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THE PERFORMANCE OF A SINGLE-STAGE IMPULSE TURBINE HAVING AN
11.0-INCH PITCH-LINE DIAMETER WHEEL WITH CAST AIRFOIL-SHAPED
AND BENT SHEET-METAL NOZZLE BLADES

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ADVANCE RESTRICTED REPORT

THE PERFORMANCE OF A SINGLE-STAGE IMPULSE TURBINE HAVING AN
11.0-INCH PITCH-LINE DIAMETER WHEEL WITH CAST AIRFOIL-SHAPED
AND BENT SHEET-METAL NOZZLE BLADES

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SUMMARY

Efficiency tests have been made on a single-stage gas turbine having an 11.0-inch pitch-line diameter wheel and a nozzle diaphragm with cast airfoil-shaped nozzle blades using atmospheric air as the driving fluid. A comparison of these tests with previous tests made on the same turbine but with a nozzle diaphragm having fabricated bent sheet-metal blades is given.

The results show an increase in efficiency in changing from the fabricated to the cast nozzle diaphragm of 0.095 at a pressure ratio of 1.5 and 0.02 at a pressure ratio of 5.2 for a blade-to-jet speed ratio of 0.4. A comparison of the air flow with the two nozzle diaphragms indicates an increase in mass-flow coefficient for the cast nozzle diaphragm over that for the fabricated nozzle diaphragm.

INTRODUCTION

The results of efficiency tests of a single-stage gas turbine having an 11.0-inch pitch-line diameter wheel with a nozzle diaphragm having fabricated bent sheet-metal blades using cold air as the driving fluid were presented in reference 1. The efficiency tests reported herein have been made on the same turbine wheel as in the reference tests but with a nozzle diaphragm using cast airfoil-shaped nozzle blades. Cold air was also used in these tests as the driving fluid.

The cast nozzle diaphragm differs from the fabricated nozzle diaphragm principally in the shape of the nozzle blades. The blades of the cast diaphragm have a more rounded entrance and the flow passages turn in a contracting section. In addition, the entrance to the nozzles of the cast diaphragm is more nearly axial than that for the fabricated diaphragm.

The purpose of the reported tests, which were conducted at the NACA Cleveland laboratory, was to determine the differences in the turbine performance caused by the change from fabricated to cast nozzle diaphragms.

APPARATUS AND METHOD

The apparatus for these tests was the same as that of reference 1 with the exception of the use of a nozzle box with a cast nozzle diaphragm. In each case, a wheel with inserted buckets was used and bucket-to-nozzle clearance was set at 0.11 to 0.12 inch.

Diagrams of the fabricated and the cast nozzle diaphragms are shown in figure 1. The principal changes from the fabricated to the cast nozzle diaphragm are as follows:

- (a) Blade angle decreased from 22° to an angle between 22° and 20° varying from nozzle to nozzle
- (b) Cone angle, defined as the angle between a line parallel to the axis of the turbine and the center line of the nozzle flow passage, changed from 0° to 15°
- (c) Blade shape changed from sheet to airfoil form with the resulting change in entrance shape
- (d) Number of nozzle openings increased from 38 to 46
- (e) Nozzle-box discharge area decreased from 10.9 to 10.3 square inches

Efficiency tests were made over the following range of conditions: The ratio of the nozzle-box inlet pressure to the discharge pressure was varied from approximately 1.36 to 6.07; at each pressure ratio, the turbine speed was varied from approximately 3000 to 21,000 rpm. The test method and the method of calculation are completely given in reference 1.

