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by Samuel M. Futral, Jr., and Donald E. Holeski

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

The investigation was conducted in argon and over a range of inlet total pressures from 9.5 to 1.3 psia (6.6 to 0.9 N/cm^2 abs). The corresponding Reynolds numbers ranged from 317 000 down to 41 000. Test results showed that efficiencies and equivalent mass flow decreased with decreasing Reynolds number. These decreases in performance were greater than those of a 6.02-in. (15.3-cm) radial-inflow turbine which was designed for the same application.

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SUMMARY

A 5-inch- (13-cm-) diameter, single-stage, axial-flow turbine, designed for a Brayton cycle application, was tested at inlet total pressures from 9.5 to 1.3 psia (6.6 to 0.9 N/cm^2 abs). The corresponding Reynolds numbers ranged from 317 000 down to 41 000. The working fluid was argon. Reynolds number is defined herein as the ratio of mass flow rate to the product of viscosity and rotor mean radius. The viscosity is determined at turbine entrance conditions.

The efficiency and equivalent mass flow rate decreased with decreasing inlet pressure and Reynolds number. At equivalent design speed and pressure ratio, total efficiency from turbine inlet to rotor exit decreased from 0.86 to 0.79 with decreasing Reynolds number. The corresponding static efficiency decreased from 0.79 to 0.74. The decrease in equivalent mass flow was about 5 percent. Equivalent torque decreased 12 percent over the range of Reynolds numbers tested. The exit diffuser effectiveness remained at a high level over the range of Reynolds number covered.

Performance was compared with that of a 6.02-inch (15.3-cm) radial-inflow turbine which was designed for the same application. These comparisons showed that the 5-inch (13-cm) axial turbine had a greater deterioration in performance with decreasing Reynolds number.

INTRODUCTION

NASA is currently investigating Brayton cycle space power systems and their components. A two-shaft system using argon as the working fluid and solar energy as the heat source is described in reference 1. The shaft output power was 10 kilowatts. Radial-flow and axial-flow turbocompressors were designed for this system and their components were experimentally investigated. The test results of the radial-inflow turbine component are presented in reference 2. The test results of the axial-flow turbine component are presented in reference 3.

Turbomachinery for a space power system may be used to produce a range of power output. This is accomplished by varying system pressure level and consequently system flow for the same cycle variables. The change in system pressure may result in changes in turbine and compressor performance through Reynolds number effects in the flow passages. Interest in a range of power levels has, therefore, led to interest in Reynolds number effects on turbine and compressor performance.

The Reynolds number effects for the radial-inflow turbine were presented in reference 4. The purpose of this report is to present the Reynolds number effects for the corresponding axial-flow turbine.

The report describes the test results of the 5-inch- (13-cm-) diameter turbine over a Reynolds number range from 317 000 down to 41 000, which corresponds to system electrical outputs of 27.2 to 3.5 kilowatts. Reynolds number is defined herein as the ratio of mass flow rate to the product of viscosity and rotor mean radius. The viscosity is determined at turbine entrance conditions. To obtain this range of Reynolds number, the inlet pressure was varied from 9.5 to 1.3 psia (6.6 to 0.9 N/cm^2 abs). The inlet total temperature was held at 582° R (323 K). These conditions correspond closely to those used for the radial-inflow turbine of reference 4.

The results of these tests are presented in terms of efficiency, mass flow rate, torque, and exit diffuser effectiveness. Aerodynamic losses of the turbine are also compared with those of the reference radial-inflow turbine.

SYMBOLS

Δh	specific work, Btu/lb (J/g)
N	turbine speed, rpm
p	absolute pressure, psia (N/cm^2 abs)
Re	Reynolds number, $w/\mu r_m$
r	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)

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, $\frac{\gamma^*}{\gamma}\left[\left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \Big/ \left(\frac{\gamma^*+1}{2}\right)^{\gamma^*/(\gamma^*-1)}\right]$

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, $(V_{cr}/V_{cr}^*)^2$

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

ν blade-jet speed ratio, U_m/V_j

τ torque, in. -lb (N-m)

Subscripts:

cr condition corresponding to Mach 1

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

m mean radius

1 station at turbine inlet

2 station at stator inlet

3 station at stator exit

4 station at rotor exit

5 station at exhaust-pipe flange

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

The turbine used in this investigation was the same as that described in reference 3. The turbine was a single-stage, axial-flow type and was designed to drive a six-stage, axial-flow compressor. The turbine and compressor are components of the 8-kilowatt

TABLE I. - TURBINE DESIGN VALUES

Design parameters	Argon		Air equivalent (a)	
	Symbol	Value	Symbol	Value
Inlet total temperature, $^{\circ}R$ (K)	T_1'	1950 (1083)	---------	------ ------
Inlet total pressure, psia (N/cm^2 abs)	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
Ratio of inlet total pressure to diffuser-exit total pressure	p_1'/p_5'	1.549	$(p_1'/p_5')_{eq}$	1.487
Ratio of inlet total pressure to diffuser-exit static pressure	p_1'/p_5	1.557	$(p_1'/p_5)_{eq}$	1.494
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
Overall total efficiency[b]	η_{1-5}'	0.842	η_{1-5}'	0.842
Overall static efficiency[b]	η_{1-5}	0.833	η_{1-5}	0.833
Reynolds number	Re	93 100	Re	93 100
Ratio of blade speed to jet speed	ν	0.621	ν	0.621

