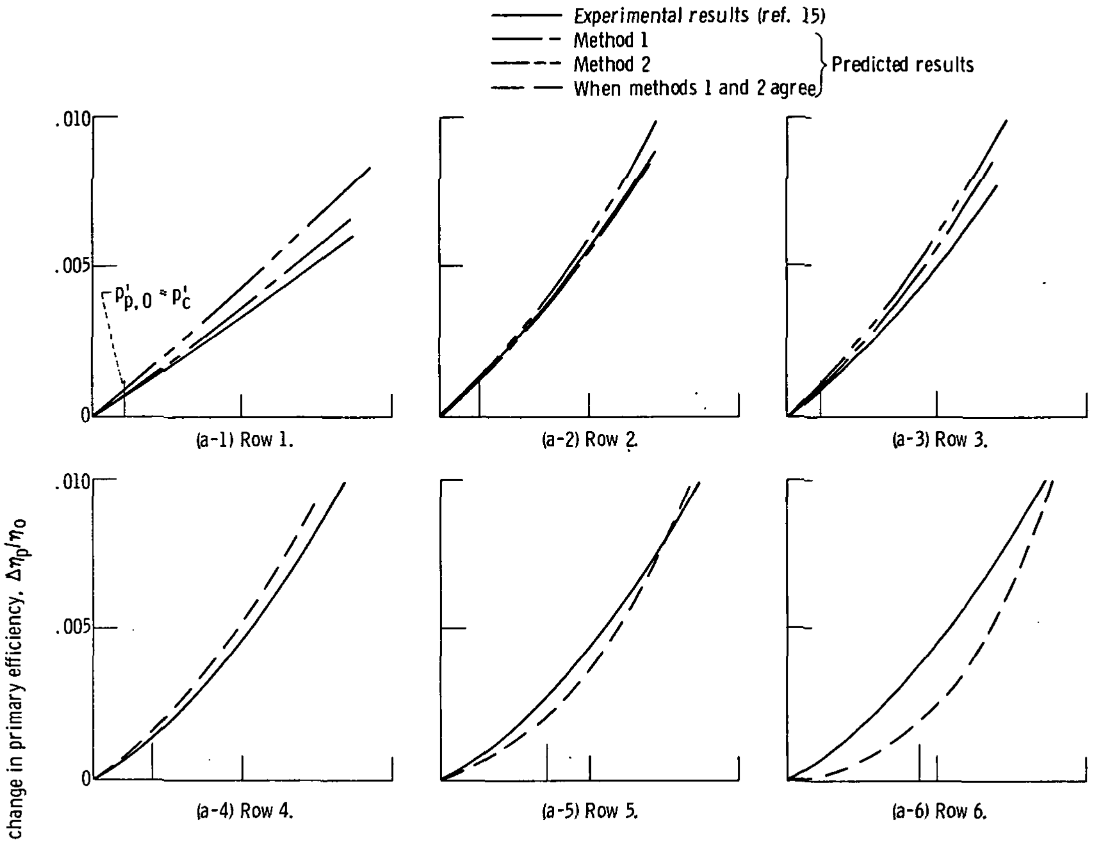


Figure 2. - Comparison of coolant-hole-row local static pressures on suction and pressure surfaces of blades for primary-air critical velocity ratio $(V/V_{cr})_{p,id,m}$ of 0.65.



(a-1) Row 1.

(a-2) Row 2.

