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Recent Radial Turbine Research at the NASA Lewis Research Center

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The high efficiencies of small radial turbines have led to their application in space power systems and numerous APU and shaft power engines. Experimental and analytical work associated with these systems has included examination of blade-shroud clearance, blade loading, and exit diffuser design. Results indicate high efficiency over a wide range of specific speed and also insensitivity to clearance and blade loading in the radial part of the rotor. The exit diffuser investigation indicated that a conventional conical outer wall may not provide the velocity variation consistent with minimum overall diffuser loss. A list of recently published NASA radial turbine reports is included.

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INTRODUCTION

The high efficiencies of small radial inflow turbines have resulted in their use in many APU's, small turboshaft engines, and space power systems. The selection and development of components for specific applications has required knowledge of Reynolds number effects, internal losses, blade-shroud clearance penalties, and other characteristics to assure adequate and safe operation.

The Lewis Research Center of NASA began in 1962 to investigate components designed under contract for Brayton cycle space power systems. The studies included internal flow analyses, as well as experimental operation of compressors, turbines, alternators, and various combinations of these. The work in radial turbines from 1962 to 1967 was highlighted and summarized in reference (1),[1] a paper presented at the Second Intersociety Energy Conversion Engineering Conference in August 1967. Since that time, work has continued in the areas of blade-shroud clearance, blade loading, exit diffusers, and a specific speed investigation with various stator and rotor areas in a single turbine. Experiments have been made with cold air and argon and the high precision instrumentation and procedures described in reference (2).

This paper includes the major results obtained in several experimental programs concluded since 1967 and others still in progress. Detailed descriptions of the research hardware and the investigations may be found in the references listed.

TEST EQUIPMENT

The apparatus used in the performance evaluations of the turbines to be discussed is shown

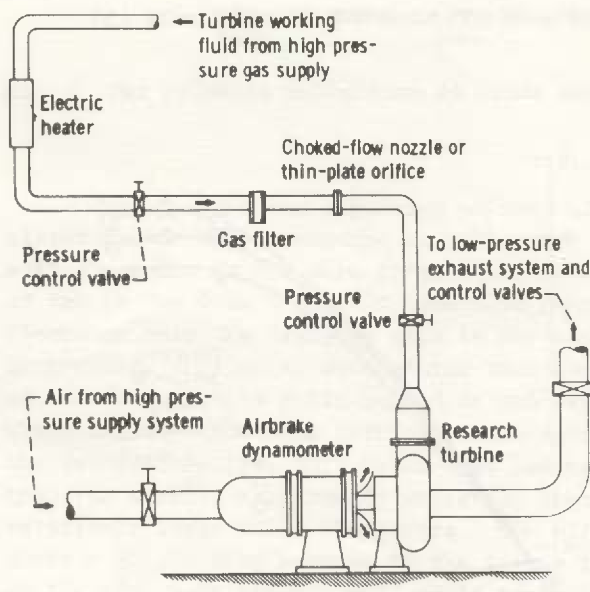

Fig. 1 Experimental equipment (2)

in Fig. 1. Argon or air, from a high-pressure supply system, was passed through a calibrated orifice plate for flow measurement upstream of the turbine. Turbine inlet and exit pressures were controlled with automatic valves during data taking. An airbrake dynamometer, cradled on air bearings, was used to absorb power, control speed, and measure torque. Internal instrumentation included static pressure taps, thermocouple rakes, and survey probes for flow angle and local total pressures and temperatures.

Fig. 2 is a photograph of one of the turbines. It is typical of those investigated, with an inlet volute, conventional stator blades, and a rotor with full and splitter blades. Its tip diameter is 15.3 cm, while other test turbines discussed herein had diameters of 11.7 and 12.6 cm. These were all low pressure ratio machines, 1.5 to 1.8.

1 Numbers in parentheses designate References at end of paper.

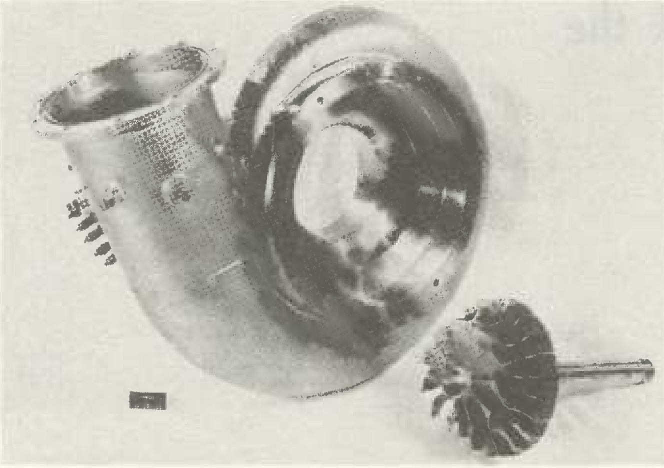

Fig. 2 Turbine rotor and scroll (3)