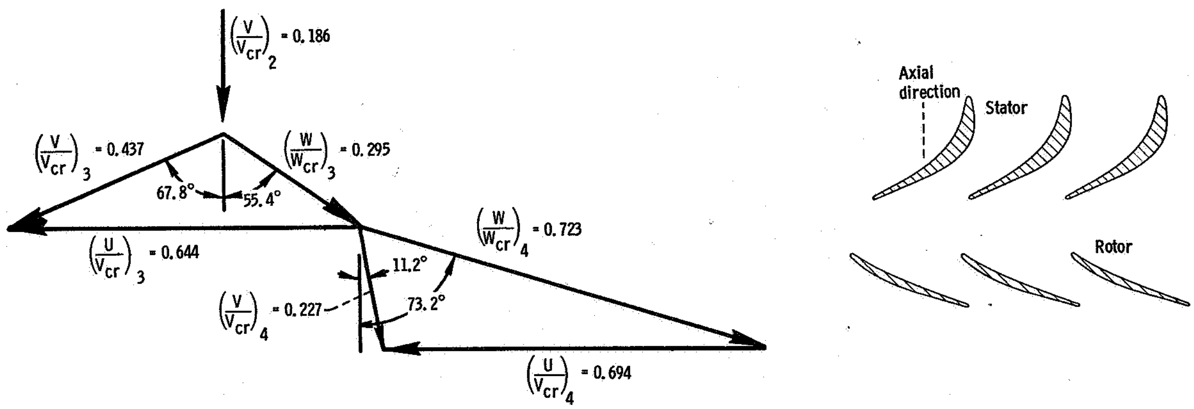
[a]U.S. standard sea-level conditions.

[b]Measured from torus-inlet flange to diffuser-exit flange.

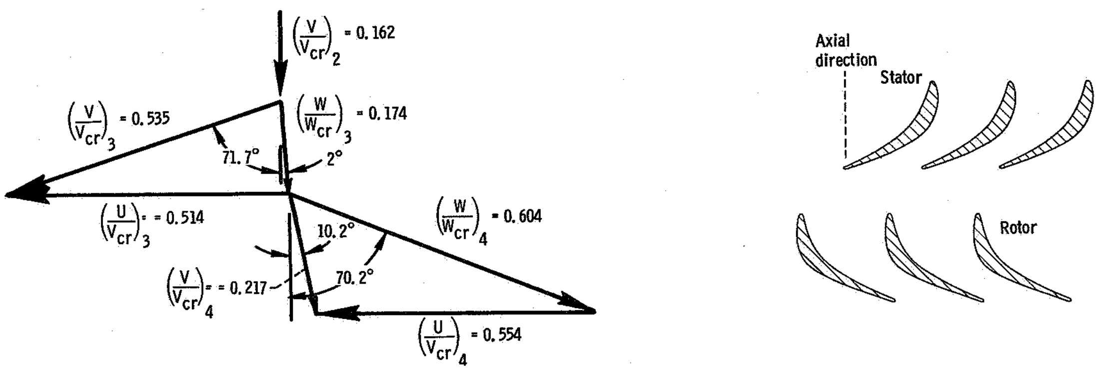
electrical output space power system of reference 1. The main features of the turbine are repeated herein. Additional information about the turbine can be found in references 3 and 5.

Design-point values for the turbine with argon as the working fluid are listed in table I; air equivalent values are also listed in the table. The equivalent pressure ratios were calculated from equivalent specific work in air. The assumption was made that the efficiency would be the same with either argon or air as the working fluid, for any given equivalent speed and pressure ratio.

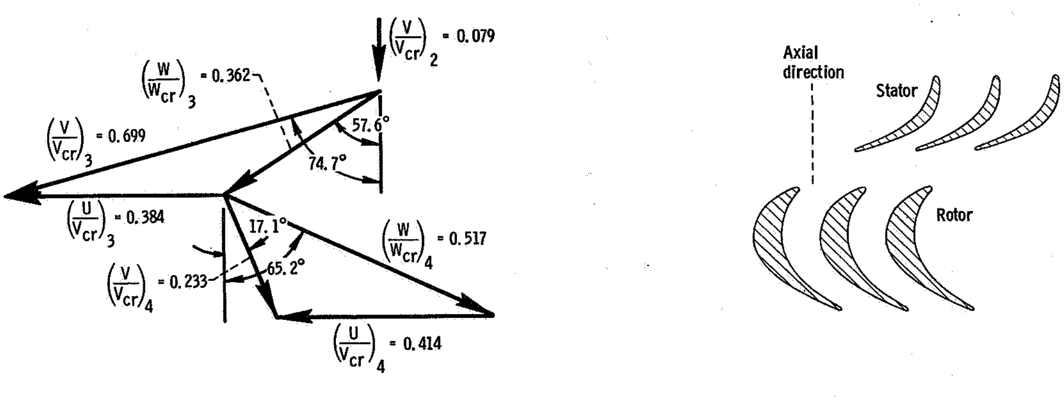
The design velocity diagrams, as taken from reference 3, are presented in figure 1. A list of velocities, in feet per second, with pressures and temperatures in the turbine



(a) Tip.



(b) Mean.



(c) Hub.