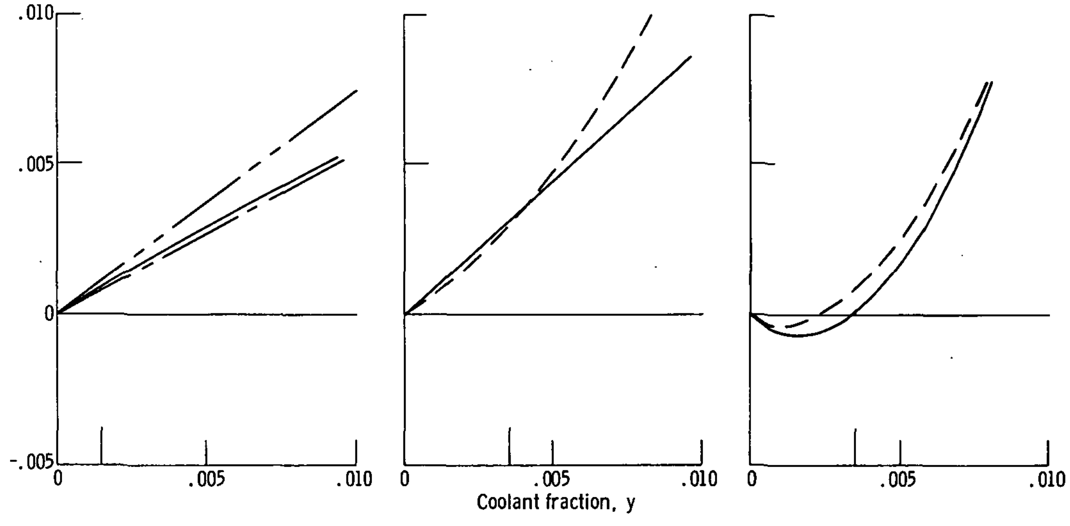
(a-3) Row 3.

(a-4) Row 4.

(a-5) Row 5.

(a-6) Row 6.

(a) Pressure surface.



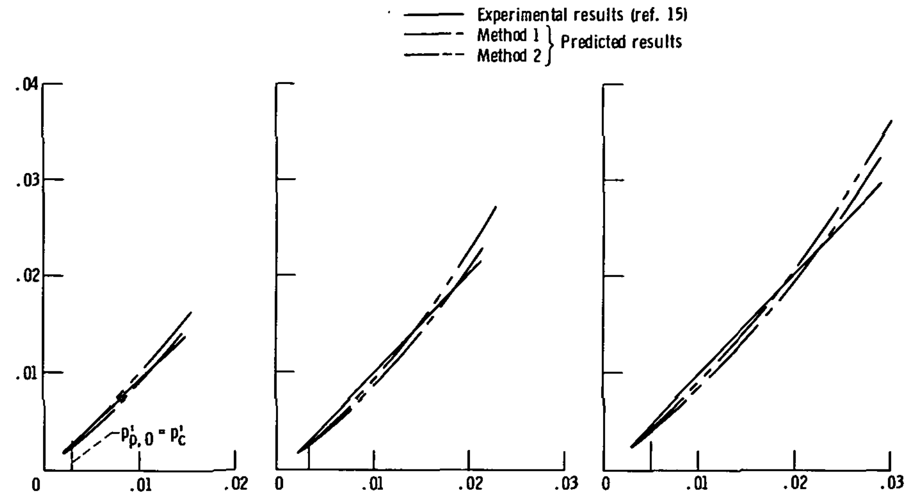
(b-1) Row 7.

(b-2) Row 8.

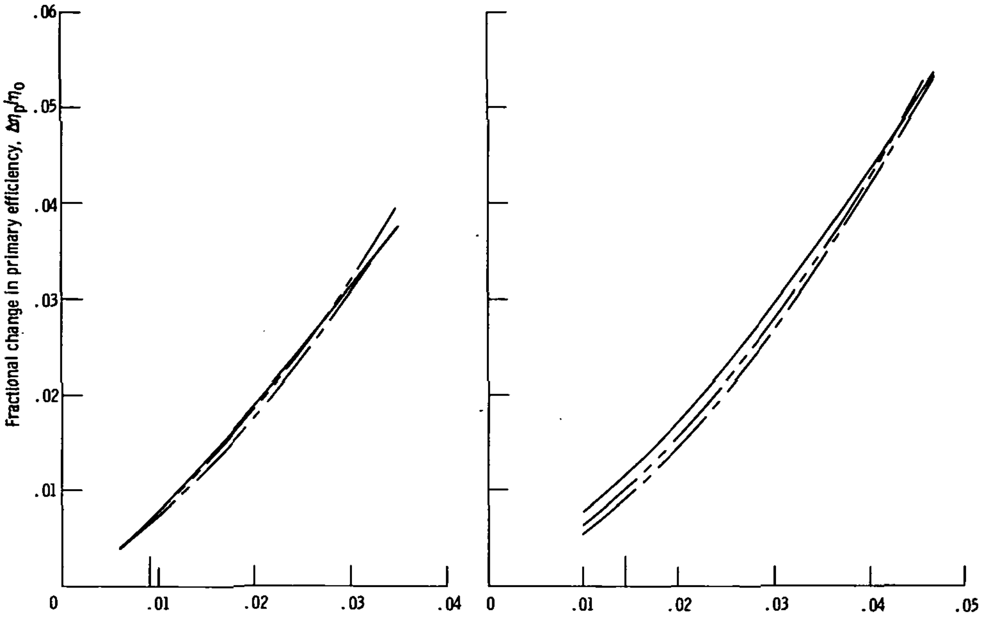
(b-3) Row 9.

