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EFFECT OF ROTOR TIP CLEARANCE ON THE PERFORMANCE OF A 5-INCH SINGLE-STAGE AXIAL-FLOW TURBINE

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ABSTRACT

Turbine efficiency decreased linearly with increasing rotor tip clearance. Static efficiency decreased 20 percent (0.79 to 0.63) as rotor tip clearance was increased from 1.2 to 8.0 percent of passage height. Rotor exit flow survey data are presented in addition to performance data. Comparison of data with three reference turbines substantiated the results obtained and indicated that rotor tip clearance effects are larger for a reaction turbine than for an impulse turbine.

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SUMMARY

An experimental investigation was made to determine the effects of increasing rotor tip clearance on the performance of a 5-inch (13-cm) axial-flow turbine. Four rotor tip clearance ranging from 1.2 to 8.0 percent of passage height were studied. Argon was used as the working fluid. The turbine was operated at constant design pressure ratio and over a range of speeds. The turbine static efficiency decreased 20 percent (0.79 to 0.63) as the rotor tip clearance was increased from 1.2 to 8.0 percent. Mass flow rate showed a 6-percent increase over the same range of rotor tip clearances. Comparison of the results of these tests with results of two other reaction turbines indicated similar effects of clearance on efficiency. Comparison with results of tests of an impulse turbine indicated that the rotor tip clearance effects were larger for the reaction turbines than for the impulse turbine.

INTRODUCTION

As part of the space-power program being conducted at the NASA Lewis Research Center, the study of various factors affecting the performance of small turbines suitable for this application is being made. One of these factors is rotor tip clearance. Large clearances are desired from a mechanical standpoint in order to allow for thermal growth of parts as well as to reduce the possibility of accidental rubs with subsequent failure. Such clearances are, however, imposed at the expense of aerodynamic performance of the turbine which is particularly important for the application being considered.

As part of this general program, Kofskey and Nusbaum (ref. 1) studied the performance of a high-reaction two-stage alternator drive turbine at two tip clearances. The results of this reference investigation indicated a substantial effect of clearance on performance with a 3.7-percent reduction in efficiency for each percent increase in clearance-to-height ratio. A broader interpretation of the results, however, could not be made because of the limited number of clearances studied.

In order to more fully explore this effect, a second high-reaction, axial-flow turbine was investigated. This turbine was 5 inches (13 cm) in diameter and was a single-stage turbine. It was designed for driving a six-stage axial-flow compressor in a 10-kilowatt two-shaft space-power system. Its design is presented in reference 2, and results of performance studies are described in references 3 and 4.

In this study four rotor tip clearances were investigated. The first was the design tip clearance, which was 1.2 percent of the annular passage height. The rotor tip diameter was then reduced by grinding to obtain the other three tip clearances. These clearances were 3.1, 5.0, and 8.0 percent of the passage height.

The tests were conducted with argon, which was the design working fluid. Inlet pressure was held constant at 9.5 psia (6.6 N/cm^2) and the inlet temperature was 582° R (323 K). These conditions provide a Reynolds number of 316 000, which is about three times that of design Reynolds number. It was judged that the effects of tip clearance could be more accurately measured at a high Reynolds number.

This report presents the performance of the turbine at each of the four tip clearances. Data are presented at design total- to static-pressure ratio, over a range of speeds. The effect of rotor tip clearance on performance of this turbine is also compared with similar data for two other reaction turbines (refs. 1 and 5) as well as an impulse turbine (ref. 6).

SYMBOLS

p	absolute pressure, psia (N/cm^2)
Re	Reynolds number, $w/\mu r_m$
r_m	mean section radius, ft (m)
T	absolute temperature, $^{\circ}$R (K)
U	blade velocity, ft/sec (m/sec)
V	absolute gas velocity, ft/sec (m/sec)
V_j	ideal jet speed corresponding to total- to static-pressure ratio across turbine, ft/sec (m/sec)
W	relative gas velocity, ft/sec (m/sec)
w	mass flow rate, lb/sec (kg/sec)

α absolute gas flow angle measured from axial direction, positive when tangential velocity component agrees with direction of rotation, deg

γ ratio of specific heats

δ ratio of inlet total pressure to U. S. standard sea-level pressure

ϵ function of γ used in relating parameters to those using air inlet conditions at U. S. standard sea-level conditions, $\frac{\gamma^*}{\gamma}\left[\frac{\left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)}}{\left(\frac{\gamma^*+1}{2}\right)^{\gamma^*/(\gamma^*-1)}}\right]$

η static efficiency (based on inlet-total- to exit-static-pressure ratio)

η' total efficiency (based on inlet-total- to exit-total-pressure ratio)

θ_{cr} squared ratio of critical velocity at turbine inlet to critical velocity at U. S. standard sea-level temperature, $\left(V_{cr}/V_{cr}^*\right)^2$

μ gas viscosity, lb/(ft)(sec), $(N)(sec)/m^2$

ν blade-jet speed ratio, U_m/V_j

Subscripts:

cr condition corresponding to Mach 1

eq air equivalent (U. S. standard sea level)