SYMBOLS

- A. nozzle-box discharge area, (sq ft)
- g acceleration due to gravity, $32.2 \text{ (ft)/(sec)}^2$ or dimensional constant, 32.2 (lb)/(slug)
- k mass-flow coefficient defined as ratio of actual mass flow to ideal mass flow

- M_a mass flow of air, (slugs)/(sec)
 N turbine speed, (rpm)
 P_d static pressure of turbine discharge at plenum chamber,
(in. Hg absolute)
 P_1 total pressure at nozzle-box inlet, (in. Hg absolute)
 R gas constant for air, 53.35 (ft-lb)/(lb)(°F)
 T_1 total temperature at nozzle-box inlet, (°F absolute)
 u blade pitch-line speed, (fps)
 v theoretical jet speed, (fps)

RESULTS AND DISCUSSION

Efficiency curves for the turbine with the cast nozzle diaphragm are shown in figure 2 for a range of pressure ratios P_1/P_d from 1.36 to 6.07, an inlet pressure P_1 of about 25 inches of mercury absolute, and an inlet temperature T_1 of about 532° F absolute. The maximum turbine efficiency η occurred at a blade-to-jet speed ratio u/v of approximately 0.43. The solid curves of figure 3 are a cross plot of figure 2. It is apparent from figures 2 and 3 that the efficiency of the turbine with a cast nozzle diaphragm increases up to a pressure ratio of about 3 and then decreases.

The occurrence of the dip in the curves for the cast nozzle diaphragm at a pressure ratio of about 1.7 has been confirmed by several check tests. Plotted on figure 3 as dashed curves are the efficiencies of the turbine with the fabricated nozzle diaphragm, the data for which were taken from reference 1 for an inlet-gas temperature of 537° F absolute and an inlet pressure of about 25.4 inches of mercury absolute. The difference in efficiency between the two turbines with different diaphragms above a pressure ratio of about 2 increases as the blade-to-jet speed ratio increases and decreases as the pressure ratio increases. For a blade-to-jet speed ratio of 0.4 the efficiency of the turbine with the cast nozzle diaphragm is approximately 0.095 higher than the efficiency with the fabricated nozzle diaphragm at a pressure ratio of 1.5 and 0.02 higher at a pressure ratio of 5.2. The comparison at a constant blade-to-jet speed ratio, however, does not completely describe the differences in performance because the maximum efficiency for the turbine with the cast nozzle diaphragm occurred at a blade-to-jet speed ratio of approximately 0.43 as against 0.40 (see reference 1) for the turbine with the fabricated nozzle diaphragm.

A separation of the effects of velocity coefficient, velocity distribution, cone angle, and blade angle on the turbine efficiency is not possible with the present data. If the assumption is arbitrarily made that the velocity diagrams of the turbines with cast and fabricated nozzle diaphragms are similar with regard to all angles, the optimum blade-to-jet speed ratio must change in the same proportion as the nozzle jet velocity coefficient. Inasmuch as the turbine efficiency varies as the square of the nozzle jet velocity coefficient, an increase in turbine efficiency of about 15 percent should be accompanied by an increase in optimum u/v of about $7\frac{1}{2}$ percent. The actual increase in optimum u/v was from 0.40 to 0.43 or $7\frac{1}{2}$ percent. At higher pressure ratios, where the expansion in the clearance spaces becomes appreciable, the increased nozzle jet velocity coefficient has proportionally less effect on the over-all velocity coefficient of the nozzle and clearance-space expansion, as well as on the turbine efficiency.

Unpublished NACA tests have shown a considerable effect of inlet-pipe design on turbine efficiency. The design used throughout the reported tests is that of reference 1. Any possible difference in the effect of the inlet duct on the turbine efficiency with different nozzle diaphragms has not been established. It is conceivable that the entrance-section effect would not be the same for different nozzle diaphragms.

Plots of the air-flow factor $\frac{M_a}{P_1} \sqrt{g R T_1}$ against the speed factor $N\sqrt{519/T_1}$ for various pressure ratios are shown in figure 4 for the cast nozzle diaphragm. Figure 5(a) is a cross plot of the data in figure 4. The data for figure 5(b), taken from reference 1, is for the fabricated diaphragm. For pressure ratios above 2.3, the air-flow factor is constant for all values of speed factor. The air-flow factor was generally higher for the turbine with the cast nozzle diaphragm. The greatest increase in the air-flow factor was at low pressure ratios with only a slight increase of about 1 percent at pressure ratios above 2.3.

