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EXPERIMENTAL RESULTS OF VARYING THE BLADE-SHROUD CLEARANCE IN A 6.02-INCH RADIAL-INFLOW TURBINE

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16. Abstract

Results are reported in terms of efficiency, mass flow rate, and turbine exit conditions. Clearances were varied from 0.25 to 7 percent of passage height at the rotor entrance and rotor exit. Graphs are presented for separating the effects of clearance variations at the rotor entrance from those at the rotor exit.

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SUMMARY

An experimental investigation was conducted to determine the effects of variations in the amount of clearance between the rotor blade and the shroud for a 6.02-inch (15.29-cm) radial-inflow turbine. Clearance was varied in three ways: (1) the scroll was moved axially, relative to the rotor, by installing shims; (2) the shroud wall was coated with lacquer to provide near zero clearance; and (3) with lacquer removed and the scroll assembly in its original position, the blade height was reduced in successive steps by machining. Clearance values from 0.25 to 7 percent of the passage height at the rotor entrance and at the rotor exit were used. Results are expressed as changes in efficiency and mass flow rate, divided by the corresponding value at the original clearance, expressed in percent.

For the clearance range of greatest interest, from 1 to 3 percent, results indicated a decrease of 0.15 percent in the total efficiency for each percent increase in axial clearance at the rotor entrance alone. For each percent increase in radial clearance at the rotor exit, however, a 1.6-percent decrease in efficiency resulted, a ratio of about 10 to 1 as compared with the clearance effect at the rotor entrance.

For increases in clearance at the rotor entrance alone, the mass flow rate decreased 0.1 percent for each percent clearance increase. For increases in clearance at the rotor exit alone, there was an increase in mass flow rate of about three times the magnitude of the decrease caused by the same percent increase in axial clearance.

Measurement of flow angle, pressure, and temperature at the turbine exit indicated that the effect of clearance changes existed at all radii, with the greatest effect occurring near the rotor tip.

INTRODUCTION

The space power program being conducted at the NASA Lewis Research Center has included the investigation of small aerodynamic components suitable for low-power Brayton cycle systems. One such component is a 6.02-inch (15.29-cm) radial-inflow turbine designed to drive the compressor in a two-shaft, 10-kilowatt Brayton power system. The turbine was investigated previously to determine its general performance. The design requirements and performance evaluation are given in reference 1. Reference 2 reported the effects of operation over a range of Reynolds number, and the effects on performance of an exit diffuser are given in reference 3. Such investigations were necessary since the aerodynamic efficiency of the turbine component has a significant effect on the cycle efficiency and the specific weight of the power system.

The investigation of this turbine was recently extended to determine the effect of variations in the clearance between the rotor blades and shroud on the turbine performance. The purpose was to obtain quantitative information on the aerodynamic penalty that would be incurred by increasing the blade-shroud clearances somewhat beyond those necessary for steady-state operation. Such additional clearances are needed as a margin of safety because of temperature transients during startup and for passing through critical speeds. The increases must, however, be weighed against the accompanying aerodynamic penalties incurred within the turbine and their subsequent effect on system performance.

The results of a limited investigation of the effect of clearance increases are reported for this turbine in reference 4. The investigation involved increasing the axial clearance at the rotor inlet by displacing the scroll axially relative to the rotor. Clearances from 1.7 to 25 percent of the passage height were used. The results indicated that increasing the axial clearance in this manner had little effect on the turbine efficiency. Since only one type of clearance increase was considered and the manner of increase would have some effect on the flow conditions with the rotor, the results presented in the reference were considered preliminary.

The present report describes a more comprehensive investigation of clearance effects on the 6.02-inch (15.29-cm) radial-inflow turbine. Initial tests involved reducing the clearance by coating the inside of the scroll with lacquer to obtain clearances of approximately 1/4 percent of the passage height throughout the rotor passages. For the remaining tests, clearance was increased by removing the lacquer from the scroll and reducing the rotor blade height by machining operations. A total variation in clearance both at the rotor entrance and exit from 1/4 to 7 percent of the passage height was used. The machining operations were scheduled in such a way that clearance changes were not made at both the rotor entrance and exit at the same time. In this way, it was possible to obtain isolated results for clearance effects at the rotor entrance and exit. Five clearance configurations were used.

Each clearance used is reported as a percentage of the total passage height, where the passage height was measured from the rotor hub to the shroud. At the rotor entrance, the clearance and the passage height were measured in the axial direction, since the flow direction at the rotor entrance had no axial component. At the rotor exit, the flow had no radial component, and the clearance and passage height were measured in the radial direction.

Unheated air was used as the working fluid for all tests. Constant inlet total pressure and constant exit static pressure were maintained. Turbine speed was varied from 30 to 110 percent of the design equivalent speed. The effects of clearance changes on performance are presented in terms of efficiencies, mass flow rates, and flow conditions observed at the turbine exit.

SYMBOLS

$\Delta h'$ specific work, Btu/lb; J/kg

N turbine speed, rpm

p pressure, psia; N/cm^2

r radius, ft; m

U blade tip speed, ft/sec; m/sec

V absolute gas velocity, ft/sec; m/sec

V_j ideal jet speed corresponding to total-static pressure ratio across turbine, 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, p_1'/p^*

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

η static efficiency

η' total efficiency

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

ν blade-jet speed ratio, U/V_j

Subscripts:

cr condition corresponding to Mach 1

ref reference

1 station at turbine inlet

2 station at turbine exit

Superscripts:

' absolute total state

* U.S. standard sea-level conditions; temperature, 518.67° R (288.15 K); pressure, 14.696 psia (10.133 N/cm^2)

TURBINE DESCRIPTION

A complete description of this turbine is given in reference 1, which is the basic performance report. The turbine was a radial-inflow type with a rotor tip diameter of 6.02 inches (15.29 cm). As mentioned in the INTRODUCTION, it was designed as a compressor drive turbine for a two-shaft system operating in a Brayton cycle. The cycle working fluid was argon. The net shaft power for the system was 10 kilowatts. The design values for the turbine are as follows:

Total efficiency, η'	0.880
Static efficiency, η	0.824
Total- to total-pressure ratio, p_1'/p_2'	1.560
Total- to static-pressure ratio, p_1'/p_2	1.613
Specific work, $\Delta h'$, Btu/lb (J/kg)	34.73 (8.078×10^4)
Speed, N, rpm	38 500
Mass flow rate, w, lb/sec (kg/sec)	0.611 (0.277)
Inlet total temperature, T_1', °R (K)	1950 (1083)
Inlet total pressure, p_1', psia (N/cm^2)	13.20 (0.101)
Blade-jet speed ratio, ν	0.697