Figure 1. - Design velocity diagrams and blade profiles.

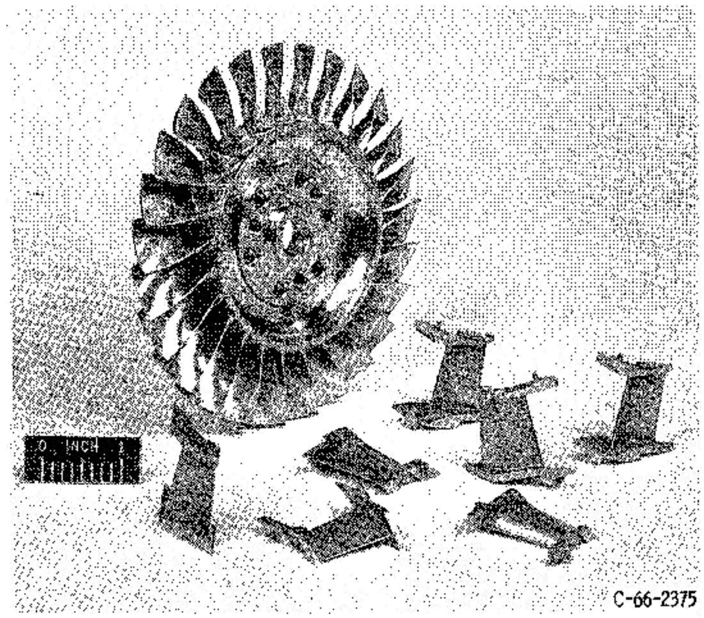


Figure 2. - Turbine rotor and stator blades.

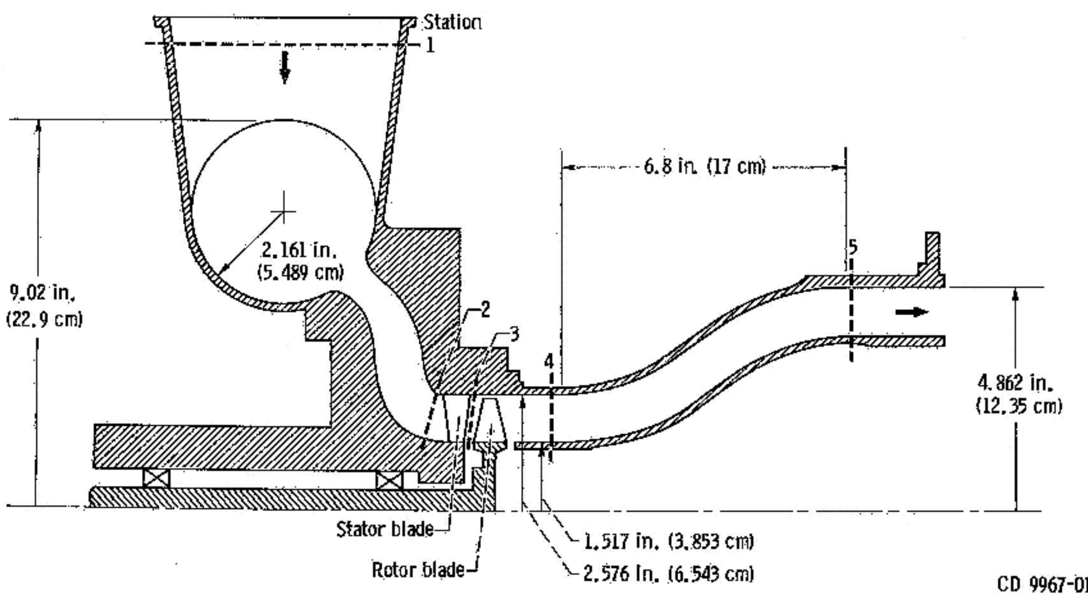


Figure 3. - Cross section of turbine.

is contained in table 2 of reference 5. As noted in reference 3, this turbine was designed with a variable specific work along the blade length.

The turbine stator had 30 blades designed for conventional converging flow passages. Figure 2 shows the turbine rotor and some of the stator blades. Figure 1 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 in figures 1 and 2.

The aerodynamic and mechanical design and fabrication of this turbine were performed by Pratt and Whitney Aircraft Company; reference 5 is the final report on the design.

A cross-sectional view of the turbine flow passages is shown in figure 3. The rotor tip diameter was 5.137 inches (13.05 cm). The average tip clearance was 0.012 inch (0.030 cm), which is about 1 percent of the blade height. The rotor hub-tip radius ratio was 0.6.

APPARATUS

The apparatus consisted of the turbine, an airbrake dynamometer, and an inlet and an 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 electric heater and was filtered. The argon then passed through a weight-flow measuring station that consisted of a calibrated choked-flow nozzle. The