1 station at turbine inlet

2 station at stator inlet

3 station at stator exit

4 station at rotor exit

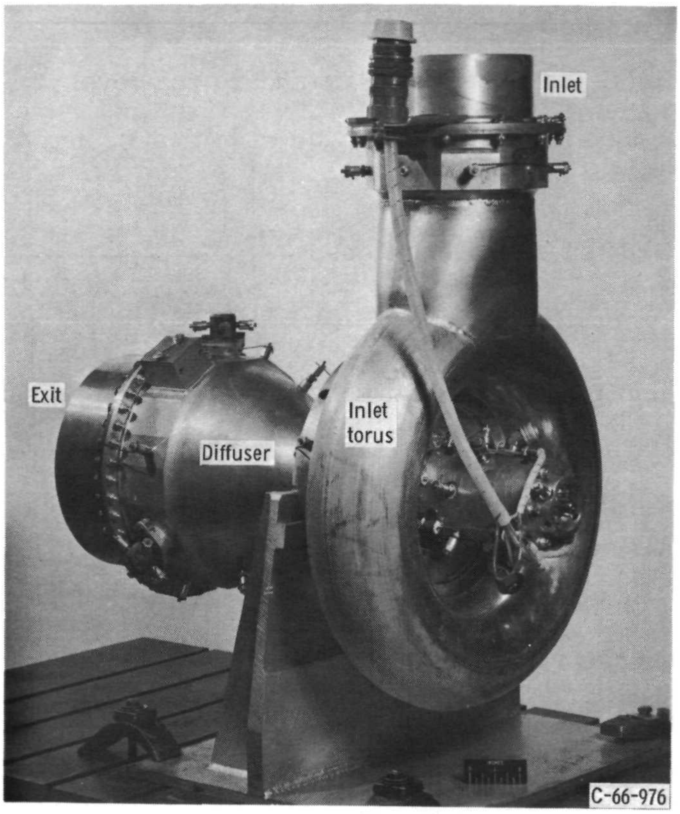
Superscripts:

' absolute total state

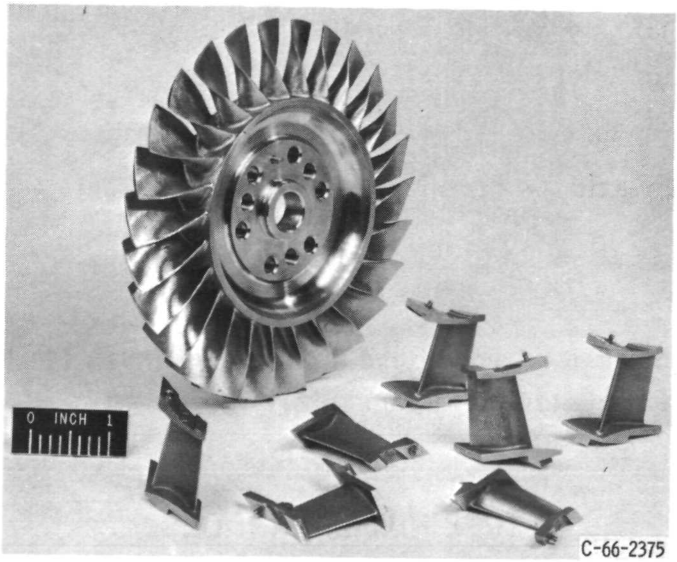
* U. S. standard sea-level conditions (temperature, 518.67° R (288.15 K); pressure, 14.696 psia (10.128 N/cm^2 abs))

TURBINE DESCRIPTION

A 5-inch (13-cm) single-stage axial-flow turbine was used for this investigation. Previous tests conducted with this turbine have been reported in references 3 and 4, with



(a) Assembled turbine.



(b) Turbine rotor and stator blades.

Figure 1. - Research turbine.

reference 3 presenting a detailed description of the turbine. The aerodynamic and mechanical design and the fabrication of this turbine were performed by Pratt and Whitney Aircraft Company. Reference 2 is their report on this project.

Photographs of the turbine are shown in figure 1. Figure 1(a) shows the research turbine assembly, and figure 1(b) shows the turbine rotor and some of the stator blades. All tests were performed with the diffuser attached as shown in figure 1(a). However, data at a station at the exit of the diffuser were not included for this test since it was felt that these data would not contribute findings significant to the effect of rotor tip clearance on performance.

A cross-sectional view of the turbine flow passages is shown in figure 2. Pertinent geometric measurements for the turbine are as follows. The rotor tip diameter was