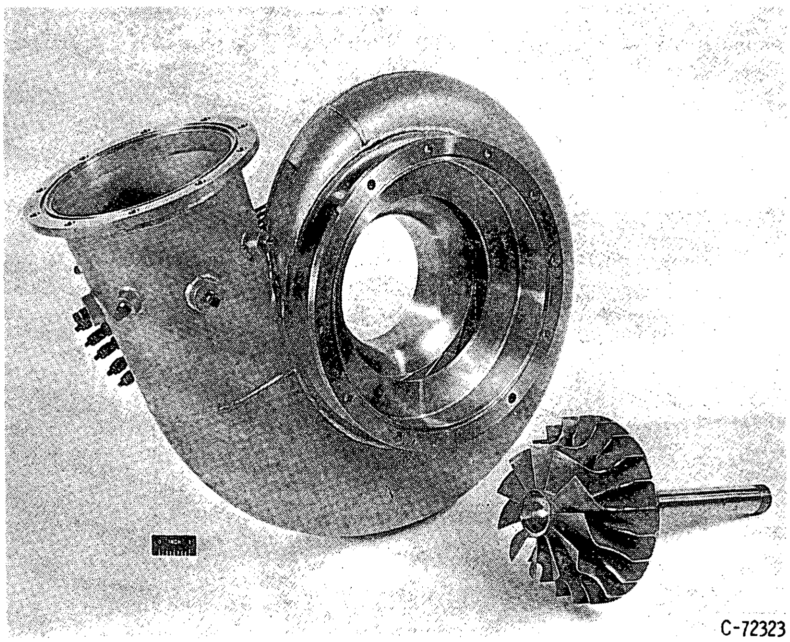


Figure 1. - Turbine rotor and scroll.

The following design equivalent values, at U.S. standard sea-level conditions, were calculated:

Equivalent mass flow rate, $w\epsilon\sqrt{\theta_{cr}}/\delta$, lb/sec (kg/sec) 1.063 (0.482)
Equivalent total- to total-pressure ratio, p_1'/p_2' 1.496
Equivalent total- to static-pressure ratio, p_1'/p_2 . . . . 1.540
Equivalent specific work, $\Delta h'/\theta_{cr}$, Btu/lb (J/kg) . . . . 11.89 (2.768×10^4)
Equivalent speed, N, rpm 22 527
Blade-jet speed ratio, ν 0.697

The turbine rotor and the scroll-stator assembly are shown in figure 1. The blade-shroud clearance of this turbine, as originally built, was not uniform along the rotor blade. The clearances at both the rotor entrance and exit measured 0.013 inch (0.033 cm) but were greater at points in between. The maximum clearance occurred at a point about midway between the rotor entrance and exit, where it measured 0.019 inch (0.048 cm).

METHODS USED TO VARY CLEARANCE

For the preliminary test described in reference 4, the effects of varying only the axial clearance at the rotor entrance were investigated. This variation was accomplished by inserting shims between the flanges of the scroll assembly and the bearing housing.

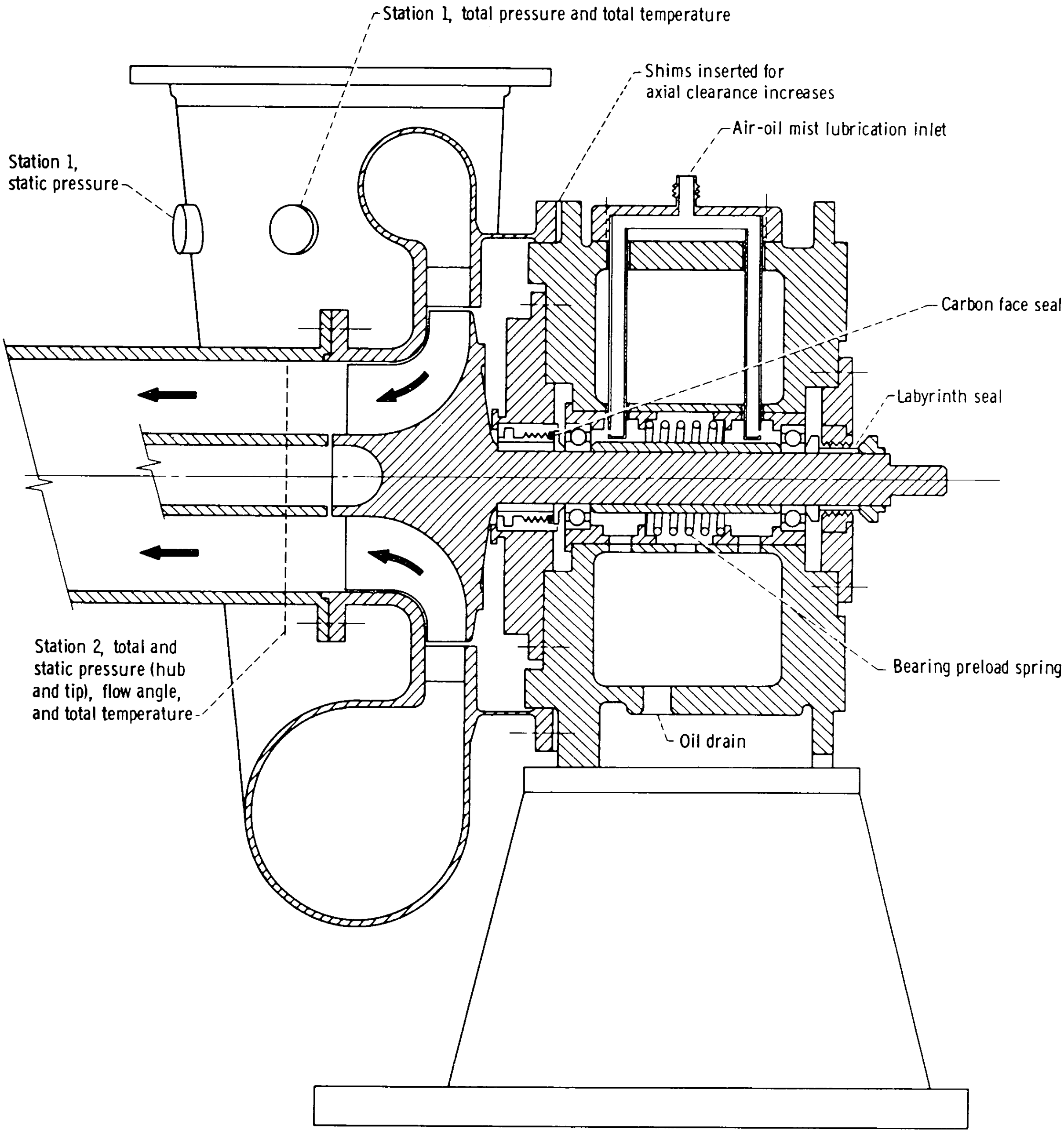


Figure 2. - Turbine showing measurement stations.