The ratio of the mass-flow coefficients may be calculated for any given pressure ratio and speed from the following equation:

$$\frac{k_c}{k_f} = \frac{\left(\frac{M_a}{P_1} \sqrt{g R T_1}\right)_c}{\left(\frac{M_a}{P_1} \sqrt{g R T_1}\right)_f} \times \frac{A_f}{A_c}$$

where the subscripts c and f designate the cast nozzle diaphragm and the fabricated nozzle diaphragm, respectively. The discharge area of the cast nozzle diaphragm is 10.3 square inches and the discharge area of the fabricated nozzle diaphragm is 10.9 square inches. The mass-flow coefficient for the cast nozzle diaphragm is approximately 7 percent higher above a pressure ratio of 2.3 and 15 percent higher at a pressure ratio of 1.5 than that for the fabricated nozzle diaphragm.

SUMMARY OF RESULTS

From a comparison of performance tests of a single-stage gas turbine having an 11.0-inch pitch-line diameter wheel using a nozzle diaphragm with cast airfoil-shaped nozzle blades with tests of the same turbine wheel using a nozzle diaphragm with fabricated bent sheet-metal blades, the following results were obtained:

1. The blade-to-jet speed ratio for maximum efficiency was approximately 0.43 for the turbine with a cast nozzle diaphragm and 0.40 for the fabricated nozzle diaphragm. This increase is probably caused principally by the increased velocity coefficient of the cast nozzle diaphragm.

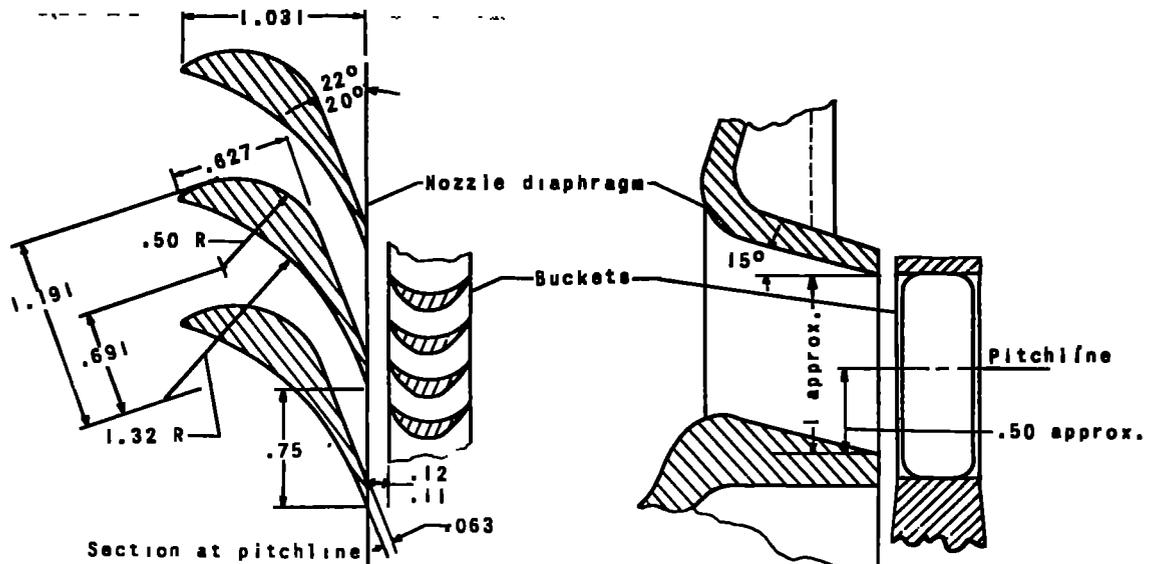
2. Efficiency of the turbine with the cast nozzle diaphragm was higher than the efficiency with a fabricated nozzle diaphragm. At a blade-to-jet speed ratio of 0.4 the increase in efficiency was 0.095 at a pressure ratio of 1.5 and 0.02 at a pressure ratio of 5.2.

