NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 786

PERFORMANCE OF BLOWDOWN TURBINE DRIVEN BY EXHAUST GAS OF NINE-CYLINDER RADIAL ENGINE

By L. RICHARD TURNER and LELAND G. DESMON

1944

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass $=\frac{W}{g}$

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e. g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15°C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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Aircraft Engine Research Laboratory
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National Advisory Committee for Aeronautics

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By L. Richard Turner and Leland G. Desmon

SUMMARY

An investigation was made of an exhaust-gas turbine having four separate nozzle boxes each covering a 90° arc of the nozzle diaphragm and each connected to a pair of adjacent cylinders of a nine-cylinder radial engine. This type of turbine has been called a "blowdown" turbine because it recovers the kinetic energy developed in the exhaust stacks during the blowdown period, that is, the first part of the exhaust process when the piston of the reciprocating engine is nearly stationary. The purpose of the investigation was to determine whether the blowdown turbine could develop appreciable power without imposing any large loss in engine power arising from restriction of the engine exhaust by the turbine.

The engine power was decreased a maximum of 1 percent by the presence of the turbine at the lowest turbine-outlet pressure as compared with the engine power delivered with a conventional collector ring discharging to an equal exhaust pressure. No engine-power loss was imposed by the presence of the turbine with turbine-outlet pressures greater than 20 inches of mercury absolute. The engine air-flow rate was not affected by the presence of the turbine. At an engine speed of 2000 rpm and an inlet-manifold pressure of 33.5 inches of mercury absolute, the turbine power varied from 9 percent of engine power with a turbine-outlet pressure of 28 inches of mercury absolute to 21 percent of engine power with a turbine-outlet pressure of 7.5 inches of mercury absolute.

INTRODUCTION

At the time of exhaust-valve opening, the pressure of the gas in the cylinder of an internal-combustion engine is considerably above atmospheric pressure; the gas is therefore capable of doing an appreciable amount of work by further expansion. When the cylinders are exhausted to a collector discharging either to the atmosphere or to the nozzle box of a conventional turbine, the kinetic energy produced at the end of the exhaust stacks by the difference between cylinder pressure and collector pressure is largely dissipated as heat in the collector. A turbine that converts this kinetic energy into shaft work has been called a "blowdown" turbine because it recovers the kinetic energy developed in the exhaust stacks during the blowdown period.

With a suitable duct arrangement and turbine-nozzle area, the power delivered by the blowdown turbine may be obtained with little or no decrease in engine power resulting from exhaust-stack restriction. For a given turbine-outlet pressure, the maximum net power of the engine and the blowdown turbine can be attained by so discharging the exhaust gas from each cylinder as a separate jet that no interaction of exhaust events occurs and thus permitting each cylinder to exhaust to the turbine-outlet pressure.

Several satisfactory exhaust-system arrangements exist. In one arrangement, which would require a large total nozzle area and would result in an excessively large turbine size, each cylinder would be connected to a separate nozzle. The turbine size may be reduced approximately one-half at the cost of a slight loss in turbine power by connecting each nozzle to two cylinders having nonoverlapping exhaust periods. In such an arrangement, the exhaust discharge of each cylinder would still be a separate event. Paired exhaust stacks, however, must be carefully designed to avoid an appreciable kinetic-energy loss at their juncture.

A description is given of the results of operation of a blowdown turbine in which each nozzle served two cylinders that have nonoverlapping exhaust-valve-opening periods. The object of the investigation was to determine the amount of power from the blowdown turbine and the effect of the presence of the turbine on engine power. An analysis is presented relating the data to the mean jet-velocity data for the NACA individual-stack jet-propulsion system. The use of a blowdown turbine and a conventional turbosupercharger connected in series is briefly discussed. The investigation was conducted at the NACA Cleveland laboratory from November 1943 through January 1944.