The location of the shims is indicated in figure 2, which shows a sectional view of the turbine assembly. The axial clearance was varied in this manner from 1.7 to 25 percent of the passage height. The passage height was 0.773 inch (1.963 cm).

In order to reduce the clearance to the practical minimum, the scroll surface which encloses the rotor tip was given several coats of sprayed lacquer. Between coats, the turbine was reassembled and rotated at low speeds. In this way, high spots on the sprayed surface could be identified and reduced by hand working until the clearance was judged to be the minimum that could be obtained without interference. A clearance value of approximately 1/4 percent of the passage height at both the inlet and exit was obtained in this manner.

The remaining tests, which are considered to be those of principal importance, involved machining operations to contour the rotor tip to the desired clearance. For these tests, all lacquer was removed from the scroll and the original position of the scroll, relative to the rotor, was maintained. The first machining operation removed material at the rotor exit but not at the entrance. The second operation removed material at the entrance but not at the exit. This stepwise procedure was followed to produce a total of four rotor configurations. For each configuration, the blade tip was contoured to produce a gradual change in clearance from the entrance end of the rotor to the exit end. The clearance values and percentages of the clearances for each configuration, including the minimum clearance, are shown in table I.

TABLE I. - CLEARANCES BETWEEN ROTOR BLADE AND SHROUD

[Passage height: at exit, 1.415 inches (3.595 cm); at entrance, 0.773 inch (1.963 cm).]

Configuration	Clearance					
	Axial (rotor entrance)			Radial (rotor exit)		
	in.	cm	Percent of passage height	in.	cm	Percent of passage height
Minimum clearance	0.002	0.005	1/4	0.004	0.010	1/4
1	.013	.033	1.7	.0425	.108	3.0
2	.023	.058	3.0	.0425	.108	3.0
3	.023	.058	3.0	.099	.251	7.0
4	.054	.137	7.0	.099	.251	7.0

APPARATUS AND INSTRUMENTATION

The apparatus and instrumentation used in these tests were similar to those used in the general performance tests described in reference 1. Air, supplied by the laboratory combustion air system, was used as the working fluid instead of argon. This air was filtered but not heated. The resulting air temperature ranged from 20° to 33° C. A general layout of the test equipment is shown in figure 3.

The pressure regulator for the inlet air line was set from the control room by means of a remote loader to compensate for any load changes or upsets in the supply system. The exhaust pressure was adjusted from the control room by means of a pneumatically operated valve. This valve was equipped with a bypass for fine adjustment.

Measurement of the mass flow rate was accomplished by the use of a choked-flow nozzle, the location of which is indicated in figure 3.

Speed control was maintained by controlling the inlet air to the airbrake dynamometer. This was done by means of a pressure regulator having a remote set point control, similar to the arrangement used for the turbine inlet air.

The speed was read out on a digital counter that received pulses from a magnetic pickup. The pickup was activated by a star wheel mounted on the turbine coupling. The

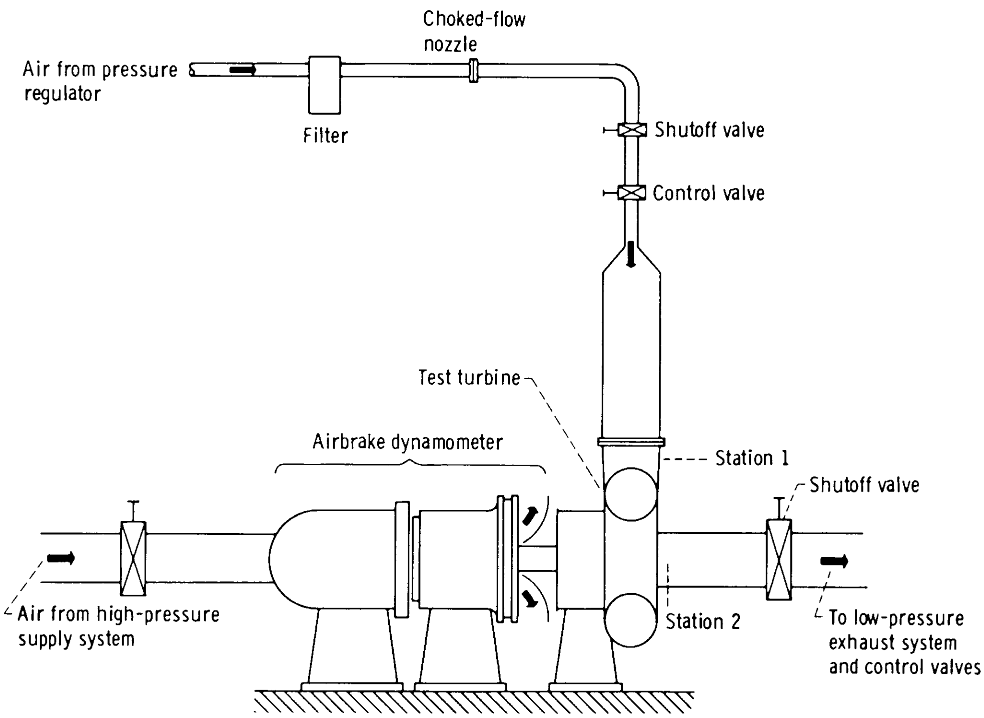


Figure 3. - Test equipment.

wheel used had six spokes, and the counter displayed events per second so that the resulting resolution for speed readout was 10 rpm.

Pressures were measured by means of absolute pressure transducers of the unbonded strain-gage type. The torque also was measured by a strain-gage transducer, which was attached to the torque arm of the dynamometer. All transducer signals were read out on an integrating digital voltmeter.

Temperatures needed for research purposes were measured by iron-constantan thermocouples and read out on a potentiometer-type instrument. Temperatures used for monitoring purposes were automatically scanned and printed out by a separate instrument.