3. The mass-flow coefficient for the cast nozzle diaphragm was approximately 7 percent higher above a pressure ratio of 2.3 and approximately 15 percent higher at a pressure ratio of 1.5 than that for the fabricated nozzle diaphragm.

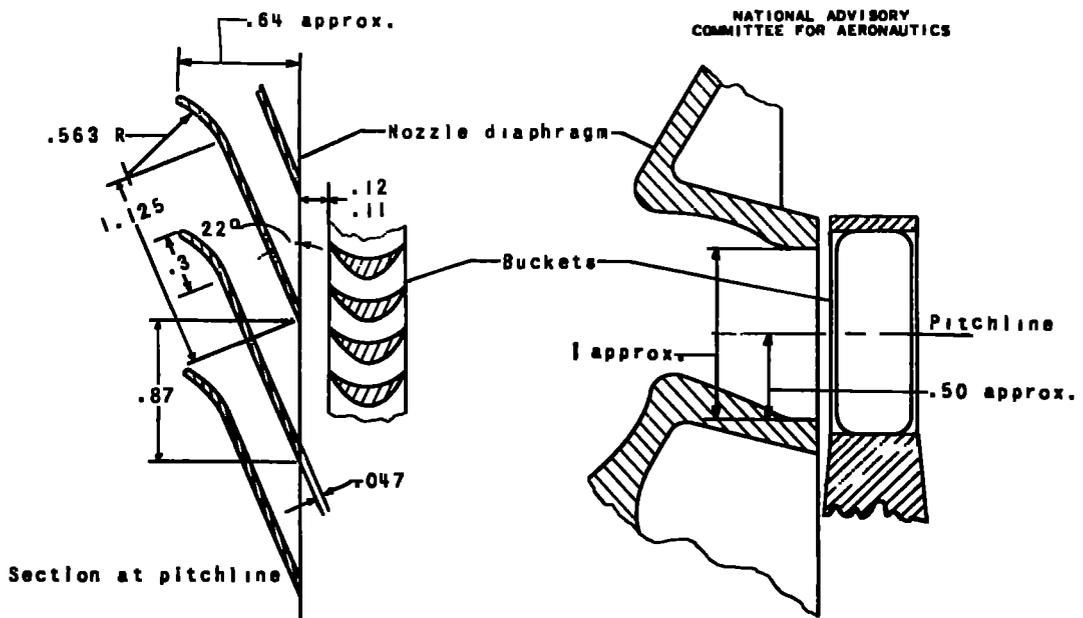
Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCE

1. Gabriel, David S., and Carman, L. Robert: Efficiency Tests of a Single-Stage Impulse Turbine Having an 11.0-Inch Pitch-Line Diameter Wheel with Air as the Driving Fluid. NACA ACR No. E5C30, 1945.



(a) Cast nozzle diaphragm.



(b) Fabricated nozzle diaphragm.

Figure 1. - Diagrams of the cast and fabricated nozzle diaphragms. All dimensions are in inches.