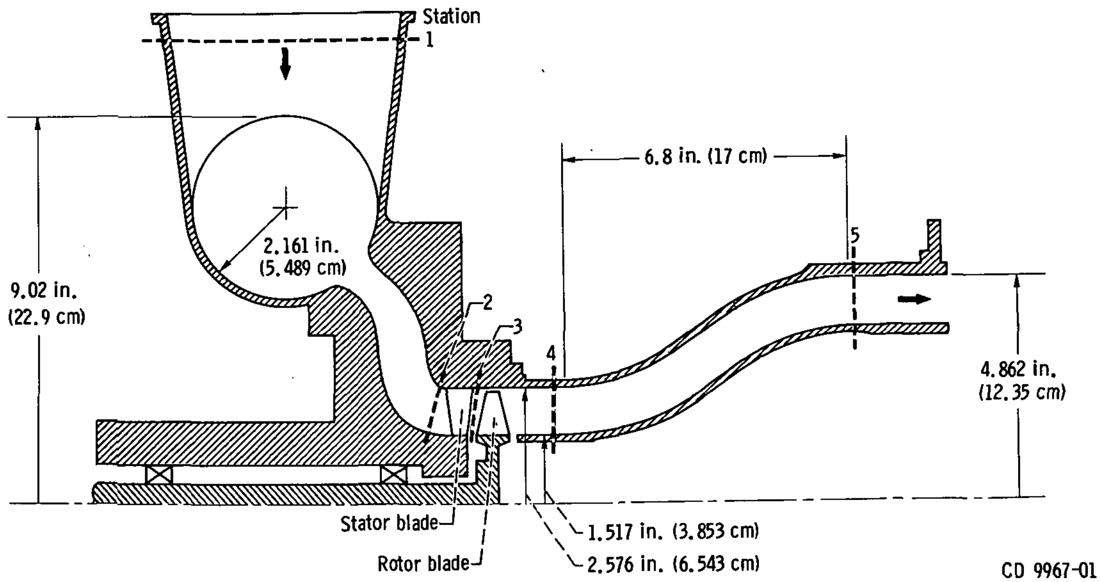


Figure 2. - Cross section of turbine.

5.126 inches (13.02 cm). The average design tip clearance was 0.013 inch (0.033 cm), which is about 1 percent of the blade height. Rotor blade height was 1.036 inches (2.631 cm) with a hub-tip radius ratio of 0.6.

The design-point values for this turbine are listed in table I. Values are tabulated for both argon and air (corrected to U.S. standard sea-level conditions) as the working fluid.

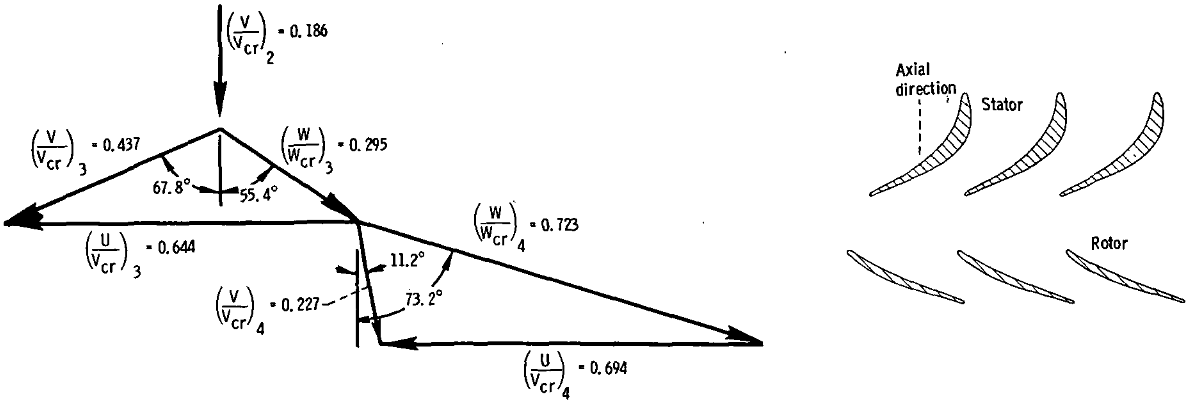
TABLE I. - TURBINE DESIGN VALUES

Design parameters	Argon		Air equivalent (a)	
	Symbol	Value	Symbol	Value
Inlet total temperature, ^{o}R (K)	T'_1	1950 (1083)	---------	-------------
Inlet total pressure, psia (N/cm^2)	p'_1	13.20 (9.10)	---------	-------------
Mass flow rate, lb/sec (kg/sec)	w	0.611 (0.277)	$w\epsilon\sqrt{\theta_{cr}}/\delta$	1.06 (0.48)
Turbine speed, rpm	N	50 000	$N/\sqrt{\theta_{cr}}$	29 260
Specific work Btu/lb (J/g)	Δh	32.82 (76.34)	$\Delta h/\theta_{cr}$	11.24 (26.14)
Torque, in.-lb (N-m)	τ	35.8 (4.04)	$\tau\epsilon/\delta$	36.3 (4.10)
Ratio of inlet total pressure to rotor-exit total pressure	p'_1/p'_4	1.543	$(p'_1/p'_4)_{eq}$	1.482
Ratio of inlet total pressure to rotor-exit static pressure	p'_1/p_4	1.592	$(p'_1/p_4)_{eq}$	1.524
Rotor-exit total efficiency	η'_{1-4}	0.849	η'_{1-4}	0.849
Rotor-exit static efficiency	η_{1-4}	0.796	η_{1-4}	0.796
Reynolds number	Re	93 100	---------	-------------
Ratio of blade speed to jet speed	ν	0.621	ν	0.621