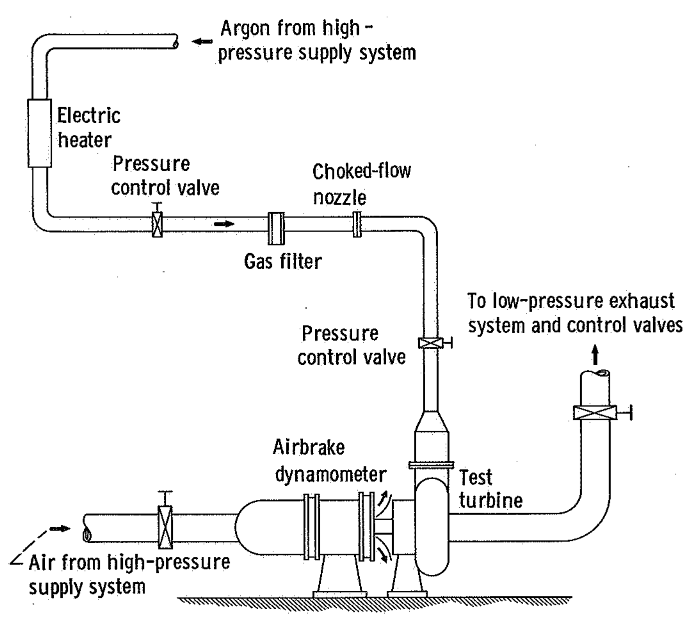


Figure 4. - Experimental equipment.

argon, after passing through the turbine, was exhausted into the laboratory exhaust system. A pressure regulator upstream of the turbine maintained the turbine inlet pressure. With a fixed inlet pressure, a remotely controlled valve in the exhaust line was used to obtain the desired pressure ratio across the turbine. The airbrake dynamometer used was the same as described in reference 3.

INSTRUMENTATION

The instrument measuring stations are shown in figure 3. The instrumentation used in these Reynolds number tests was similar to that described in reference 3. The only difference was that calibrated pressure transducers were used during the two highest Reynolds number tests of this investigation. The reason for this is that the manometers that were described in reference 2 were limited to measure a maximum pressure of 3.7 psia (2.6 N/cm^2 abs). All data except manometer readings were recorded on an integrating digital data recorder. A digital computer processed all data.

PROCEDURE

The turbine was tested at six different inlet pressures in order to obtain the Reynolds number effects upon performance. At each inlet pressure, the turbine speed was held constant at the equivalent design speed of 29 260 rpm. The exhaust pressure was varied in order to obtain data over a range of blade-jet speed ratios. The total- to static-pressure ratio in argon ranged from 1.3 to 2.0. Table II presents the six different inlet

TABLE II. - INLET CONDITIONS CORRESPONDING TO

REYNOLDS NUMBERS INVESTIGATED

[Inlet total temperature, T_1', 582° R (323 K).]

Reynolds number, Re	Inlet total pressure, p_1'	
	psia	N/cm^2 abs
317 000	9.5	6.6
215 000	6.5	4.5
116 000	3.6	2.5
[a]95 000	[a]2.9	[a]2.0
65 000	2.0	1.4
41 000	1.3	.9

[a]Obtained from ref. 3.

conditions with the corresponding Reynolds numbers. These Reynolds numbers are calculated from data obtained when the turbine was operating at design equivalent speed and blade-jet speed ratio. Data at an inlet pressure of 2.9 psia (2.0 N/cm^2 abs) were obtained from reference 3.

The Reynolds number 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 mean radius of the rotor.

The blade-jet speed ratio ν, used in the presentation of the results, was calculated in all cases from the ratio of turbine-inlet total pressure to rotor-exit static pressure.

Bearing and seal friction torque used in calculation of the turbine torque was the same as in reference 3 (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.