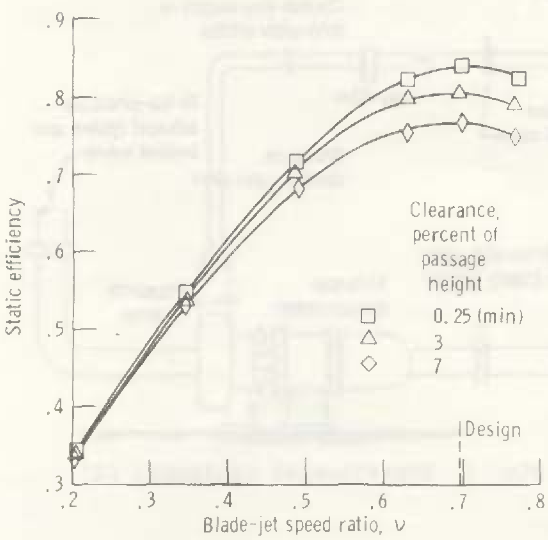

Fig. 3 Effect of uniform clearance values on static efficiency for varying blade-jet speed ratios (3)

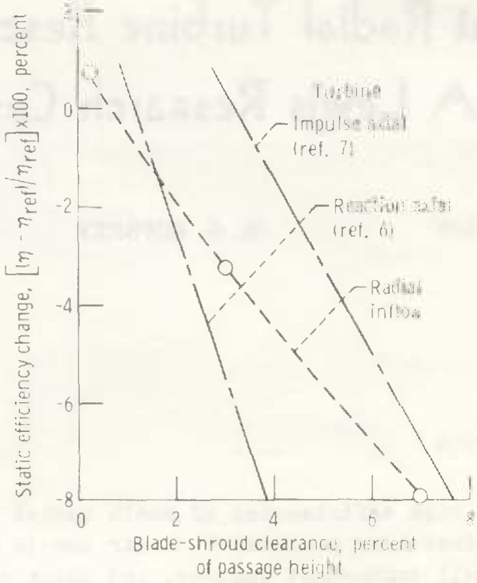

Fig. 4 Comparison of effect on static efficiency of clearance variation for three turbines. Uniform percent clearance at rotor entrance and exit for radial-inflow-turbine (3)

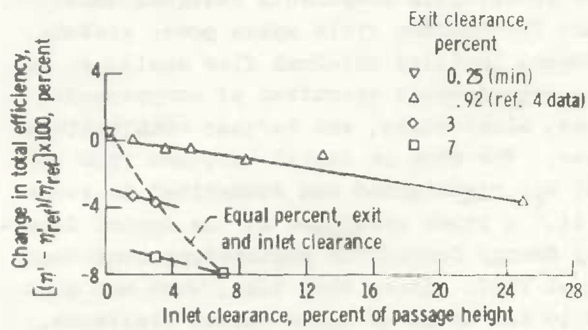

Fig. 5 Summary of inlet and exit clearance effects on total efficiency at design equivalent values of speed and pressure ratio (3)

BLADE-SHROUD CLEARANCE EFFECTS

The effect of blade-shroud clearance on turbine performance is of interest because of mass flow, blade loading, and efficiency considerations. The clearance must be adequate to avoid contacts during speed and thermal transients, but minimized to avoid blade unloading and excessive loss generation. Besides this operational concern, knowledge is also desirable for better understanding of the flow and comparison with axial turbine clearance effects. A test program involving varying clearance and clearance distribution was carried out with a 15.3-cm turbine designed to drive the compressor of a two-shaft space power system. This investigation, described in reference (3), included step changes in clearance in the inlet portion of the rotor and also in the exit portion. These were carried out so that separate trends could be established with local clearance change, as well as with uniform incremental changes in terms of percent of passage height.