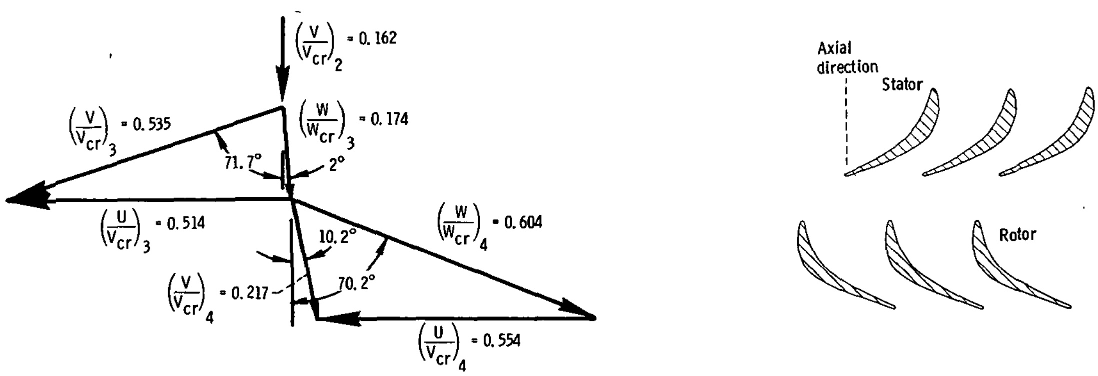
[a]U. S. standard sea-level conditions.

The design turbine velocity diagrams, from the basic performance report (ref. 3) are presented in figure 3. The velocities are shown and labeled in terms of critical velocity ratios. A list of velocities, in feet per second, with pressures and temperatures in the turbine is contained in table 2 of reference 2. Examination of the velocity diagram shows this turbine to be a subsonic reaction turbine. A reaction turbine has a static-pressure drop with an acceleration of flow through the rotor. The amount of reaction present in a turbine is usually discussed in terms of the percent reaction. The definition of reaction used here is the ratio of relative specific kinetic energy increase in the rotor to the turbine specific work, expressed as a percent. Using this definition, the reaction at the hub is 22 percent, at the mean 56 percent, and at the tip 73 percent.

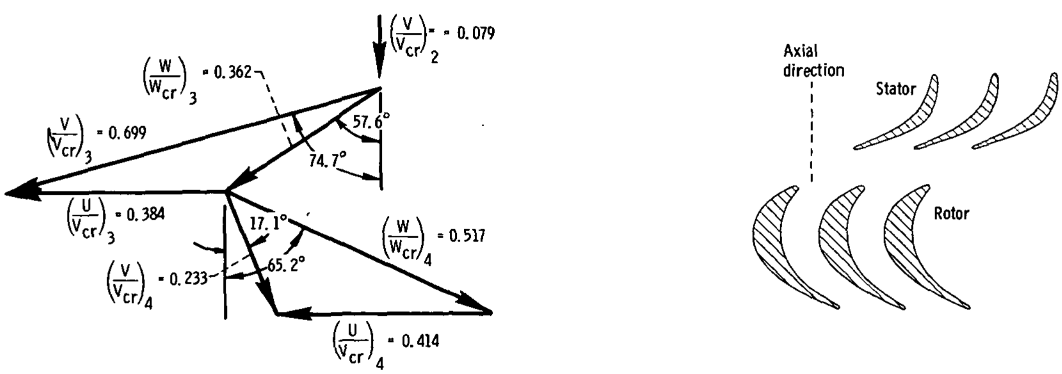
The turbine stator had 30 blades designed for conventional converging flow passages. Figure 3 shows stator and rotor blade profiles for hub, mean, and tip sections. The rotor had 26 blades, and the blade twist, which was considerable, can be seen by comparing blade profiles of figure 3. Figure 1(b) also shows the twist of the rotor blades.



(a) Tip.



(b) Mean.



(c) Hub.

Figure 3. - Design velocity diagrams and blade profiles.

APPARATUS

The apparatus consisted of the turbine, an airbrake dynamometer, and an inlet and exhaust piping system. The arrangement of the apparatus is shown schematically in figure 4. Pressurized argon was used as the driving fluid for the turbine. The argon was heated by an electrical heater and was filtered; it then passed through a weight-flow measuring station having a calibrated choked-flow nozzle. After passing through the turbine, the argon was exhausted into the laboratory exhaust system. A pressure regulator upstream of the turbine maintained the turbine-inlet pressure. With a fixed inlet

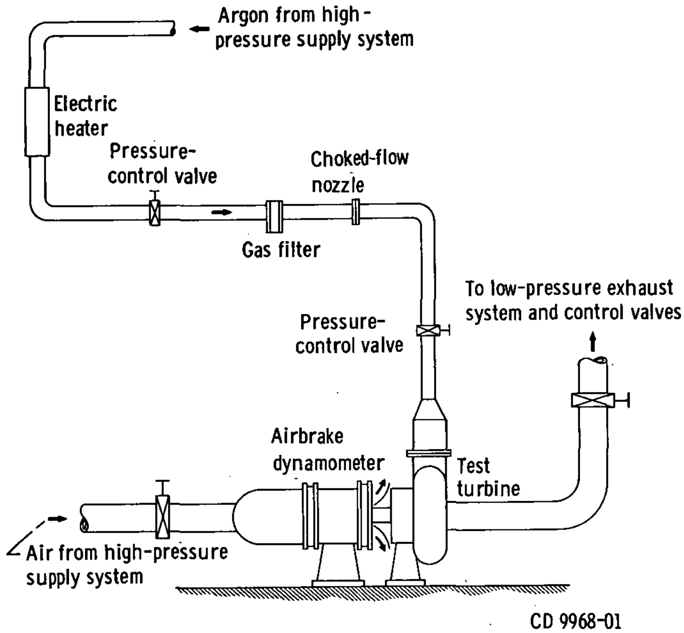


Figure 4. - Experimental equipment.

pressure, a remotely controlled valve in the exhaust line was used to maintain the desired pressure ratio across the turbine. The airbrake dynamometer used was the same as described in reference 3. The dynamometer was used to absorb the turbine output power and to obtain the desired turbine speed.