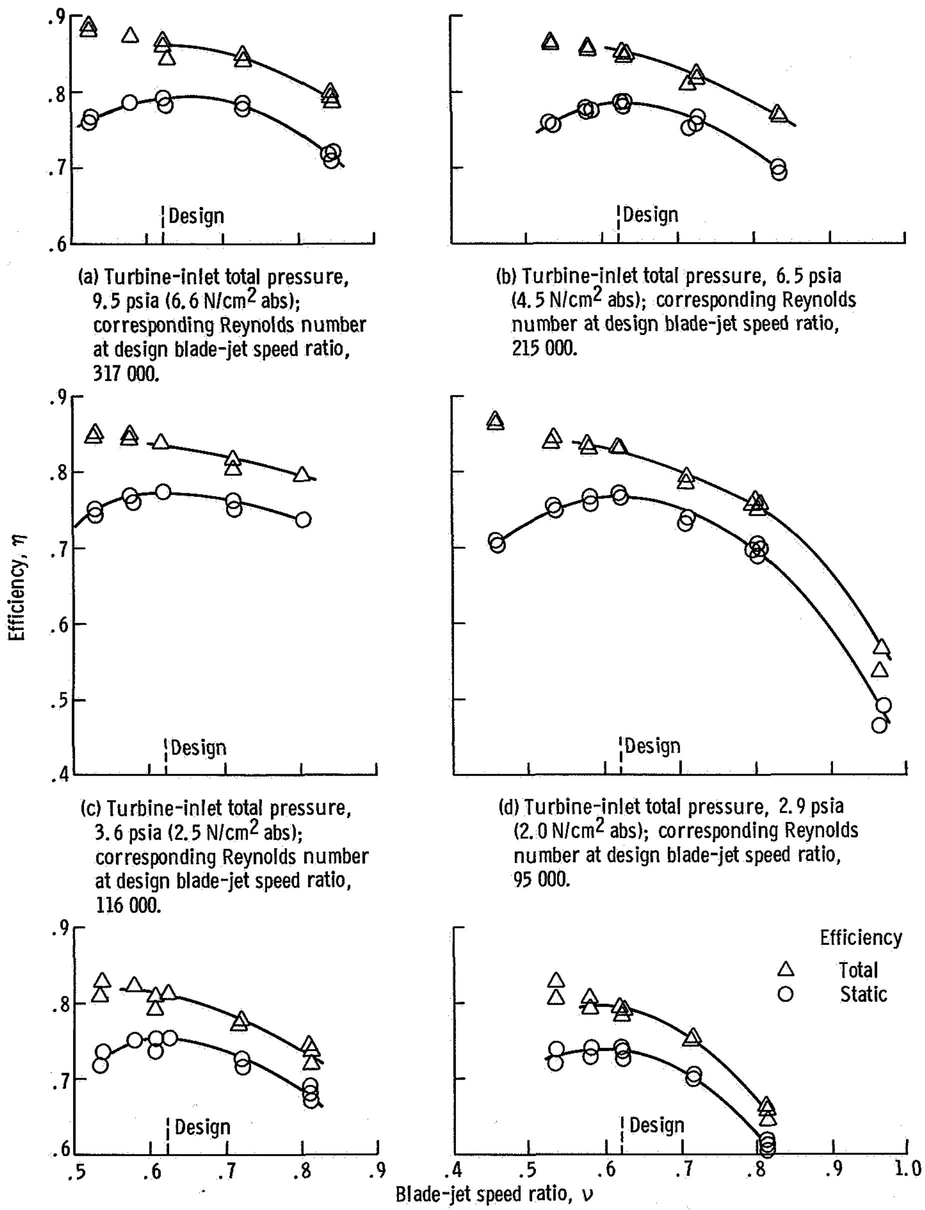
RESULTS AND DISCUSSION

The 5-inch (13-cm) turbine was investigated over a range of inlet total pressures from 9.5 to 1.3 psia (6.6 to 0.9 N/cm^2 abs). The tests were conducted at design equivalent speed and at various pressure ratios.

Performance Results

The principal results of the performance investigation are shown in figures 5 and 6 in terms of efficiency. Figure 5 presents the turbine efficiency, based on rotor-exit conditions, as a function of blade-jet speed ratio. Data for each part ((a) to (f)) of figure 5 were taken at constant inlet pressure. At each inlet pressure, there corresponds a value of Reynolds number for design equivalent speed and pressure ratio. These values are presented in table II. Figure 5 shows that the efficiency variations with blade-jet speed ratio are similar for all of the inlet pressures investigated. The figure also shows that the level of the efficiency varies with the pressure level and thus with Reynolds number. The curves of total efficiency are not drawn through the points at low blade-jet speed ratios. The computed values were somewhat questionable because of the large gradient in flow angle at these blade-jet speed ratios. The angle-measuring probe was located at a fixed radial position and, therefore, may not have provided a representative angle to use in the calculation of rotor-exit total pressure.

Figure 6 presents the turbine overall efficiency, based on diffuser exit conditions plotted against blade-jet speed ratio. The blade-jet speed ratio corresponds to that of



(a) Turbine-inlet total pressure, 9.5 psia (6.6 N/cm^2 abs); corresponding Reynolds number at design blade-jet speed ratio, 317 000.

(b) Turbine-inlet total pressure, 6.5 psia (4.5 N/cm^2 abs); corresponding Reynolds number at design blade-jet speed ratio, 215 000.

(c) Turbine-inlet total pressure, 3.6 psia (2.5 N/cm^2 abs); corresponding Reynolds number at design blade-jet speed ratio, 116 000.

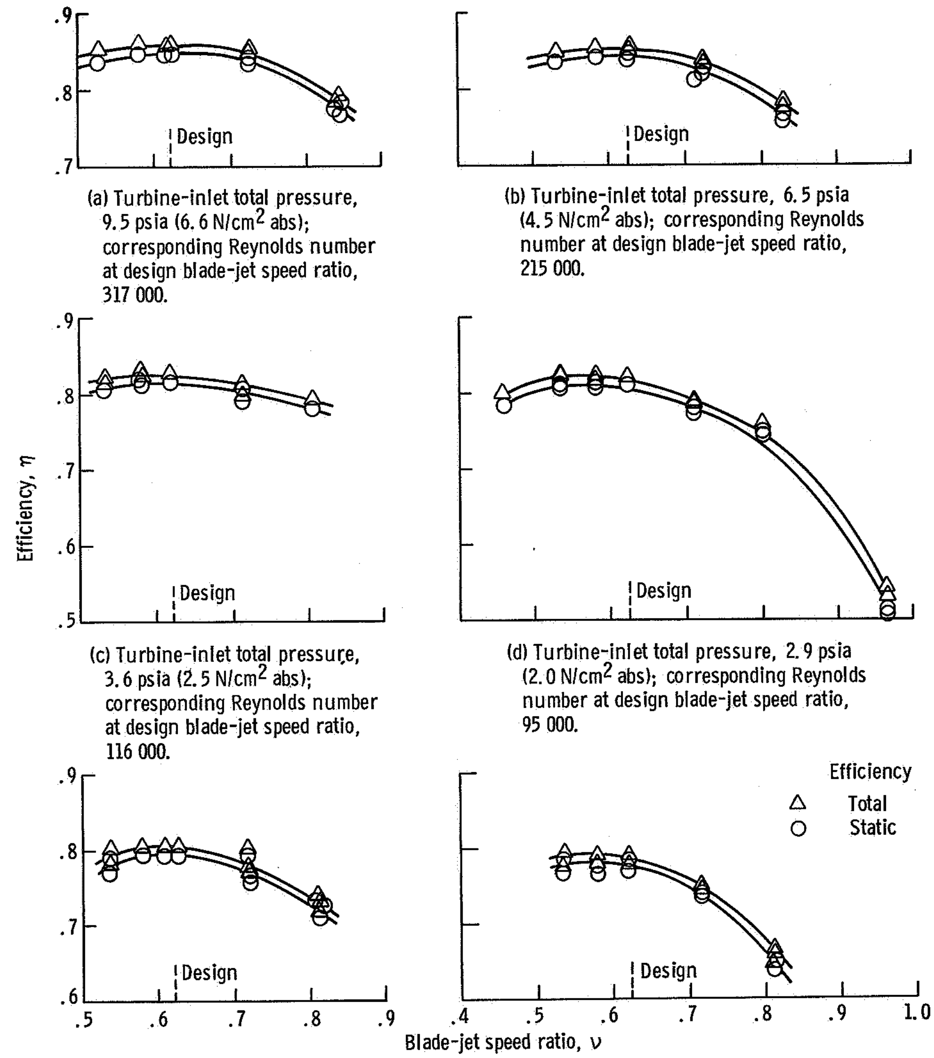
(d) Turbine-inlet total pressure, 2.9 psia (2.0 N/cm^2 abs); corresponding Reynolds number at design blade-jet speed ratio, 95 000.