Minimum clearance was established by coating the shroud with lacquer and hand finishing. Measurements showed about 0.25 percent of passage height from inlet to outlet for this minimum clearance case. Fig. 3 shows that peak static

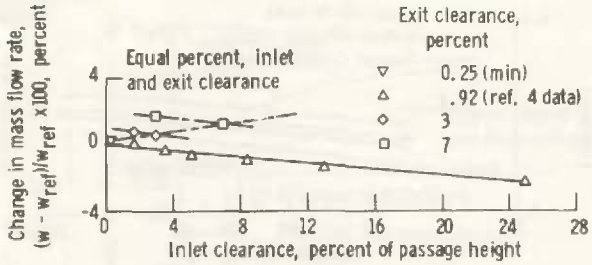

Fig. 6 Summary of inlet and exit clearance effects on mass flow rate at design equivalent values of speed and pressure ratio (3)

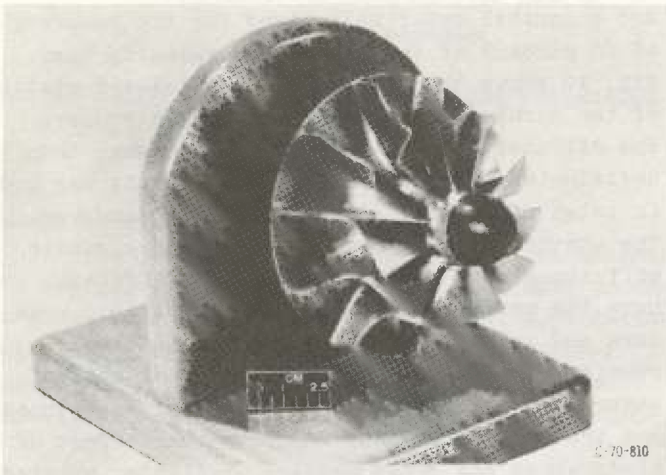

Fig. 7 Rotor with splitter blades removed (4)

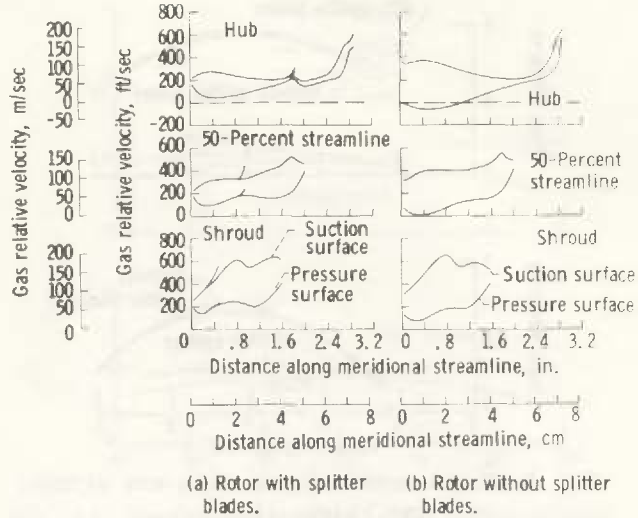

Fig. 8 Gas relative velocities at blade surface (4)

efficiency dropped from 0.84 to 0.81 and then 0.77 as clearance was increased uniformly from 0.25 to 3.0 and 7.0. The effect on total efficiency was about the same. The increased clearances were obtained by removing the lacquer from the shroud and grinding material from the blade tips. The trend shown in Fig. 3 may be compared with similar trends in axial flow turbines. Fig. 4 shows the effect of clearance on the static efficiencies of this radial turbine and two axial flow turbines. The turbines had different design point clearances as shown and different sensitivity to blade-shroud clearance. It should be noted that in all cases shown, the clearance was increased from the design value by removing blade material. The slopes of the curves show that the radial-inflow turbine was least sensitive to clearance change. One percent of passage height removed from the blade resulted in 1.3 percent loss in specific work output. Corresponding values for the impulse and reaction axial turbines were 1.8 and 3.0.

Fig. 5 shows the separated effects of inlet clearance and exit clearance on efficiency. The exit clearance is the more influential by a factor of ten in the 0 to 8 percent clearance range. Clearance near the trailing edge is obviously the controlling influence, determining that fraction of the flow that is fully turned to the exit blade angle. Since the turbine stator sets up the available whirl, this means that the design specific work is very nearly achieved, even with relatively large inlet clearances. The efficiency shows a slight drop because of the losses incurred in the clearance space. This would probably be true in the case of an axial turbine with extremely high solidity.

The effects of inlet and exit clearance on mass flow are shown in Fig. 6. Here again, the exit clearance is most influential, since the exit flow area is the effective orifice in the rotor. Reference (3) discusses these effects in some detail and also includes the results of radial surveys of flow angle, total pressure, and total temperature at the turbine exit for each clearance configuration.