Measurements of flow angle at the turbine exit were obtained by the use of a self-alining probe and actuator. The actuator made possible the radial positioning of the

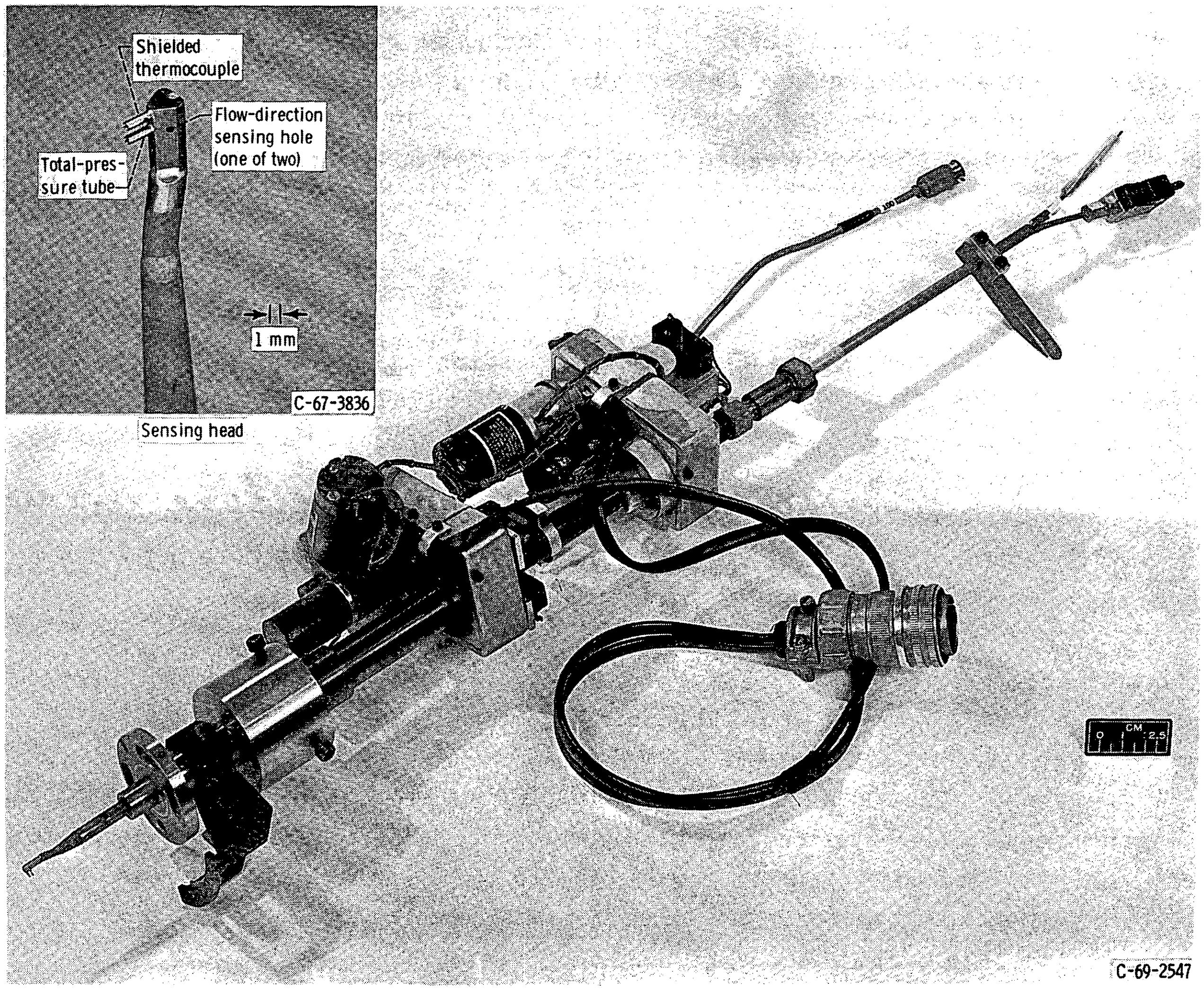


Figure 4. - Probe and actuator.

probe from the control room. In addition to balancing ports, the probe also carried a total-temperature thermocouple and a total-pressure tube. Photographs of the probe actuator equipment and the probe are shown in figure 4. Detailed descriptions of the probe and its capability are given in reference 5.

TEST PROCEDURE

For each value of clearance, the testing procedure was the same. The inlet total pressure was held constant at a value of 9.5 psia (6.55 N/cm^2) and the exhaust static pressure at 6.17 psia (4.25 N/cm^2). This maintained the design equivalent total-static pressure ratio of 1.54 for all tests. The inlet temperature was not controlled but ranged from 20° to 33° C. The turbine speed was adjusted to give the required percentage of design equivalent speed. The percentages used were 30, 50, 70, 90, 100, and 110. For each clearance value, a radial survey at the rotor exit was made at design equivalent speed. Measurements of flow angle, total pressure, and total temperature were taken at 16 radii for each survey.

All data were manually recorded and then processed by a digital computer.

RESULTS AND DISCUSSION

In discussing the experimental results, the clearance values are always stated as percentages of passage height. The clearances are given in table I, expressed both in dimensions and as percentages of passage heights. In the curves that follow, a distinction is made between cases where the same percentage clearance is present at the rotor entrance and exit and cases where those percentages are different. This distinction is made to separate, so far as is possible, the effect of variations in the clearance at the rotor entrance from the effect of those at the rotor exit.

Uniform Clearance Variations

The effects of clearance on total and static efficiences for cases of 1/4, 3, and 7 percent uniform clearances are presented in figures 5 and 6. The maximum efficiency loss occurred near the design blade-jet speed ratio of 0.697. The maximum decrease in efficiency caused by increasing clearances from the minimum to 7 percent was about 7.5 points for both total and static efficiency.

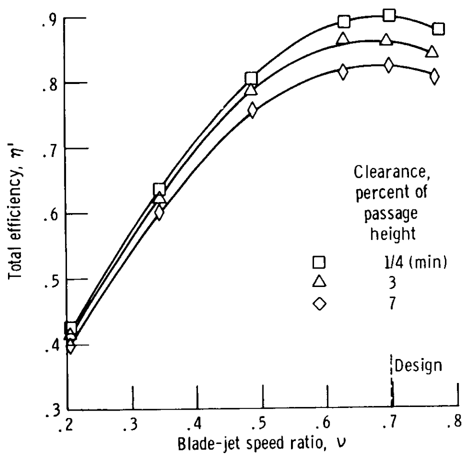


Figure 5. - Effect of uniform clearance values on total efficiency for varying blade-jet speed ratios.

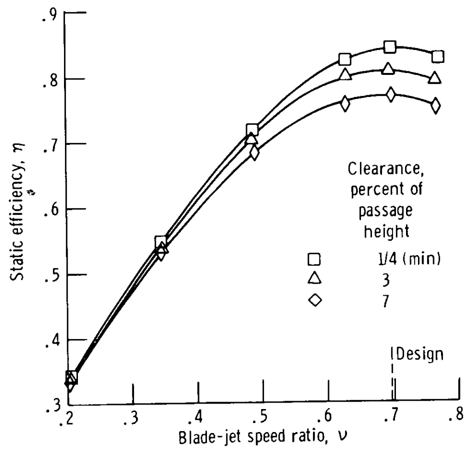


Figure 6. - Effect of uniform clearance values on static efficiency for varying blade-jet speed ratios.