(e) Turbine-inlet total pressure, 2.0 psia (1.4 N/cm^2 abs); corresponding Reynolds number at design blade-jet speed ratio, 65 000.

(f) Turbine-inlet total pressure, 1.3 psia (0.9 N/cm^2 abs); corresponding Reynolds number at design blade-jet speed ratio, 41 000.

Figure 5. - Efficiency based on rotor exit conditions as function of blade-jet speed ratio for various turbine-inlet total pressures.

figure 5 and was computed from rotor-exit conditions. The data of figure 6 are similar in form to those presented in figure 5. Data used in preparing figures 5 and 6 were taken during the same tests. Figure 6 shows also that the efficiency variations with blade-jet speed ratio are similar for all of the inlet pressures investigated. In addition, the figure shows that the level of efficiency varies with the pressure level. The differences between total and static efficiencies remain constant over the range of blade-jet speed ratios investigated. This difference is also shown to be unaffected by the inlet-pressure range.



(a) Turbine-inlet total pressure, 9.5 psia (6.6 N/cm² abs); corresponding Reynolds number at design blade-jet speed ratio, 317 000.

(b) Turbine-inlet total pressure, 6.5 psia (4.5 N/cm² abs); corresponding Reynolds number at design blade-jet speed ratio, 215 000.

(c) Turbine-inlet total pressure, 3.6 psia (2.5 N/cm² abs); corresponding Reynolds number at design blade-jet speed ratio, 116 000.

(d) Turbine-inlet total pressure, 2.9 psia (2.0 N/cm² abs); corresponding Reynolds number at design blade-jet speed ratio, 95 000.

(e) Turbine-inlet total pressure, 2.0 psia (1.4 N/cm² abs); corresponding Reynolds number at design blade-jet speed ratio, 65 000.

(f) Turbine-inlet total pressure, 1.3 psia (0.9 N/cm² abs); corresponding Reynolds number at design blade-jet speed ratio, 41 000.

Figure 6. - Efficiency based on diffuser exit conditions as function of blade-jet speed ratio for various turbine-inlet total pressures.

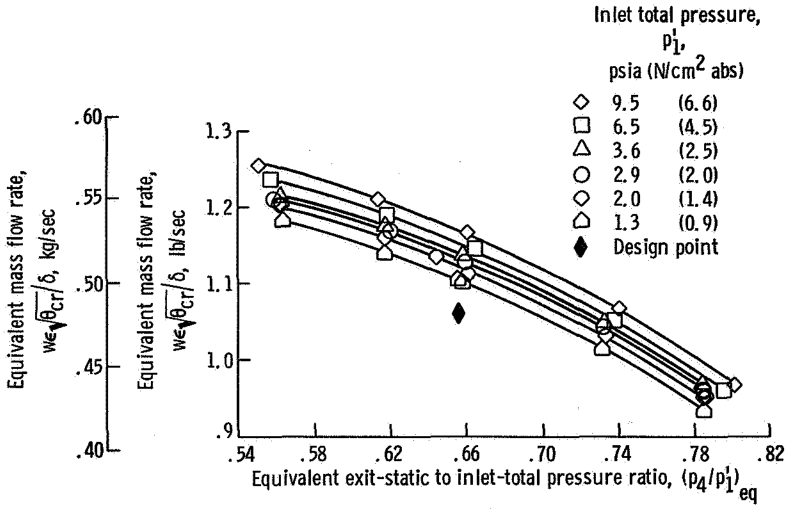


Figure 7. - Variation of equivalent mass flow rate with pressure ratio over a range of inlet total pressures.