(b) Suction surface.

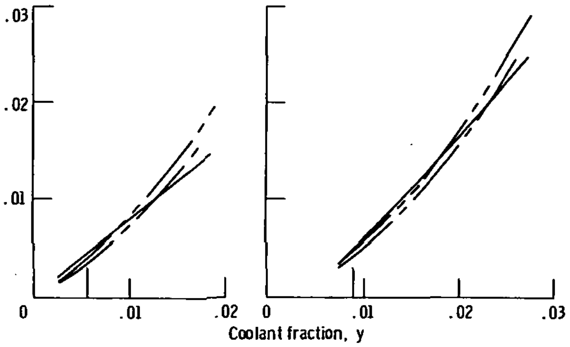
Figure 3. - Comparison of predicted and experimental changes in efficiency for single-row coolant ejection in expansion region of blade surface.



(a) Rows 1 and 2. (b) Rows 1 to 3. (c) Rows 1 to 4.

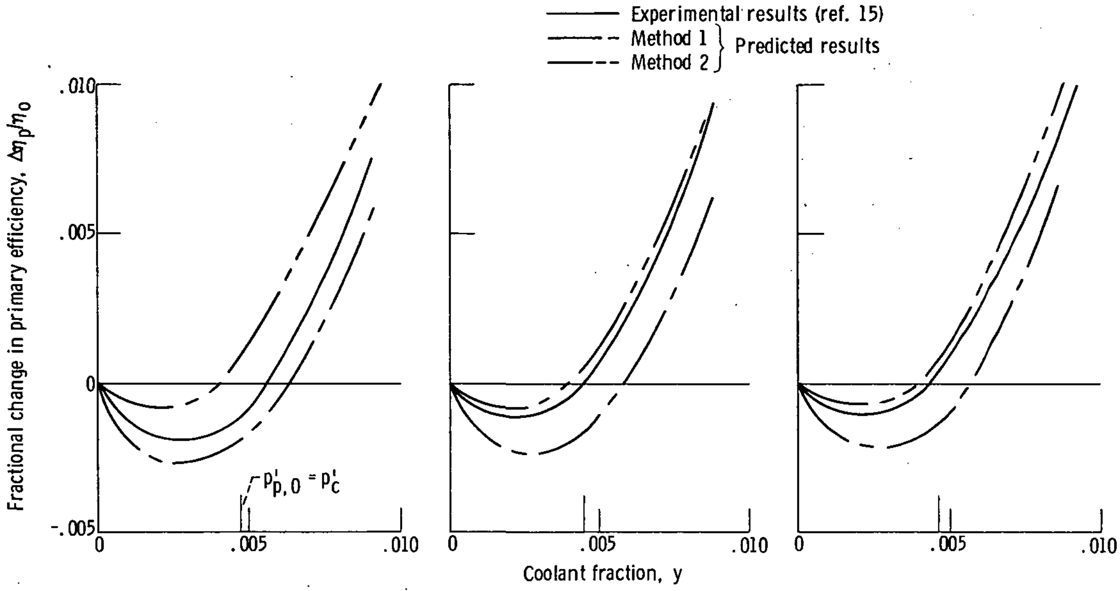


(d) Rows 1 to 5. (e) Rows 1 to 6.



(f) Rows 7 and 8. (g) Rows 7 to 9.

Figure 4. - Comparison of predicted and experimental changes in efficiency for multirow coolant ejection in expansion region of blade surface.