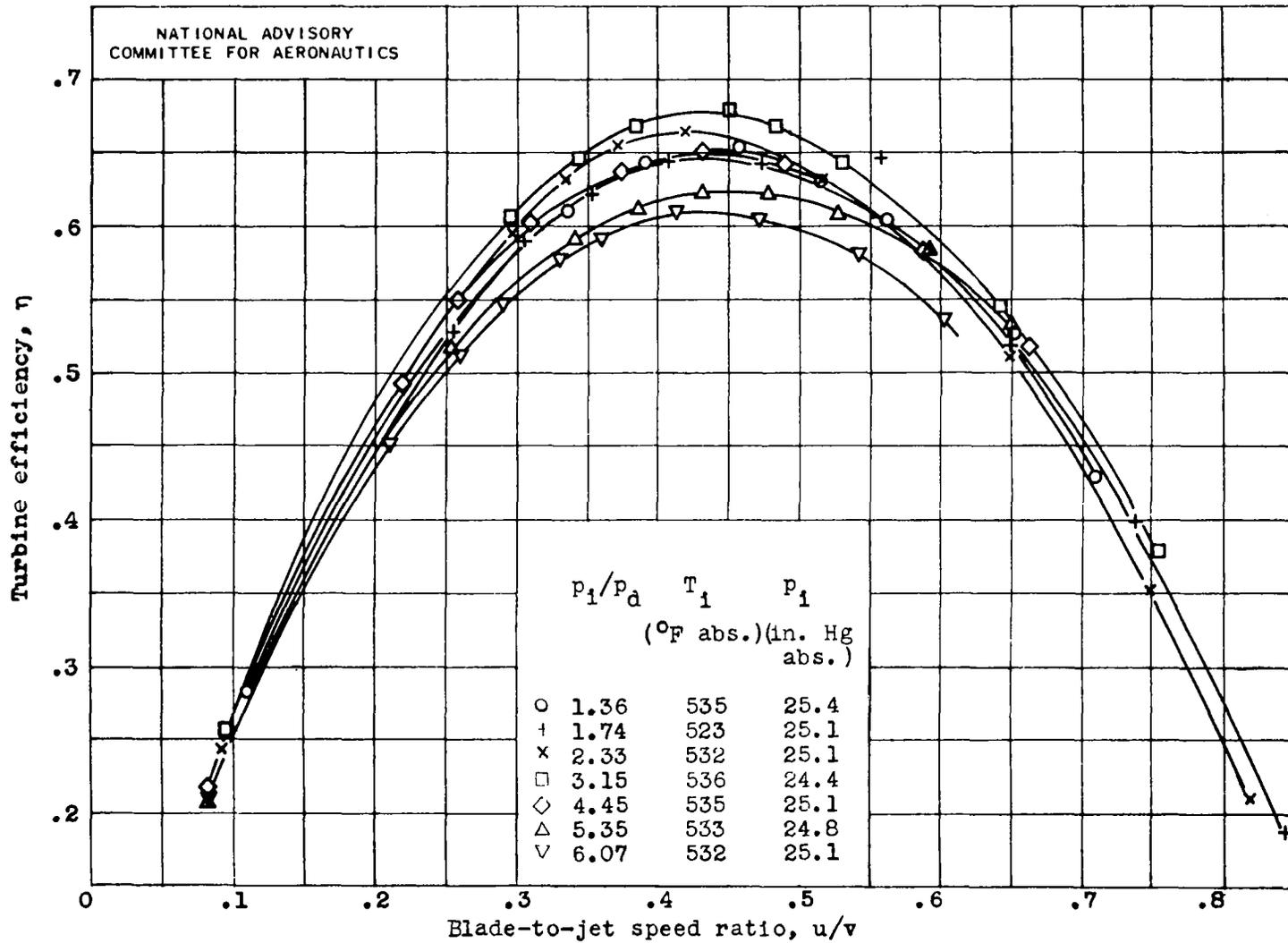


Figure 2. - Variation of turbine efficiency with blade-to-jet speed ratio for various pressure ratios using cast nozzle diaphragm.