INSTRUMENTATION

The measuring stations are shown in figure 2. At station 1 instruments included static-pressure taps and a total-temperature rake. Static pressure taps were also located at stations 2, 3, and 4. A self-alining probe for flow angle, total pressure, and total temperature measurements was located at station 4. Calibrated pressure transducers were used for these tests. Torque was measured with commercial stain gage load cell, and speed was measured with electromagnetic pickups and a shaft mounted gear. A more detailed discussion of instrumentation may be found in references 3 and 4. All data were recorded on an integrating digital data recorder. A digital computer processed all data.

PROCEDURE

The turbine was tested at four different rotor blade tip clearances in order to obtain tip clearance effects on performance. These clearances and corresponding percentages of passage height are as follows:

Clearance		Percentage of passage height
in.	cm	
0.013	0.033	1.2
.032	.081	3.1
.052	.132	5.0
.084	.213	8.0

The tip clearances were obtained by successive grinding operations on the rotor tip.

At each of the four rotor tip clearances, data were taken at fixed inlet pressure, inlet temperature, and at design total- to static-pressure ratio. The turbine speed was varied from 50 to 110 percent of equivalent design speed in order to obtain data over a range of blade-jet speed ratios.

Test conditions for the investigation were

Inlet total pressure, p'_1, psi; N/cm^2 . . . . 9.5; 6.6
Inlet total temperature, T'_1, ^{o}R; K 582; 323
Pressure ratio, $(p'_1/p_4)_{eq}$ 1.52
Speed range, percent of equivalent design speed . . . . 50, 70, 90, 100, and 110

At a clearance of 1.2 percent limitations of the dynamometer prevented testing at 50 percent of design equivalent speed. The lowest speed obtained at this clearance was 59 percent.

All tests were conducted using argon. For the above inlet conditions the turbine Reynolds number was 316 000 for design-point operation. The turbine design Reynolds number is 93 100. The Reynolds number, as used in this report, is defined as $Re = w/\mu r_m$, where w is the turbine mass-flow rate, μ is the gas viscosity at the turbine-inlet total conditions, and r_m is the radius of the rotor at the mean section of the blades.

Bearing friction, seal friction, and external windage torque used in calculation of the turbine torque was the same as in reference 3, (e.g., 0.74 (in.)(lb), 0.08 (N)(m) at equivalent design speed).

The performance calculations were made in the same manner as reported in reference 3. The turbine total efficiency as presented was computed from a calculated total pressure at the rotor exit. The calculated total pressure was obtained from measured values of flow angle, static pressure, and mass flow rate. The flow angle used was obtained from an angle probe that was set at mean radius. Radial gradients in flow angle, therefore, are not included in this calculation.

Radial surveys of flow were conducted at one circumferential position at the rotor exit for each tip clearance investigated. The turbine was operated at equivalent design speed and pressure ratio for these tests. Total temperature, total pressure, and flow angle data were taken at 16 radial positions with a self-balancing probe. Radial surveys of flow were not made at the stator exit because instrumentation could not be installed.

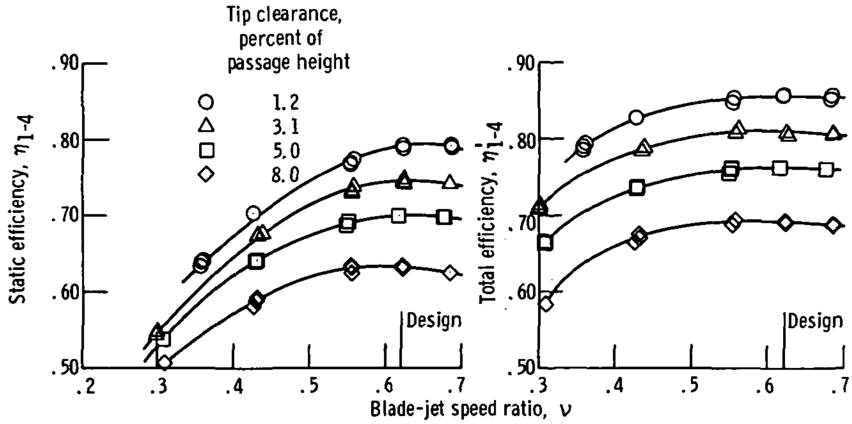
RESULTS AND DISCUSSION

The results of this investigation are presented in three sections. The first section describes the turbine performance at the four rotor tip clearances. Results of radial surveys at rotor exit are then presented in the second section. Finally, in the third section a comparison of the results obtained from this investigation will be made with those of references 1, 5, and 6.

Overall Performance

The effect of the rotor tip clearance variation on turbine efficiency is shown in figure 5 where total and static efficiencies are shown as a function of blade-jet speed ratio for each of the four clearances investigated. In each figure the curves shown are similar to each other for each clearance but the level of efficiency decreases markedly with increasing clearance.

The total and static efficiencies at the design blade-jet speed ratio of 0.621 were taken from figure 5 and tabulated in table II. This information was also used to obtain



(a) Static efficiency. (b) Total efficiency.