SPLITTER BLADE REMOVAL

The effect of blade loading near the rotor inlet was examined experimentally in an 11.7-cm scale model of the turbine used in the clearance investigation. The splitter blades were removed, doubling the blade loading in the upstream half of the rotor, Fig. 7. Channel velocities were then calculated for both cases, with and without splitters. The results are shown in Fig. 8. The negative velocities on the pressure side of the

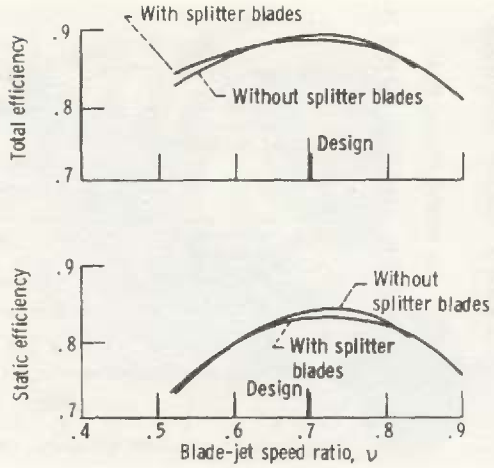

Fig. 9 Turbine efficiency with and without splitter blades (4)

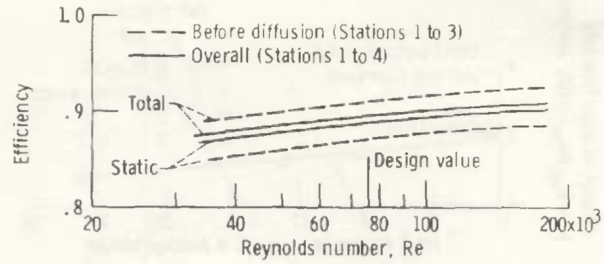

Fig. 10 Effect of Reynolds number on turbine efficiency at equivalent design and pressure ratio (6)

blade indicate a flow eddy extending from the hub almost to the meridional 50 percent streamline. The large increase in loading upstream of the splitter trailing edge location is also shown.

Turbine performance data were taken over a range of speed and pressure ratio, showing very little difference between the splitter and the no-splitter cases. Fig. 9 shows the variation in efficiency with blade-jet-speed ratio at design speed. Note that the efficiency with no splitters was slightly higher than with the fully bladed rotor at design point operation. The loss increase due to the loading increase was apparently offset by the reduced surface area. This result and the results of the clearance investigation indicate an insensitivity to poor flow conditions near the leading edge as indicated by the channel velocity calculation. An estimate of solidity based on average blade spacing provides some insight into this. After removal of the splitters, the average ratio of chord to spacing was about 2.6, approximately double the solidity required for an axial turbine with comparable turning. Also, the inlet kinetic energy is very low, and the rotor reaction, defined as the ratio of relative kinetic energy increase to turbine specific work, is 0.2. This light loading and favorable reaction provides an appreciable margin for the kind of flow modifications resulting from the splitter removal. The splitter investigation was reported in reference (4).

EXIT DIFFUSER INVESTIGATIONS

Three diffusers were designed for the turbines of a 2- to 10-kw space power system (5). The first of these had a cylindrical inner body and a conical outer wall sized for the recovery of 60 percent of the rotor exit velocity head. Fig. 10 shows the efficiencies, total and static, of the turbine with and without the diffuser. The diffuser loss was considerably higher than anticipated. The diffuser loss accounts for 0.02 in total efficiency at design Reynolds number. The static pressure recovery provided a static efficiency gain of 0.015. Conical diffusers have the maximum rates of change of static pressure and velocity at the inlet. This should provide minimum loss and minimum likelihood of separation because the boundary layer is thinnest and the Reynolds number highest. The effect of blade wakes and rotor passage gradients, however, are not taken into account in the boundary-layer analyses used and could affect the separation characteristics of the boundary layer. Consequently, a second diffuser was designed to allow some mixing upstream of the most rapid change in velocity. Static pressure was scheduled to vary linearly from inlet to exit of the diffuser as shown in Fig. 11(a). The corresponding velocity schedule is also shown in Fig. 11(b). The resulting wall contour, with a tapered inner body, is the trumpet-like shape in Fig. 12. A third diffuser was very similar to the second, but with a cylindrical body.

Fig. 13 shows the overall total efficiency and static efficiency of the turbine with each diffuser. The gain with the diffusers designed for a linear variation in static pressure was about 0.01 in total efficiency. The diffuser loss was cut in half. Measurement accuracy was critical here, with the gain in efficiencies shown resulting from small differences in measured pressures at the design Reynolds number operating point. The measurements were confirmed, therefore, at a higher level, 13.8 N/sq cm inlet compared to 4.8 N/sq cm inlet, in order to increase the certainty of the conclusions.