Figure 7 presents the variation of equivalent mass flow rate $w\epsilon\sqrt{\theta_{cr}}/\delta$ with equivalent pressure ratio $(p_4/p_1')_{eq}$ for lines of constant inlet pressure p_1'. Data for this figure were obtained by operating the turbine at equivalent design speed and at six values of inlet pressure. For any given inlet pressure, the variation of mass flow rate with pressure ratio is typical of subsonic axial-flow turbines. The figure shows that a decrease in inlet pressure decreases the equivalent mass flow rate. At design-point operation and design Reynolds number the equivalent mass flow rate was 1.13 pounds per second (0.513 kg/sec).

In order to show more effectively the results of the tests conducted, the mass flow rate and efficiency data are replotted. The data are plotted as a function of Reynolds number.

Figure 8 presents the variation of total and static efficiencies, based on rotor-exit conditions, with Reynolds number. The curves shown are for turbine operation at design blade-jet speed ratio. The decrease in efficiencies with decreasing Reynolds number is quite apparent from both curves. For the Reynolds number range investigated (317 000 to 41 000), the static efficiency η_{1-4} dropped 5 percentage points. A static efficiency of 0.79 was measured at the highest Reynolds number and 0.74 was measured at the lowest Reynolds number. The total efficiency η_{1-4}' dropped about 7 percentage points, from 0.86 to 0.79, over this Reynolds number range. This decrease in efficiency, or increase in losses, is larger than what normally might be expected.

Figure 8 also presents the variation of total and static efficiencies, based on diffuser exit conditions, with Reynolds number. The curves shown are for turbine operation at design blade-jet speed ratio. The decrease in efficiencies with decreasing Reynolds numbers is similar to the curves based on rotor-exit conditions. The only apparent

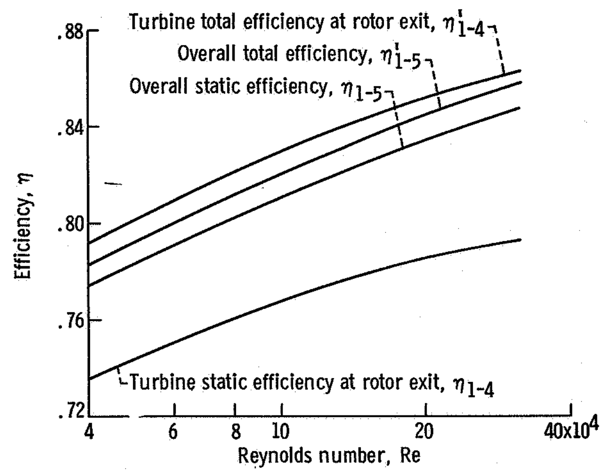


Figure 8. - Effect of Reynolds number on efficiency at design blade-jet speed ratio.

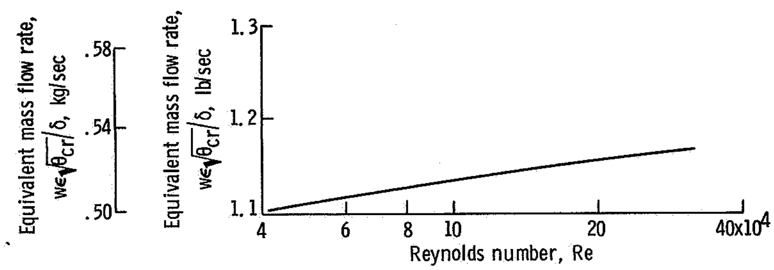


Figure 9. - Effect of Reynolds number on equivalent mass flow rate at design blade-jet speed ratio.

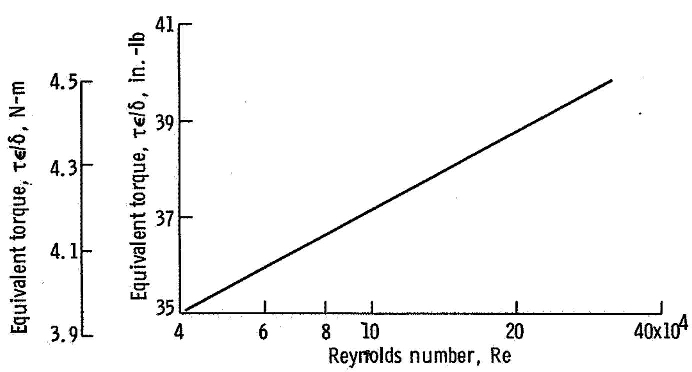


Figure 10. - Effect of Reynolds number on equivalent torque at design blade-jet speed ratio.

difference is the difference between total and static efficiencies. The difference is much less at the diffuser exit than at the rotor exit because of the action of the diffuser.

The variation of equivalent mass flow rate $w\epsilon\sqrt{\theta_{cr}}/\delta$ with Reynolds number is presented in figure 9. The values of mass flow rate used in this figure are at design blade-jet speed ratio and were obtained from figure 7. Figure 9 shows a 5 percent decrease in equivalent mass flow rate with Reynolds number over the Reynolds number range.

The variation of equivalent torque $\tau\epsilon/\delta$ with Reynolds number is presented in figure 10 to illustrate the effect of Reynolds number on turbine power. As in the preceding figures, the curve shown is for equivalent design speed and pressure ratio. This figure shows a decrease in equivalent torque as the Reynolds number decreases. The lowest value of equivalent torque is 12 percent lower than that obtained at the highest Reynolds number. Some of this decrease is a result of the equivalent mass flow rate decrease of 5 percent; the remainder results from the decrease in efficiency.