Values of static efficiency from figure 6 at design blade-jet speed ratio were used to calculate values of an efficiency change, which is defined as $(\eta - \eta_{ref})/\eta_{ref}$. These values were expressed as percentages and plotted against the percentage of blade-shroud clearance in figure 7. The reference values used for efficiencies for this and other plots were those obtained from the turbine with the original clearance, prior to any changes, at design equivalent operating conditions. These values are 0.893 for total efficiency and 0.834 for static efficiency.

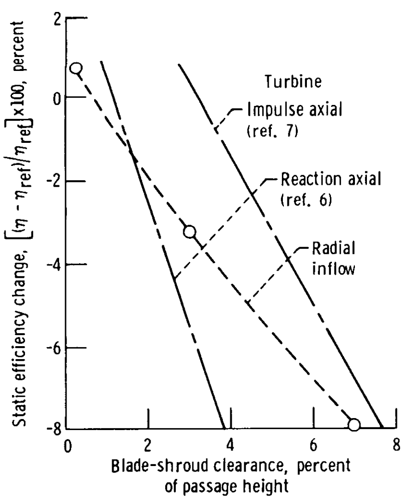


Figure 7. - Comparison of effect on static efficiency of clearance variation for three turbines. Uniform percent clearance at rotor entrance and exit for radial-inflow turbine.

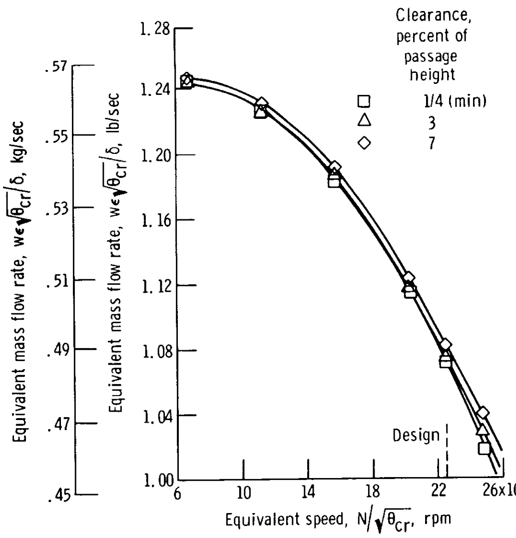


Figure 8. - Effect of uniform clearance values on equivalent mass flow rate for various speeds.

The effect of clearance variations on static efficiency for this turbine is compared with that for two axial-flow turbines. Reference 6 gives results for a 5-inch (12.7-cm) single-stage reaction turbine, and reference 7 gives results for a 10.5-inch (26.7-cm) single-stage impulse turbine. The results, which are plotted in figure 7, indicate that the radial-inflow turbine does not have as great an efficiency loss, for a given percent clearance increase, as the two axial-flow turbines.

The effect of clearance variations on mass flow rate is shown in figure 8 for the cases used in figures 5 and 6 for efficiencies. In general, increases in clearances lead to small increases in the mass flow rate. More details of the relations between mass flow rate and clearance are shown in a later figure where the effects of clearances at the rotor exit and entrance can be separated.

Information from figure 8 at design equivalent speed is plotted in figure 9. In this

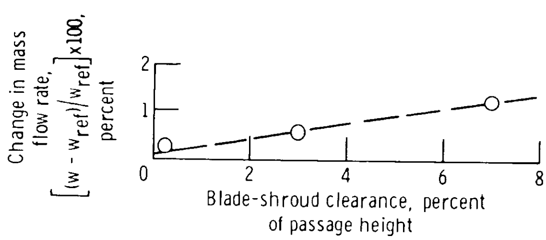


Figure 9. - Effect of uniform blade-shroud clearance on mass flow rate at design equivalent speed.

figure, the change in mass flow rate, defined as $(w - w_{ref})/w_{ref}$, is plotted against the tip clearance. The equivalent mass flow rate of 1.068 pounds per second (0.484 kg/sec) at the original clearance is used as a reference. The dashed line indicates that the change in mass flow rate undergoes an increase of about 0.16 percent for each percent increase in clearance, where the clearance percentages are the same at the rotor entrance and exit.

Results of 16-point surveys at the rotor exit are shown in figure 10. The data were taken with the turbine operating at equivalent design speed and pressure ratio. The same set of clearance values were used as in the foregoing figures.

Figure 10(a) shows that clearance has a strong effect on the rotor exit angle, particularly at the tip, even for small clearance differences.

The distribution of total pressure with radius ratio is shown in figure 10(b). Little variation is noted across the passage for the minimum clearance. However, a distinct total-pressure increase occurs near the rotor tip as the clearance is increased.

A value of local total efficiency was calculated for each data point and is shown in figure 10(c). For each radius, a value of ideal work was calculated from the total tem-

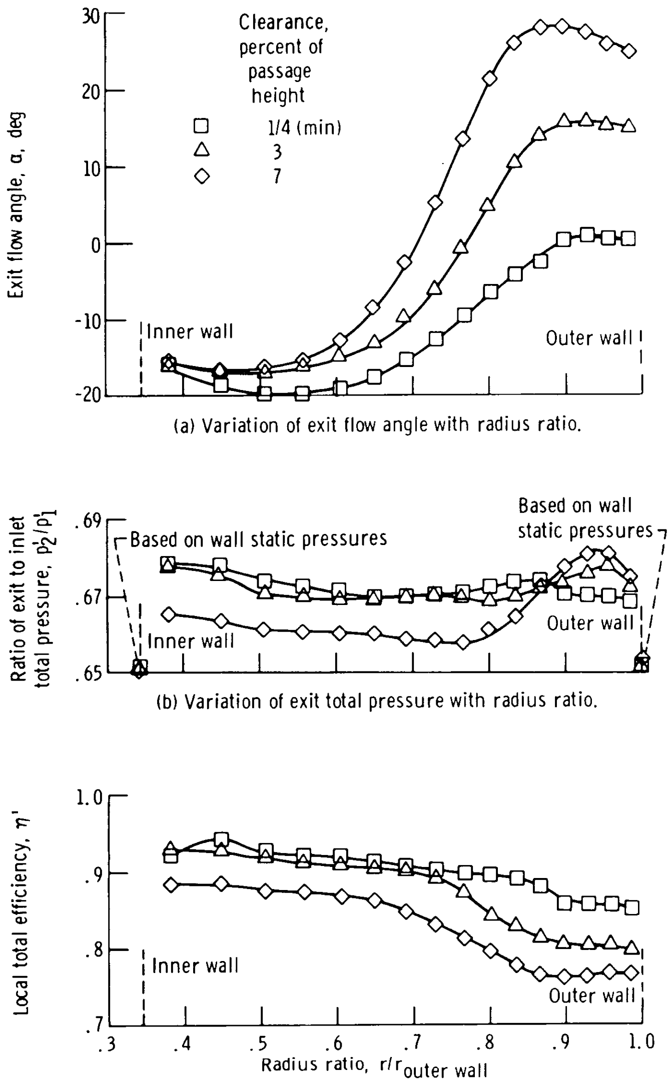


Figure 10. - Results of survey at turbine exit at equivalent design speed and pressure ratio (uniform clearance).