Figure 5. - Variation of efficiency with blade-jet speed ratio at design pressure ratio for four tip clearances.

TABLE II. - EXPERIMENTAL EFFICIENCIES FOR FOUR ROTOR TIP CLEARANCES

[Ratio of blade speed to jet speed, 0.621.]

Tip clearance		Percent of passage height	Efficiency	
in.	cm		Static	Total
0.013	0.033	1.2	0.79	0.86
.032	.081	3.1	.74	.81
.052	.132	5.0	.70	.76
.084	.213	8.0	.63	.69

the effect of clearance on efficiency as shown in figure 6. Here, the change in efficiency from that at the minimum clearance, expressed in percent, is shown as a function of the rotor tip clearance, which is expressed as a percent of annular passage height. The figure shows an approximately linear decrease in both efficiencies with increasing rotor tip clearance. At a tip clearance ratio of 8 percent the static efficiency has decreased 20 percent (efficiency change from 0.79 to 0.63) from that at the 1.2 percent clearance ratio. A similar reduction was also obtained for the total efficiency. From these results it can be determined that over the range of clearances investigated a 1-percent increase in rotor tip clearance to height ratio resulted in a reduction in either total or static efficiency of approximately 3.2 percent.

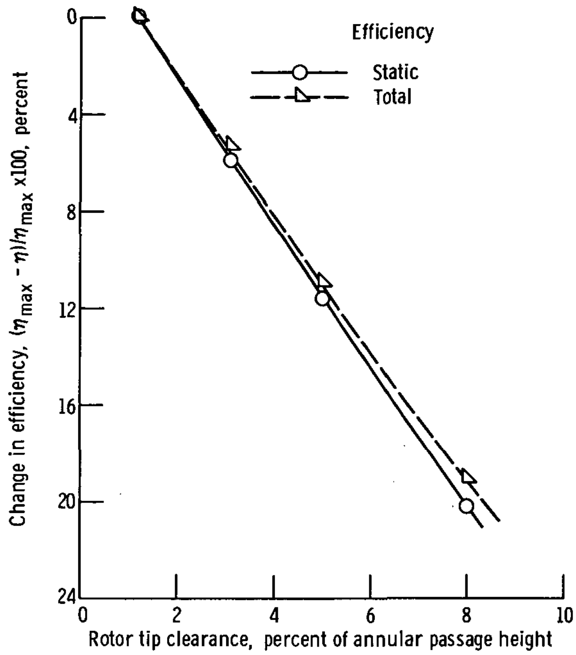


Figure 6. - Effect of rotor tip clearance on performance at design equivalent speed and pressure ratio.

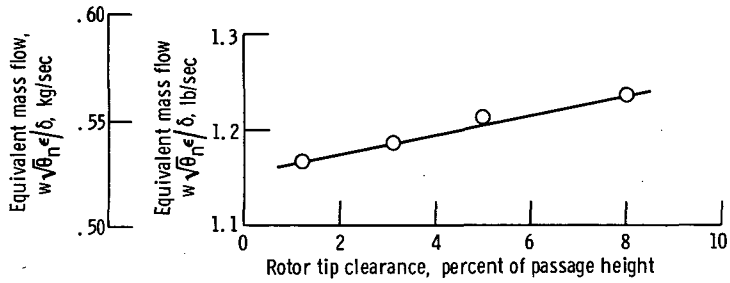


Figure 7. - Effect of rotor tip clearance on equivalent mass flow at design equivalent speed and pressure ratio.

The equivalent mass flow variation with rotor tip clearance at design speed and pressure ratio is shown in figure 7. This figure shows that the mass-flow rate increases with increasing rotor tip clearance. A 6-percent increase occurred over the rotor tip clearance range tested. This increase also appears to be linear for the range of tip clearances investigated. An increase in mass flow rate would normally be expected in a subsonic turbine since the rotor flow area is increased by removing material from the rotor blade. However, the percentage increase in mass flow rate was somewhat larger than the percentage increase in flow area. This is evidently caused by a combination of high velocities at the rotor tip region, radial-flow gradients, and leakage over the rotor blade tips.

Rotor Exit Radial Surveys

Surveys of exit flow angle, total pressure, and total temperature were made radially at the rotor exit at design speed and total- to static-pressure ratio. These surveys were conducted at one circumferential position. The results of these surveys are presented in figure 8 where exit flow angle, total pressure data, and total efficiency are shown plotted against radius ratio. Total temperature data were taken for the purpose of calculating mass-weighted values for the average exit flow angle and radial variation in efficiency.

Figure 8(a) shows the exit flow angle variation with radius ratio for the four rotor tip clearances investigated. This figure shows that the exit flow angle changes considerably. Two effects are noted. First, the exit flow angle in the tip region changes with changes of rotor tip clearance. At the smallest rotor tip clearance of 1.2 percent the measured exit flow angle near the tip was near axial. At the largest tip clearance of 8 percent the measured exit flow angle near the tip was about 40° from axial, thus showing a large change. The second effect is that the average flow angle across the passage varies with changes of tip clearance. As the tip clearance was increased, the average exit flow angle moved to the axial direction showing progressive underturning as more fluid flowed through the clearance. This would be expected even without an efficiency change, due to the effective increase in rotor throat area with subsequent change in reaction split between the stator and rotor.