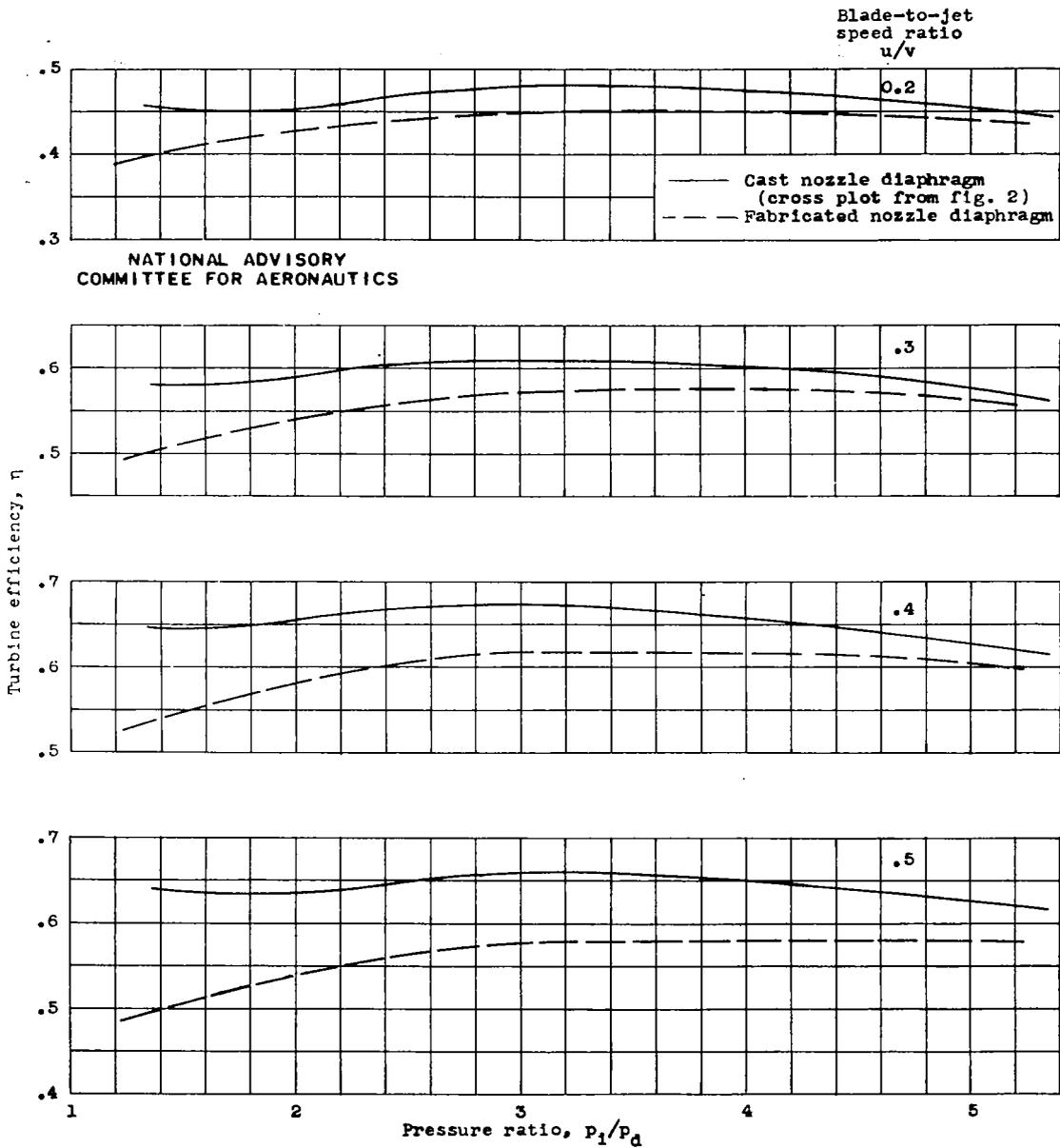


Figure 3. - Comparison of the turbine efficiency with a cast nozzle diaphragm with the turbine efficiency with a fabricated nozzle diaphragm.