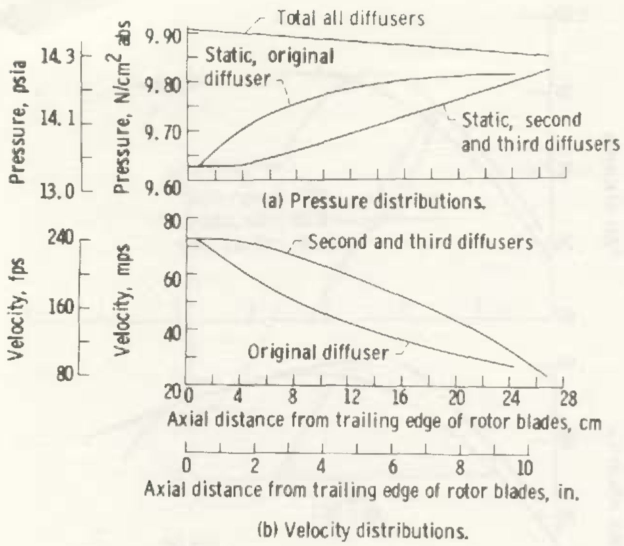

Fig. 11 Diffuser design pressures and velocities (5)

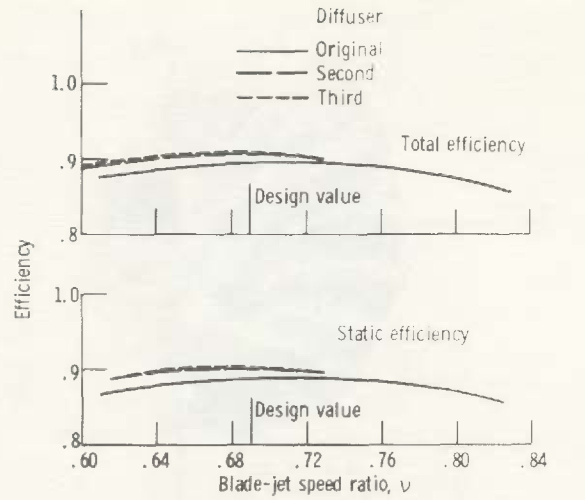

Fig. 13 Variation of turbine efficiency with blade-jet speed ratio at equivalent design speed for the three diffusers

SPECIFIC SPEED INVESTIGATIONS

The development of high-speed turbomachinery is expensive. It is, therefore, desirable to use a given basic design for a variety of applications with different power levels. The closed-loop space power program includes a range of power levels with the common requirement of high efficiency. The desired operating range could be achieved without major change in the turbine and compressor by three methods. Operating pressure could be changed with nominally constant pressure ratios. This would change mass flow but not volume flow. Metering areas could be changed by simply changing blade angles. This could change vol-