Mass averaged flow angle values were computed and are as follows:

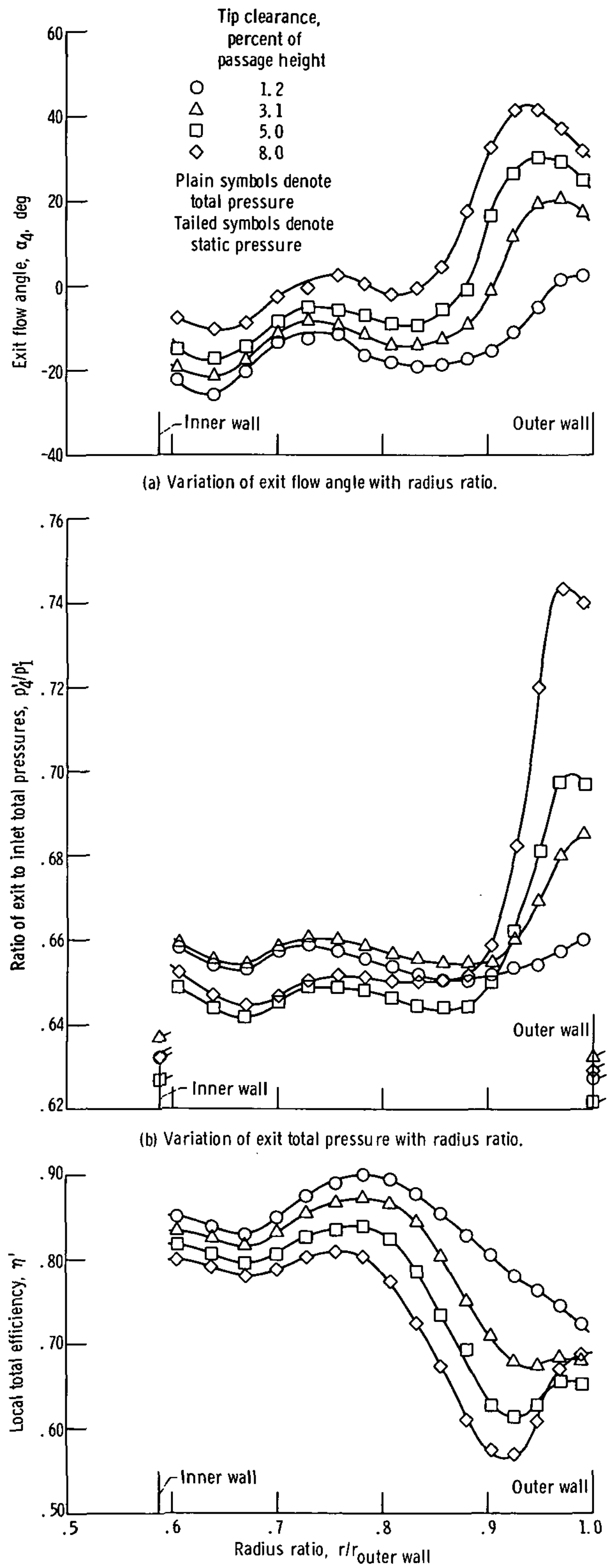
1.2 percent tip clearance, deg	-13.6
3.1 percent tip clearance, deg	-3.4
5.0 percent tip clearance, deg	+5.0
8.0 percent tip clearance, deg	+15.3

These values are more positive in direction than the measured flow angles at the mean radius due to the increased flow that occurs in the tip region as the tip clearance is increased.

The exit flow angle variation of reference 3 is different from the data presented in this report for the same tip clearance. This could be due to different Reynolds numbers at which the data were taken. Data of reference 3 were taken at a Reynolds number of about 95 000, whereas data for this report were taken at Reynolds number of 316 000.

Radial variation in total pressure at the rotor exit is presented in figure 8(b) for the four rotor tip clearances investigated. Also shown are the average measured wall-static pressures, which indicate slight deviations from the desired constant value set for the surveys. All data shown have been normalized by dividing by the turbine-inlet total pressure. The curves are similar except for the tip region. The effect of increasing tip clearance can easily be seen by the rise in exit total pressure at the tip.

Figure 8(c) presents the variation of total efficiency across the passage for the four



(a) Variation of exit flow angle with radius ratio.

(b) Variation of exit total pressure with radius ratio.

(c) Variation of total efficiency with radius ratio.

Figure 8. - Survey results at rotor exit at design equivalent speed and pressure ratio.

rotor tip clearances investigated. The local total efficiency was calculated from total temperature and total pressure data taken during the radial surveys of flow. Figure 8(c), shows the large variation in local efficiency that occurs across the passage. Also shown is that, as the rotor tip clearance increases, the total efficiency decreases. The largest change in total efficiency occurs in the blade portion from the mean radius to the tip, thus showing that the flow is affected by changes in tip clearance over a large portion of the blade. The change in efficiency in the region from the hub to the mean could be attributed to the change in the stator and rotor reaction as clearance is increased.

Comparison of Results With Other Turbine Investigations

Data from the turbine investigated in this report and from three other experimental investigations will be compared in this section. References 1, 5, and 6 present the results of the other experimental investigations. Figure 9 shows, for the various turbines, the percentage change in turbine static efficiency as the rotor tip clearance is increased. The rotor tip clearance again is expressed as a percentage of annular passage height.