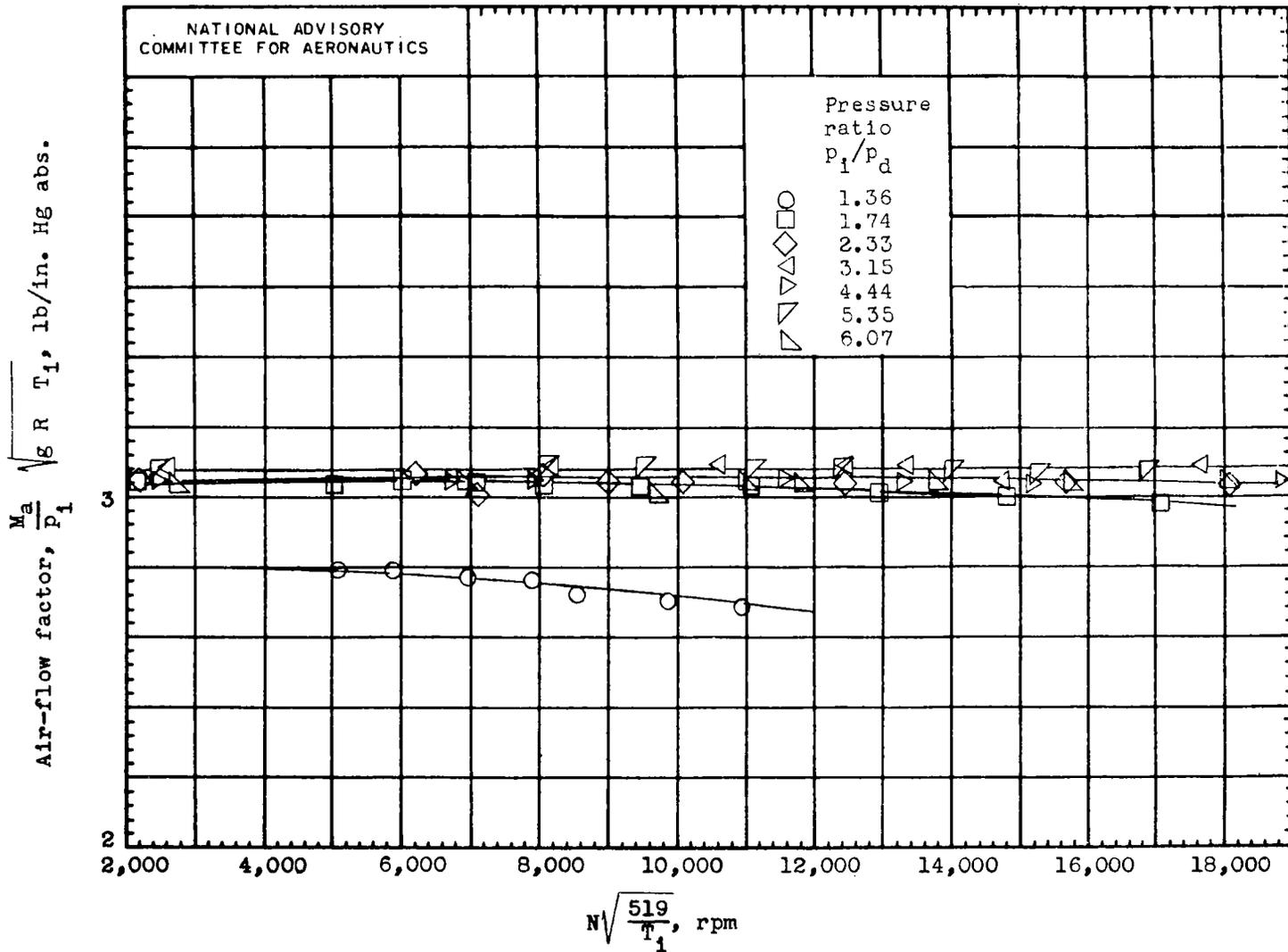


Figure 4. - Variation of the air-flow factor with turbine speed for various pressure ratios using the cast nozzle diaphragm.