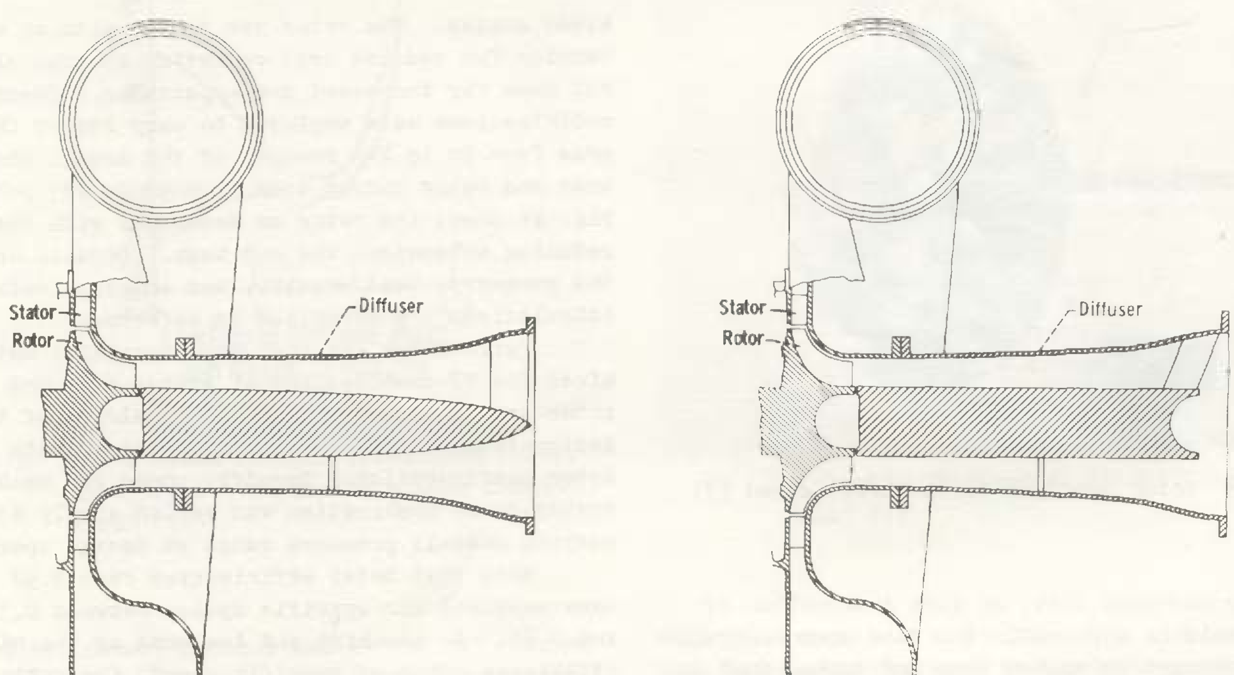

Fig. 12 Turbine with diffuser (5)

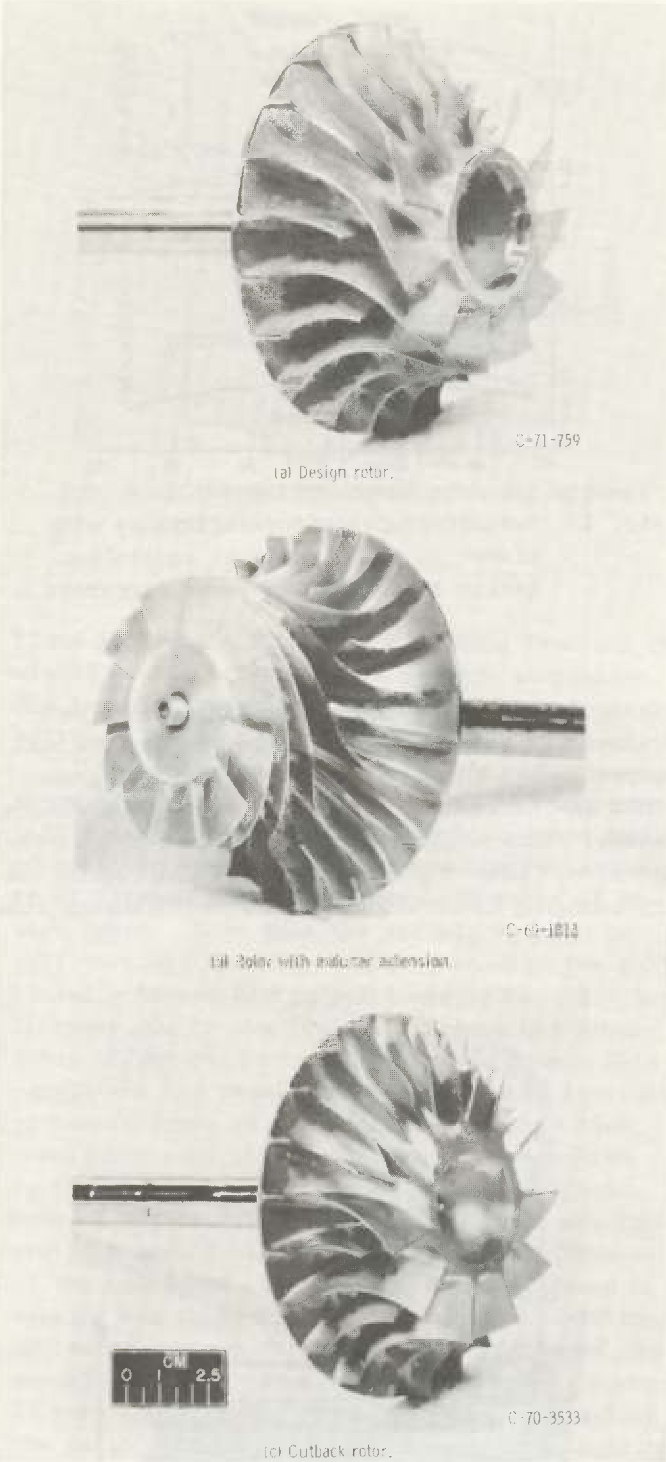

Fig. 14 Rotor configurations investigated (7)