Figure 9 again shows that for the 5-inch (13-cm) axial turbine (described in this report) the decrease in efficiency is linear with increasing rotor tip clearance. A 20-percent change (0.79 to 0.63) in static efficiency occurred when the rotor tip clearance was increased from 1.2 to 8 percent. As mentioned in the INTRODUCTION and in

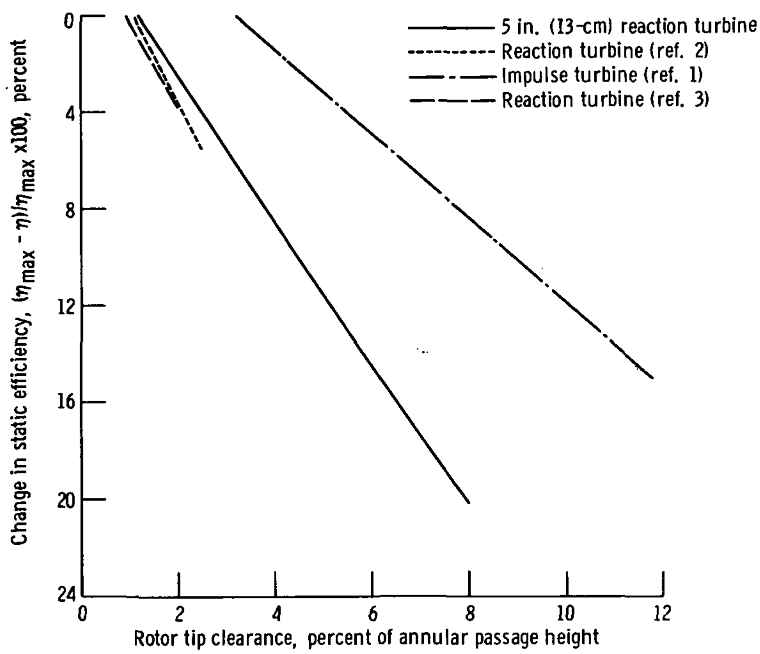


Figure 9. - Effect of rotor tip clearance on turbine performance at design equivalent speed and pressure ratio.

the TURBINE DESCRIPTION sections this turbine was designed as a high-reaction turbine. Another turbine, very similar in design to the 5-inch (13-cm) turbine, was the two-stage axial-flow turbine reported by Kofskey and Nusbaum (ref. 1). They tested the turbine at two tip clearances. The change in performance is also shown in figure 9. Although only two tip clearances were investigated, the slope of the line is about the same as that of the 5-inch (13-cm) axial turbine.

A third experimental investigation on a reaction turbine was performed by Messegee (ref. 5). Data from that report are shown on figure 9 as a dashed line. Again only two tip clearances were investigated but the slope of the line is nearly the same as the other two reaction turbines. Caution should be applied in using these data because the change in rotor tip clearance was obtained by increasing the outer-wall diameter. Wall losses could occur that might be included in tip clearance effects. In all other investigations the rotor tip diameter was reduced. The turbine tested by Messegee had an approximately 50-percent reaction at the tip section.

For comparison, Kofskey's data (ref. 6) are shown also in figure 10. This turbine was an impulse turbine. Figure 9 shows the slope of the line to be less than for the reaction turbines; that is, an increase in rotor tip clearance resulted in a smaller decrease in static efficiency for the impulse turbine.

The variation of mass flow with varying rotor tip clearance was also compared. All the reaction turbines appeared to have a similar increase of mass flow with increasing rotor tip clearance. The impulse turbine also had an increase in mass flow with increasing rotor tip clearance, but the increase in mass flow was relatively small as compared with the reaction turbine.

SUMMARY OF RESULTS

This report has presented the results of an experimental investigation made to determine the effects of increasing rotor tip clearance on the performance of a 5-inch (13-cm) axial turbine. The 5-inch (13-cm) axial turbine was a high reaction turbine. Tests were made using argon as the working fluid at four tip clearances ranging from 1.2 to 8 percent of passage height. Data were taken at design pressure ratio and over a range of speeds. Comparison of results for this turbine were made with three other reference turbines. The results of this investigation can be summarized as follows:

1. At design speed and total- to static-pressure ratio, the turbine static efficiency decreased linearly by 20 percent (0.79 to 0.63) as the rotor tip clearance was increased from 1.2 to 8 percent of passage height. A similar decrease in total efficiency was measured. Thus, for this turbine, a 1-percent increase in clearance to height ratio resulted in approximately a 3-percent reduction in efficiency.

2. Equivalent mass flow increased linearly with increasing rotor tip clearance. A 6-percent increase occurred over the rotor tip clearance range covered.

3. Radial surveys at the rotor exit showed that the flow was altered as the rotor tip clearance was increased. The most noticeable changes occurred in the tip region where large amounts of underturning, large increases in total pressure, and substantial reductions in efficiency were observed.

4. Comparison of the results of this investigation with those of two reference reaction turbines indicated similar effects of clearance on efficiency. Comparison with a reference impulse turbine investigation indicated that the rotor tip clearance effects were larger for the reaction turbines than for the impulse turbine.

Lewis Research Center,
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