Comparison With Radial-Inflow Turbine Performance

Data from the 6.02-inch (15.3-cm) radial-inflow turbine of reference 4 were compared with the results presented herein on the 5-inch (13-cm) axial-flow turbine. The efficiency, equivalent mass flow rate, and equivalent torque declined more rapidly with decreasing Reynolds number for the axial turbine than for the radial-inflow turbine. Both turbines were tested over approximately the same Reynolds number range (for the radial-inflow turbine the range is 225 000 down to 20 000). For comparison purposes, the radial turbine performance results over its Reynolds number range are as follows: The total efficiency decreased 5 percentage points, from 0.90 to 0.85; the corresponding static efficiency decreased 4 percentage points, from 0.84 to 0.80; the turbine equivalent weight flow rate decreased 2 percent; and the equivalent torque decreased 6 percent. These values are for operation at equivalent design speed and pressure ratio.

Examination of the experimental data was made and a loss ratio was computed. This loss ratio, $(1 - \eta')/(1 - \eta'_{ref})$, was plotted as a function of Reynolds number ratio in figure 11. The faired data of total efficiency at design blade-jet speed ratio from figure 8 were used. The reference value of Reynolds number is 317 000, the highest value ob-

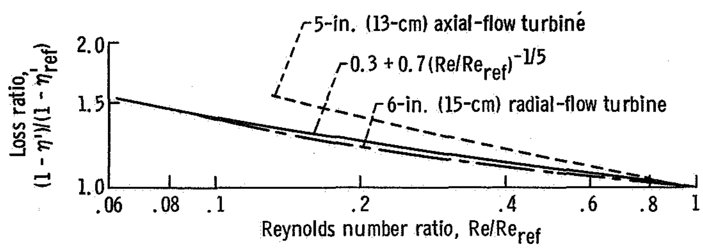


Figure 11. - Variation of loss ratios with Reynolds number ratio.

tained at design operating point.

As in reference 4, the experimental data were also compared with an empirical equation (obtained from ref. 6).

$$\frac{1 - \eta'}{1 - \eta'_{ref}} = 0.3 + 0.7\left(\frac{Re}{Re_{ref}}\right)^{-1/5}$$

The assumptions made for this equation are that 70 percent of the turbine losses are associated with skin friction, and that they vary inversely with the 1/5 power of Reynolds number ratio. The remaining 30 percent of the losses are assumed to be kinetic losses. This empirical equation is plotted in figure 11. The losses for the 5-inch (13-cm) axial-flow turbine are greater than predicted by the equation.

The loss ratio data from the radial turbine (ref. 4) are also plotted in figure 11 for comparison. The reference value of Reynolds number used for these data was 225 000. These data show that the radial turbine had lower losses than the axial turbine over the Reynolds number range.

Axial-Turbine Diffuser Effectiveness

The diffuser effectiveness, defined as the quotient $(p_5 - p_4)/(p'_4 - p_4)$, is shown in figure 12 as a function of Reynolds number. In order to obtain the effectiveness value

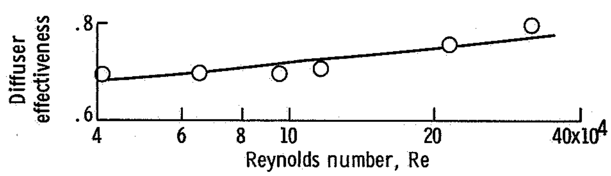


Figure 12. - Variation of diffuser effectiveness with Reynolds number at design operating point.

for this figure, all pressures were calculated from smoothed data. Values of turbine-inlet total pressure p'_1 used in the calculations were averaged values. Values of actual specific work and efficiencies were taken from faired curves. Only data at design blade-jet speed ratio were used in the calculations. The circular symbols in figure 12 indicate points where calculations were made. The figure shows that the diffuser effectiveness remains at a rather high level (0.7 to 0.8) over the Reynolds number range covered. A reduction in effectiveness with reduced Reynolds number can be noted. However, such a trend could be the result of slight data inaccuracies even though faired data were used.

SUMMARY OF RESULTS

A 5-inch (13-cm) axial turbine, designed for a Brayton cycle application, was investigated over a range of inlet total pressures from 9.5 to 1.3 psia (6.6 to 0.9 N/cm^2 abs). The corresponding Reynolds numbers ranged from 317 000 down to 41 000. The results of this evaluation are summarized as follows:

1. Turbine performance declined as the Reynolds number was decreased. The total efficiency from turbine inlet to rotor exit decreased from 0.86 to 0.79 over the range covered. The corresponding static efficiency across the rotor decreased from 0.79 to 0.74. Turbine equivalent mass flow rate decreased 5 percent, thus resulting in 12 percent reduction in equivalent torque over the range tested.

2. Deterioration in efficiency with decreasing Reynolds number was greater for this axial turbine than for a reference 6.02-inch (15.3-cm) radial turbine designed for the same application. The corresponding increase in turbine losses with decreasing Reynolds number was also greater than would be predicted by a previously used empirical equation.

3. The turbine diffuser effectiveness, calculated from values taken from faired curves, remained at the 0.7 to 0.8 level over the range of Reynolds number covered.

Lewis Research Center,
National Aeronautics and Space Administration,
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