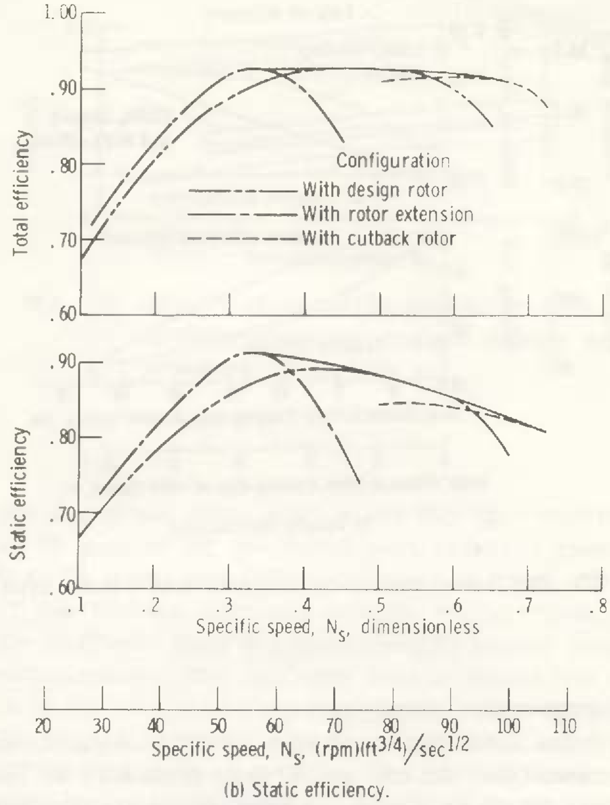

Fig. 15 Variation of efficiency with specific speed at equivalent design speed (with best stator-rotor combination) (7)

ume flow and mass flow, or some combination of these could be employed. The flow area approach has advantages in system size and system duct and heat-exchanger pressure drops.

The 12.6-cm turbine mentioned previously (6) was modified to accept a series of stator blade rows with different numbers of blades and blade angles. The rotor was fitted with an extension for reduced area operation and was also cut back for increased area operation. These modifications were employed to vary stator throat area from 20 to 144 percent of the design throat area and rotor throat area from 53 to 137 percent. Fig. 14 shows the rotor as designed, with the reducing extension, and cut back. Details on the geometry, test results, and internal velocity calculations are described in reference (7).

Performance was then experimentally determined for 13 combinations of stator area and rotor area. Fig. 15 shows the envelopes of the design-speed efficiency curves obtained with each rotor configuration. Specific speed for each stator-rotor combination was varied simply by varying overall pressure ratio at design speed.

Note that total efficiencies over 0.90 were measured for specific speeds between 0.37 and 0.80. At the high and low ends of the high efficiency range of specific speed, the ratio of stator throat area to rotor throat area was near the design ratio. Efficiency was lower for area ratios not near the design ratio. The best combination in terms of design area were 42 to

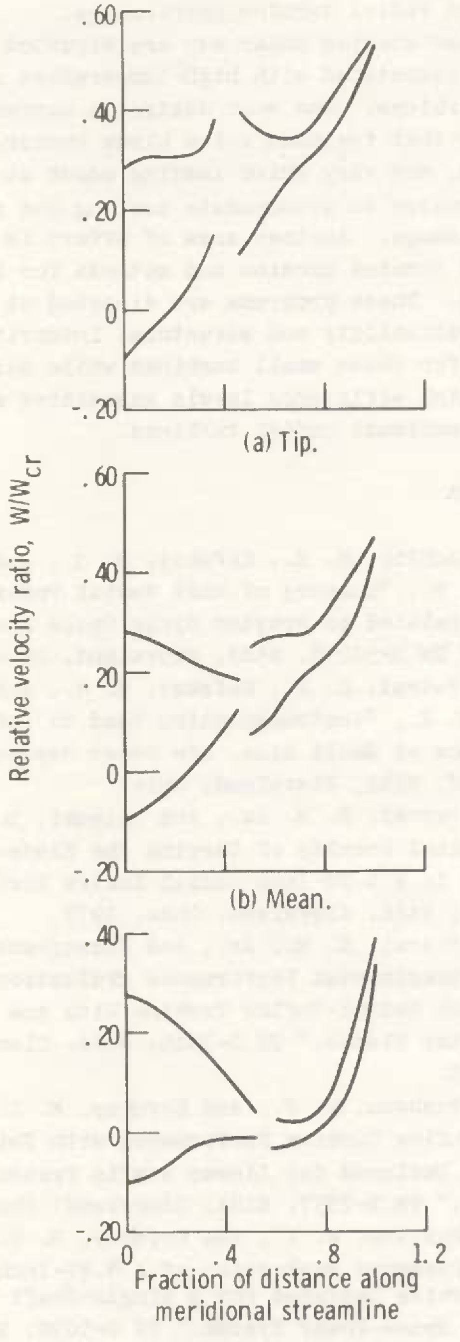

Fig. 16 Rotor blade surface velocities (rotor extension) (42 percent stator throat area) (7)