perature and total pressure at the turbine inlet and the total pressure as indicated by the probe equipment at the turbine exit. In the calculation of actual work for each radial position, a momentum method was used. First, the exit momentum and mass flow rate were calculated for each of the 16 equal area increments at the turbine exit, using the total and static pressures, the total temperature, and the angle. Then, a mass-averaged value of exit momentum was obtained and used with brake specific work to calculate a value of inlet momentum. This inlet momentum was assumed constant for all radial positions. Finally, the actual work was calculated for each radial position from the inlet momentum and the local value of the exit momentum. Combining this value with the previously calculated ideal work yielded a value of the local total efficiency for each radial position. Figure 10(c) shows that increases in clearance cause decreases in the local total efficiency at all radii, but the effect is more pronounced near the tip.

Isolation of Inlet Clearance and Exit Clearance Effects

In the foregoing figures, only cases where the clearance percentages were the same at rotor entrance and exit were shown. Cases where the clearance percentages were varied at one end of the rotor for a fixed clearance at the other are shown in figures 11 to 15. Some of the previously presented data is included for purposes of comparison. The main purpose of this type of presentation is to separate, so far as possible, the effects of clearance at the rotor entrance and that at the exit.

Shown in figure 11 are two pairs of clearance values where the difference is only in the axial clearance at the rotor entrance. Data for the minimum clearance are repeated. For a value of 3-percent radial clearance at the rotor exit, the two sets of data shown differ very little in efficiency, less than 1/2 percent, although a difference of 1.3 percent exists in axial clearance. At a radial clearance of 7 percent, the maximum efficiency difference is about 1 percent for an axial clearance difference of 4 percent.

Efficiencies taken from these faired curves at design blade-jet speed ratio were used to calculate changes in efficiency with changes in clearance (see fig. 12). If

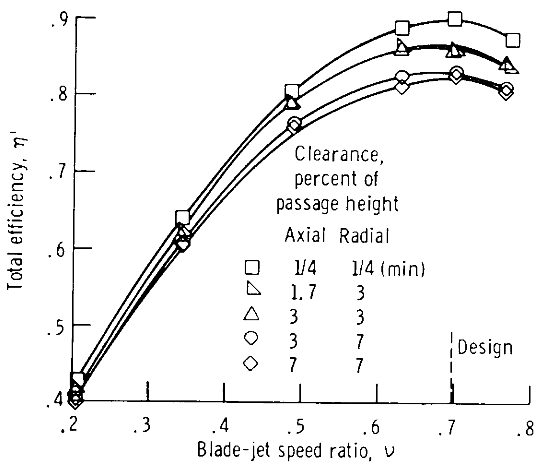


Figure 11. - Effect of combinations of clearance values on total efficiency for varying blade-jet speed ratios.

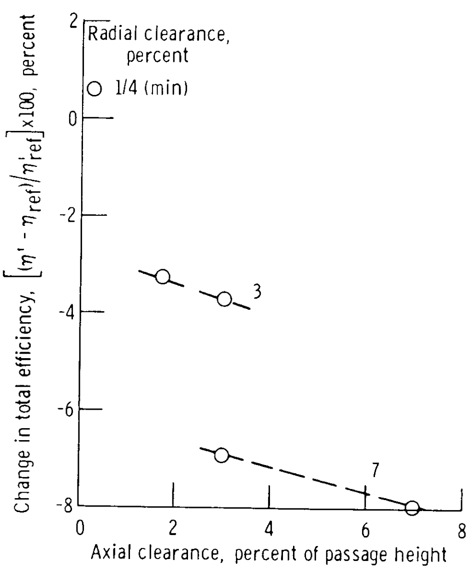


Figure 12. - Effect on total efficiency of combinations of radial and axial blade-shroud clearances at design blade-jet speed ratio.

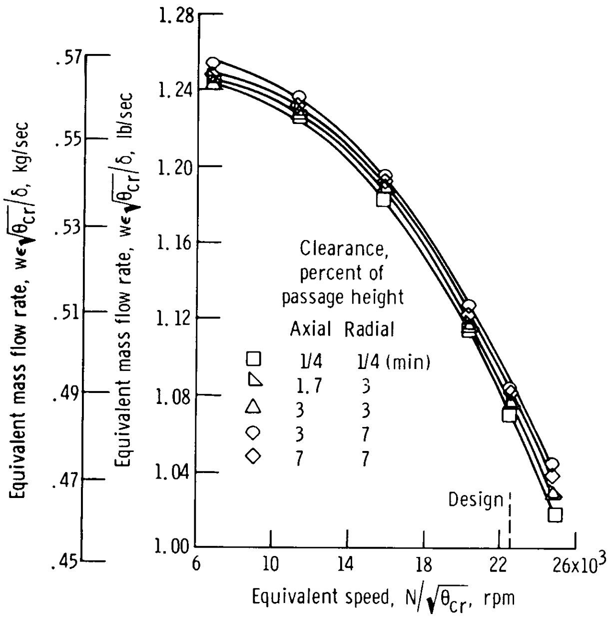


Figure 13. - Effect on equivalent mass flow rate of combinations of clearance values for various speeds.