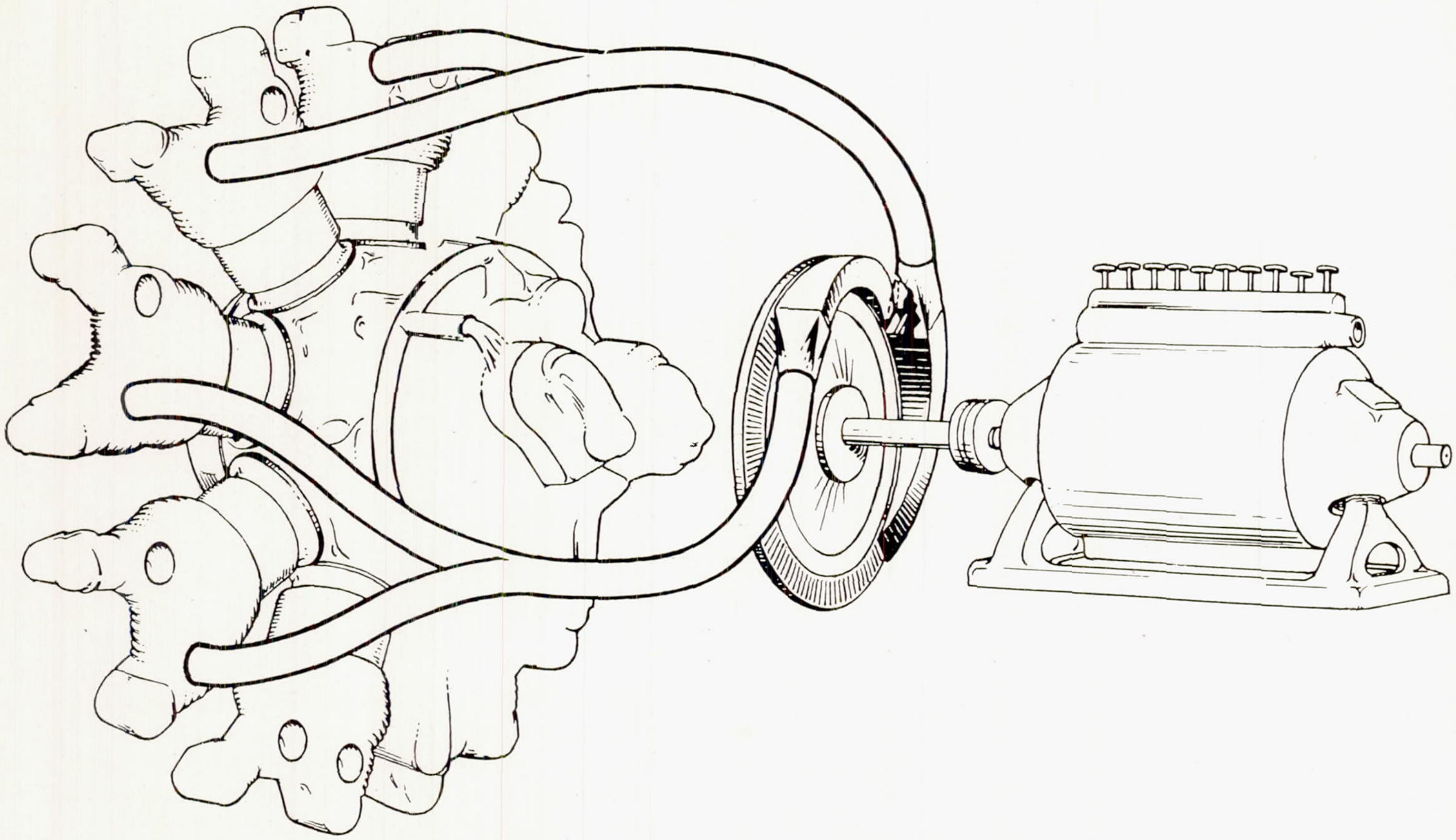


FIGURE 1.—Diagrammatic drawing of blowdown turbine for nine-cylinder radial engine with dynamometer load showing two of four nozzle boxes.

APPARATUS AND METHODS

Construction of blowdown turbine.—A diagrammatic drawing of the blowdown turbine used in the investigation is shown in figure 1. The turbine wheel was a production-model turbosupercharger wheel of the impulse type. The pitch-line diameter was 11 inches; the bucket height was 1.2 inches. Four separate nozzle boxes, each of which covered a 90° arc of the nozzle diaphragm, were constructed with a nozzle angle of 21° and an outlet area normal to the flow of 2.11 square inches. This outlet area was chosen by the methods of reference 1 as the area that would cause no loss in engine power for a jet-stack installation at rated operating conditions of the engine (2200 rpm at 34 in. Hg absolute with sea-level exhaust pressure).

The exit of each nozzle box is divided into nine nozzles by flat vanes sufficiently long to guide the exhaust-gas flow at the inlet and outlet ends.