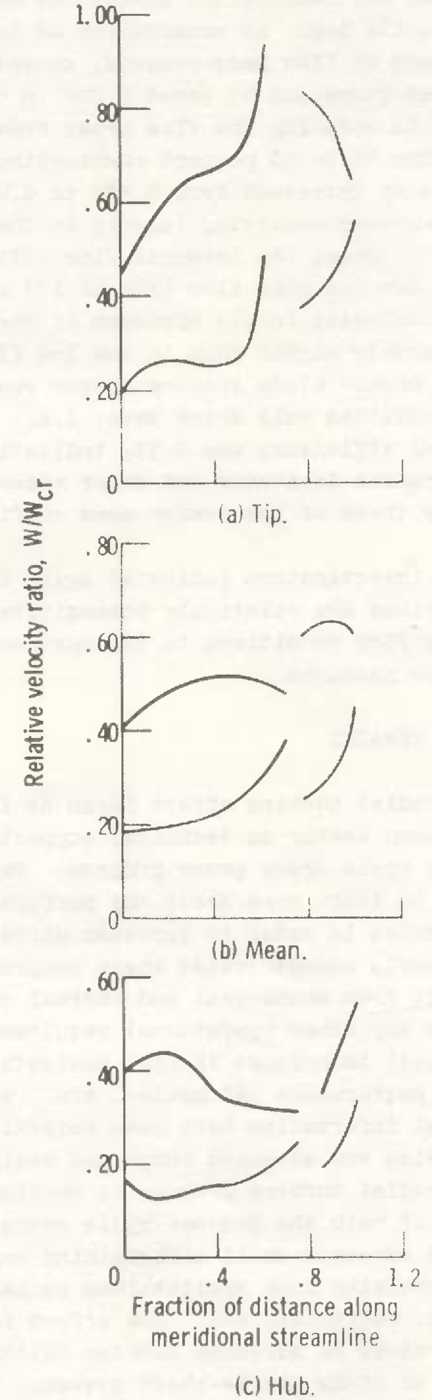

Fig. 17 Rotor blade surface velocities (rotor cutback) (144 percent stator throat area) (7)

53 (stator-rotor) percent and 144 to 137 percent. These provided just about design stator reaction. Velocities in the flow passages upstream of the throats, however, deviated considerably from the design internal velocities because of the different volume flows. The high volume flow was more than four times the low volume flow. Blade surface velocities for each stator-rotor combination were calculated and included in the reference. The low flow case solution, Fig. 16, indicated a large pressure surface flow eddy extending from the leading edge halfway through the splitter

blades on the shroud and well beyond the splitter blades along the hub. Also, velocities near the inlet are quite low. An examination of internal losses, based on flow measurements, showed that rotor losses increased by about 0.006 in total efficiency in reducing the flow areas from design values to the 42 to 53 percent combination. Overall efficiency decreased from 0.930 to 0.895 with the loss increase occurring largely in the stator.

Fig. 17 shows the internal flow velocities calculated for the high flow (144 to 137 percent) case. The velocity levels upstream of the throat are considerably higher than in the low flow case, indicating higher blade loading, lower reaction, and all velocities well above zero, i.e., no flow eddy. Total efficiency was 0.92, indicating very slight increases in stator and rotor viscous losses over those of the design area configuration.

This investigation indicated again that radial turbines are relatively insensitive to unfavorable flow conditions in the upstream part of the rotor passages.

CONCLUDING REMARKS

The radial turbine effort began at the Lewis Research Center as technical support for the Brayton cycle space power program. The intent was to learn more about the performance characteristics in order to increase efficiency and to properly assess losses where compromises might result from mechanical and thermal considerations or any other operational requirements. The analytical techniques in flow analysis, off-design performance estimation, etc., and experimental information have been helpful in system studies and advanced component designs.

The radial turbine program is continuing in support of both the Brayton cycle space power program and advanced small airbreathing engine programs involving such applications as helicopter, APU, vehicular, etc. One effort in process involves an advanced turbine suitable for the 2- to 10-kw single-shaft system. The design employed knowledge obtained in the radial turbine studies, as well as some axial turbine investigations. The turbine has stators with converging endwalls for low-velocity turning, no splitters, and tandem rotor blades. A second effort is the study of the effect of rotor tip cutback on radial turbine performance.

Other studies under way are directed at problems associated with high-temperature cooled radial turbines. One such design is currently under way that includes a low blade number, no splitters, and very thick leading edges at reduced diameter to accommodate cooling and resist erosion damage. Another area of effort is that of radial turbine erosion and methods for its reduction. These programs are directed at achieving the reliability and structural integrity required for these small turbines while maintaining the high efficiency levels associated with more conventional radial turbines.

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