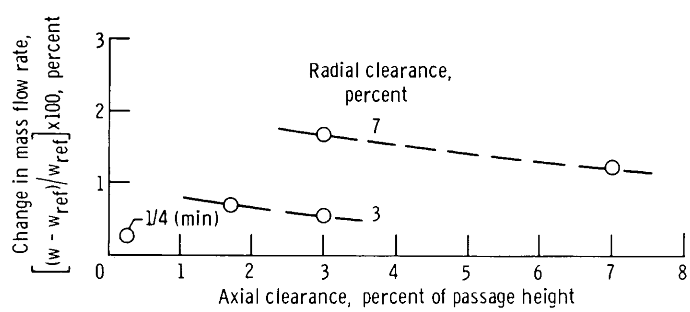
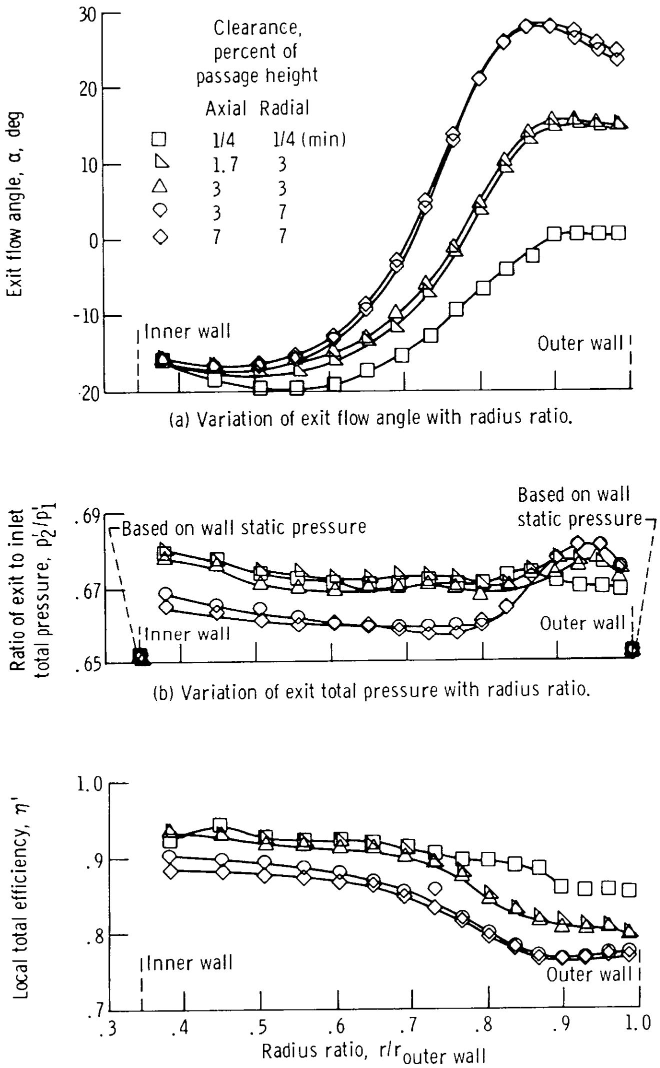


Figure 14. - Effect of blade-shroud clearance on mass flow rate for combinations of radial and axial clearances at design equivalent speed.

straight lines are assumed for constant values of radial clearance, the slopes are seen to be very nearly equal. This indicates that the effect of axial clearance on efficiency is nearly independent of the value of radial clearance.

For the same set of clearance cases, the variation in equivalent mass flow rate is shown in figure 13. The curves indicate a small increase in mass flow rate with increased radial clearance. A small increase in axial clearance, however, results in a small decrease in the flow rate.

Using values from the faired curves of figure 13, a change in the flow rate was calculated and is plotted in figure 14. If straight lines through points of equal radial



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

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

(c) Variation of local total efficiency with radius ratio.

Figure 15. - Results of survey at turbine exit at equivalent design speed and pressure ratio.

clearance are assumed, the effect of a change in axial clearance on mass flow rate is nearly independent of the radial clearance.

Flow conditions at the rotor exit are shown in figure 15. Cases were selected so that the effect of axial and radial clearance could be separated. The effects on flow angle, shown in figure 15(a), indicate that the changes caused by radial clearance increases far overshadow those caused by axial clearance increases. For the measuring station nearest the rotor tip, the maximum change in flow angle was about 25° for a clearance change of about 7 percent.

The radial distribution of local total pressure is shown in figure 15(b). As with exit angle distribution, cases that differ only in the amount of axial clearance show curves that are close together. The rise in total pressure near the rotor tip can be clearly seen, and it increases as clearance increases.

The local total-efficiency plot of figure 15(c) shows the curves for different radial clearances well separated with very little separation for cases where the axial clearances differ. These curves were obtained in the same manner as those in figure 10(c). As in figure 10(c), the decrease in efficiency with an increase in clearance is greater near the rotor tip.

Combined Clearance Effects

Composites, which include the principal features of the results already discussed, are presented in figures 16 and 17. Also included are the results of the test (ref. 4) where the axial clearance was varied by means of shims. These figures deal with the

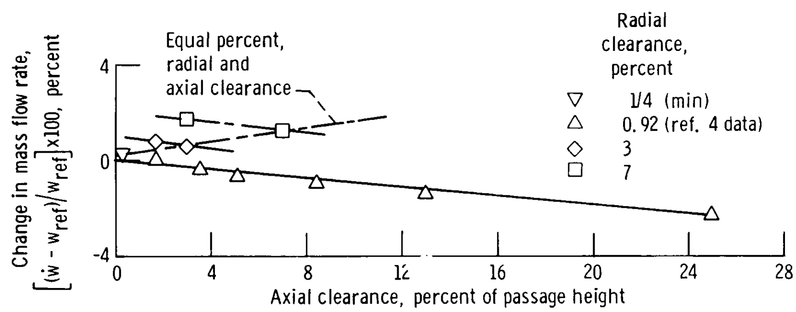


Figure 16. - Summary of radial and axial clearance effects on mass flow rate at design equivalent values of speed and pressure ratio.

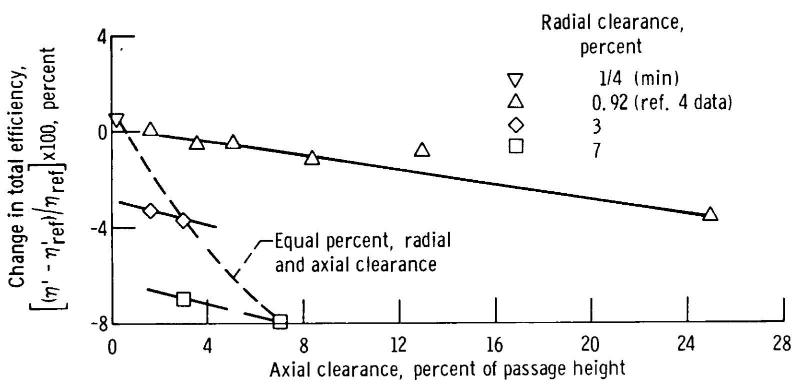


Figure 17. - Summary of radial and axial clearance effects on total efficiency at design equivalent values of speed and pressure ratio.

effects of clearance on total efficiency and mass flow rate. The flow rate effects are discussed first.