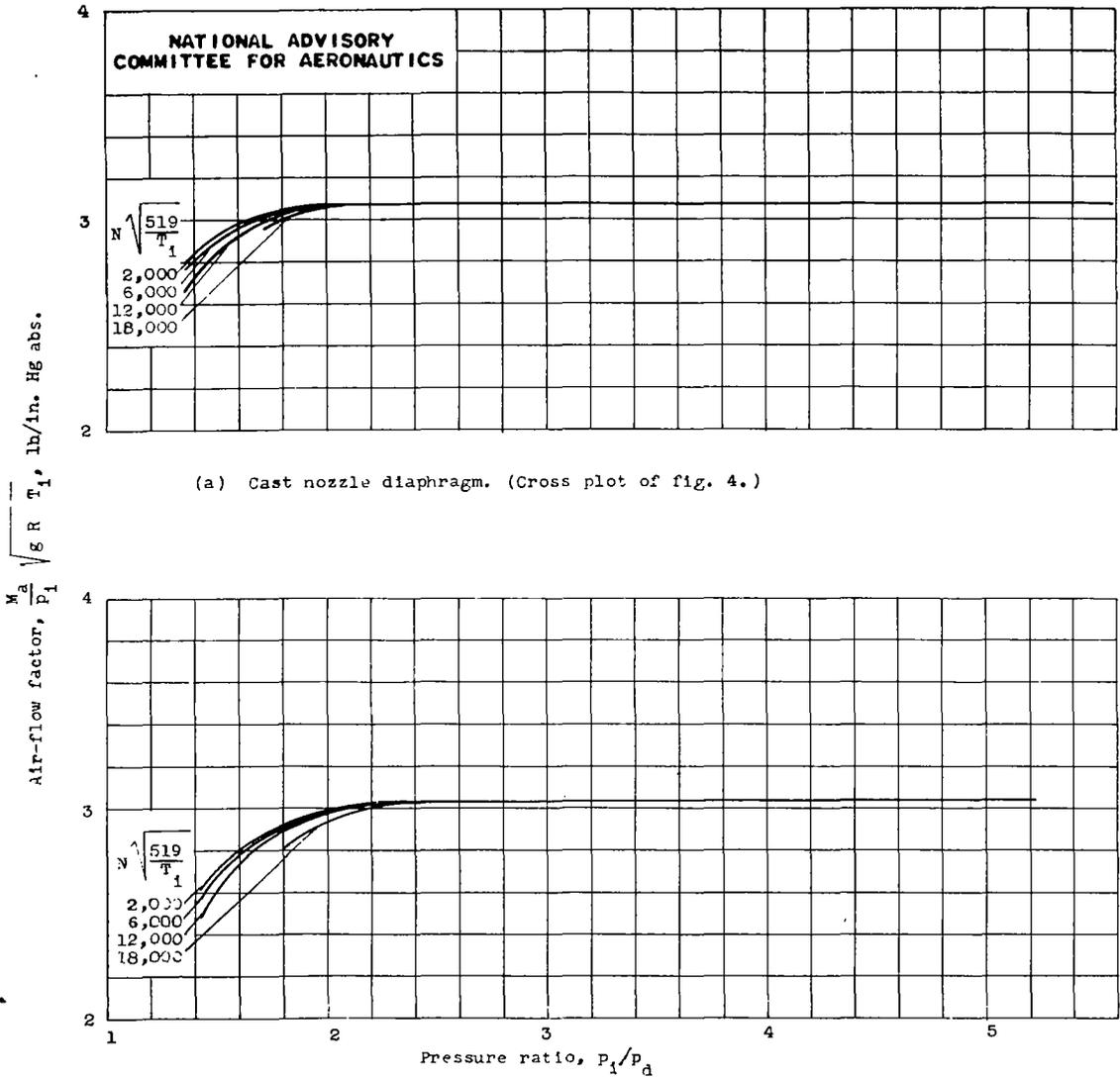


Figure 5. - Comparison of air-flow factors for the cast and the fabricated nozzle diaphragms.

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