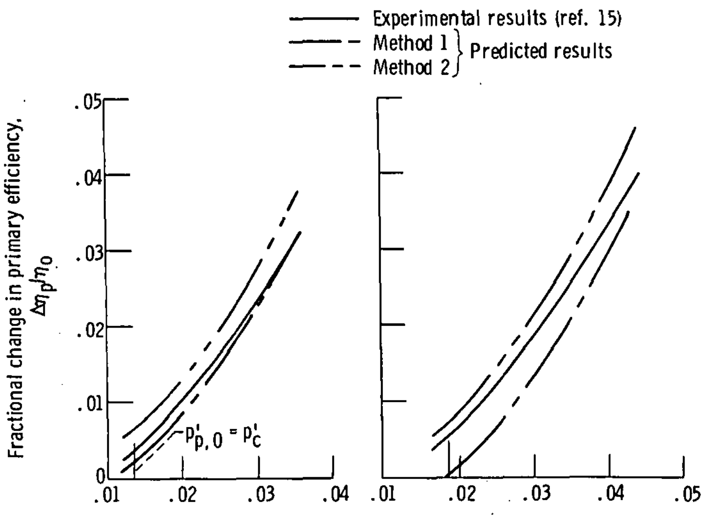


(a) Row 10.

(b) Row 11.

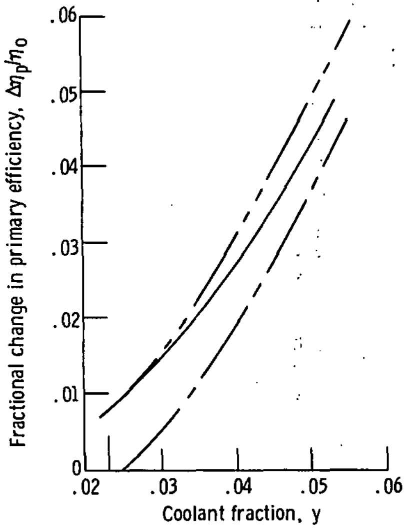
(c) Row 12.

Figure 5. - Comparison of predicted and experimental changes in efficiency for single-row coolant ejection in diffusion region of blade suction surface.



(a) Rows 7 to 10.

(b) Rows 7 to 11.



(c) Rows 7 to 12.

Figure 6. - Comparison of predicted and experimental changes in efficiency for simultaneous coolant ejection from expansion and diffusion regions of blade suction surface.

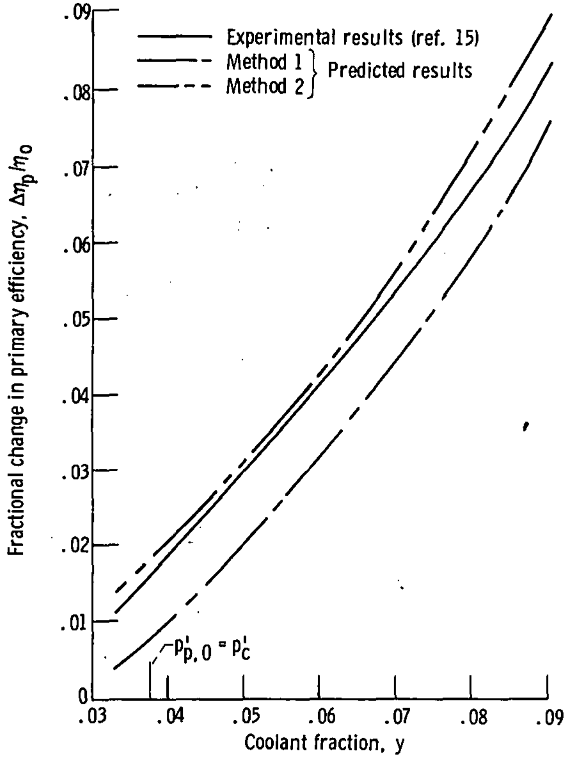


Figure 7. - Comparison of predicted and experimental changes in efficiency for coolant ejection from all 12 coolant rows (full film cooling).

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16. Abstract

Published experimental aerodynamic efficiency results were compared with results predicted from two published analytical methods. This is the second of two such comparisons. One of the analytical methods was used as published; the other was modified for certain cases of coolant discharge from the blade suction surface. The results show that for 23 cases of single-row and multirow discharge covering coolant fractions from 0 to about 9 percent, the difference between the experimental and predicted results was no greater than about 1 percent in any case and less than 1/2 percent in most cases.

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