The effects of mass flow rate for operation at design equivalent speed and pressure ratio are summarized in figure 16. The straight lines used to connect the 3- and 7-percent radial clearance points have very nearly the same slope as the line used to represent axial clearance variation by using shims. The line obtained from the data of reference 4 is for a fixed 0.92-percent radial clearance and is a least-squares fit. It was realized that, when the shims were used, the procedure could alter the turbine geometry slightly at the rotor inlet and thus obscure somewhat the effect of the clearance variation. However, examination of the three lines of figure 16, which represent fixed radial clearances, leads to the conclusion that the quantity $(w - w_{ref})/w_{ref}$ will decrease approximately 0.1 percent for a 1-percent increase in axial clearance alone.

Points in figure 16 were used to calculate the effects of variation in radial clearance at two fixed values of axial clearance. At 1.7-percent axial clearance, the quantity $(w - w_{ref})/w_{ref}$ increases by 0.315 percent for each percent radial clearance increase. At a fixed axial clearance of 3 percent, $(w - w_{ref})/w_{ref}$ increases 0.257 percent for each percent increase in radial clearance. Since considerable difference exists between these two values, it is concluded that the effect on mass flow rate of a change in radial clearance cannot be considered independent of the amount of axial clearance present. However, a comparison of the effects on mass flow rate of varying independently the radial clearance and the axial clearance can be made. For a 1-percent increase in radial clearance alone, there is an increase in mass flow rate, which is about three times the size of the decrease in mass flow rate caused by a 1-percent increase in axial clearance.

Figure 17 is similar to 16 in that it provides a summary of the test results at design equivalent speed and pressure ratio. The quantity $(\eta' - \eta'_{ref})/\eta'_{ref}$, referred to as total efficiency loss, is plotted in percent against the percent clearance. All total efficiency data at design equivalent speed and pressure ratio are shown. The efficiency data for 0.92-percent radial clearance have somewhat more scatter than the data for mass flow rate, and some of this scatter may be caused by the displacement of the stator relative to the rotor. However, the scatter is not great for axial clearances below 7 percent, and the change in $(\eta' - \eta'_{ref})/\eta'_{ref}$ is about 0.15 percent for each percent increase in axial clearance. In order to increase the usefulness of the results, extrapolations were made to construct a cross-plot of figure 17. The useful range of clearances is considered to be from about 1 to 7 percent, and this range was used to construct figure 18. Straight lines were used through the 3- and 7-percent radial clearance points in figure 17, and the 0.92-percent radial clearance line was used. The curves of figure 18 should be useful in estimating the effect of clearance changes on efficiency for radial-inflow-type turbines of about the size of the turbine tested.

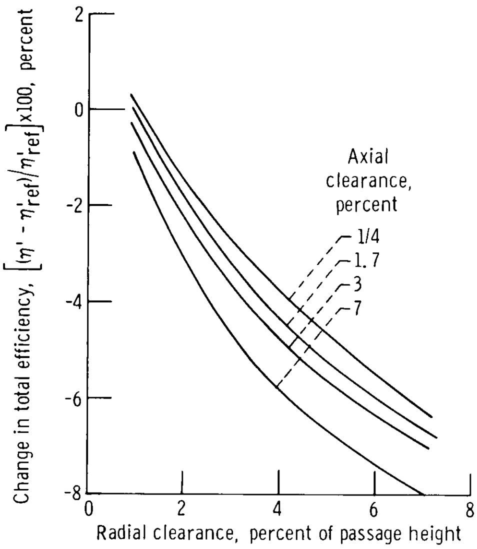


Figure 18. - Effect of clearance on total efficiency (includes straight-line extrapolations from fig. 17).

Although it is not possible to cite overall figures in connection with clearance effects on efficiency, average slopes in the range of greatest interest (from 1- to 3-percent clearance) from figures 17 and 18 may be used to compare the effects of radial and axial clearance variations. These slopes indicate a change in $(\eta' - \eta'_{ref})/\eta'_{ref}$ of about 1.6 percent for a 1-percent change in radial clearance, as compared with a change of about 0.15 percent in $(\eta' - \eta'_{ref})/\eta'_{ref}$ for a 1-percent increase in axial clearance. On this basis, a change in radial clearance has about 10 times the effect on total efficiency as the same percent change in axial clearance. Between 3- and 7-percent radial clearance, the total efficiency decreases less rapidly with increases in radial clearance, but the effect is always greater than that caused by increases in axial clearance.

SUMMARY OF RESULTS

An investigation was conducted to determine the effects of variations in the blade-shroud clearance for a 6.02-inch (15.29-cm) radial-inflow turbine. Clearance changes were scheduled in such a way as to isolate the effects of changes in axial clearance at the rotor entrance from the effects of radial clearance changes at the rotor exit. The evaluation was made over a range of speeds at design equivalent pressure ratio. Unheated air was used as the working fluid. A comparison was made with the clearance effects for two previously tested axial-flow turbines. The following results were obtained:

1. For clearances from 1 to 7 percent of the passage height, a decrease of 0.15 percent in total efficiency occurred for each percent increase in axial clearance at the rotor entrance.

2. For clearances from 1 to 3 percent of the passage height, which is the range of greatest interest, a decrease of 1.6 percent in total efficiency occurred for each percent increase in radial clearance at the rotor exit. Thus, clearance increases at the rotor exit had about 10 times the effect on total efficiency as increases in clearance at the rotor entrance.

3. From 3- to 7-percent radial clearance, the rate at which total efficiency decreased with an increase in radial clearance became smaller, but it was always greater than the decrease caused by a corresponding increase in axial clearance.

4. For radial clearances up to approximately 7 percent of the passage height, the effect of variations in axial clearance was not strongly influenced by the amount of radial clearance present.

5. For a clearance increase at the rotor entrance of 1 percent of the passage height, the mass flow rate decreased 0.1 percent.

6. An increase in radial clearance alone caused an increase in mass flow rate that was about three times the magnitude of the decrease caused by the same percent increase in axial clearance.

7. Radial surveys at the turbine exit showed that clearance increases affected the flow conditions at all radii, but the effect near the tip was greatest. Effects of clearance increases at the rotor exit were greater than the effects of clearance increases at the rotor entrance.

8. For the same percent clearance increases at the rotor entrance and exit for the radial-inflow turbine, a comparison was made with results for two axial-flow turbines. The static efficiency of the radial-inflow turbine was less affected by clearance increases than that of the two axial-flow turbines.

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