A drawing of one of the nozzle boxes is shown in figure 2. Photographs of a nozzle box and of the nozzle-diaphragm assembly are reproduced in figure 3. The entire turbine was enclosed in a metal housing; the four turbine-inlet ducts extended through sliding glands to the outside of the housing. A labyrinth seal gland for the turbine shaft was provided around the opening between the inside of the housing and an

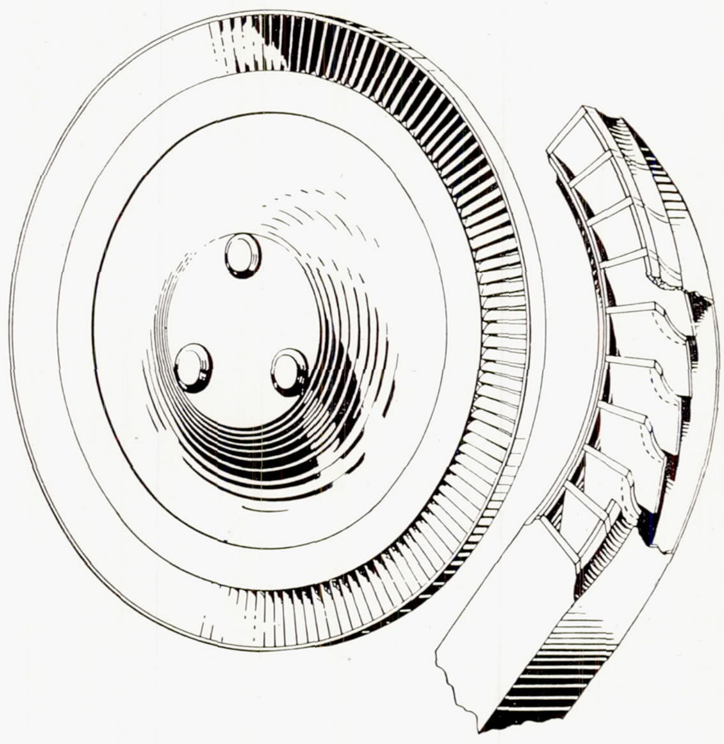
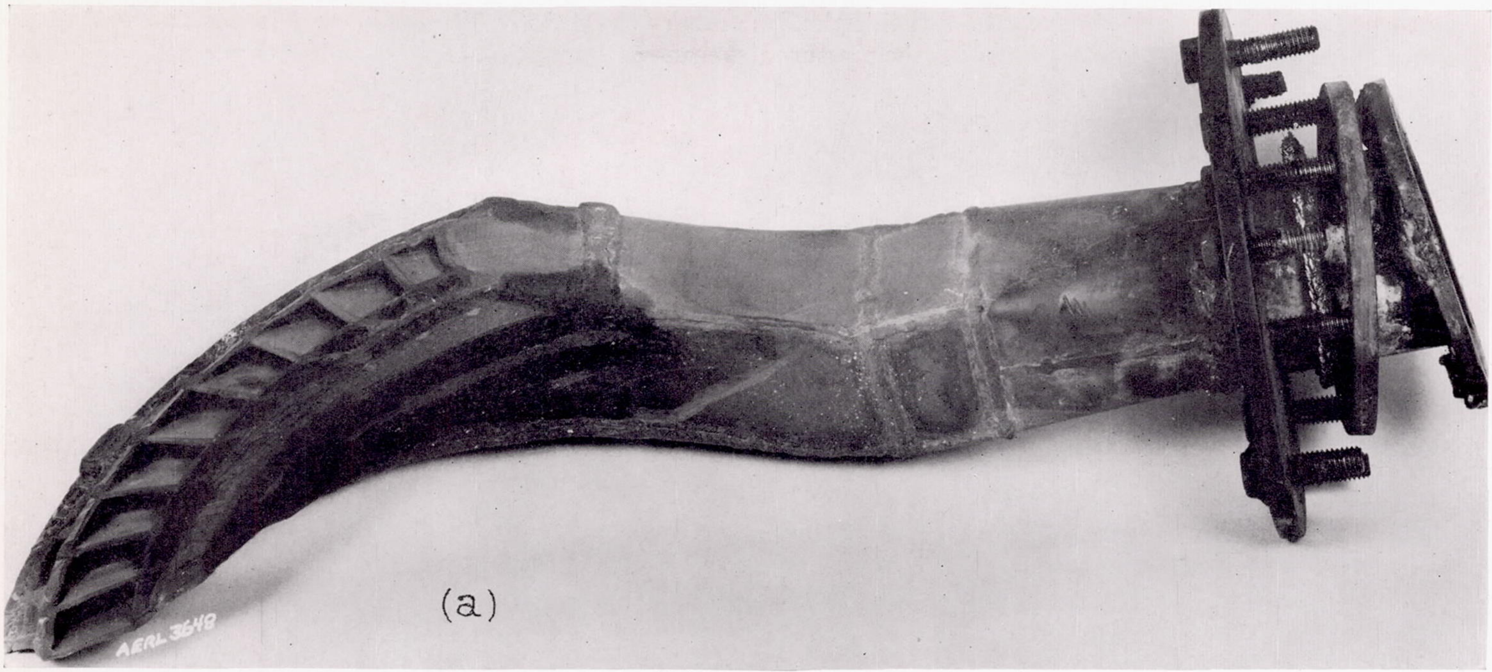
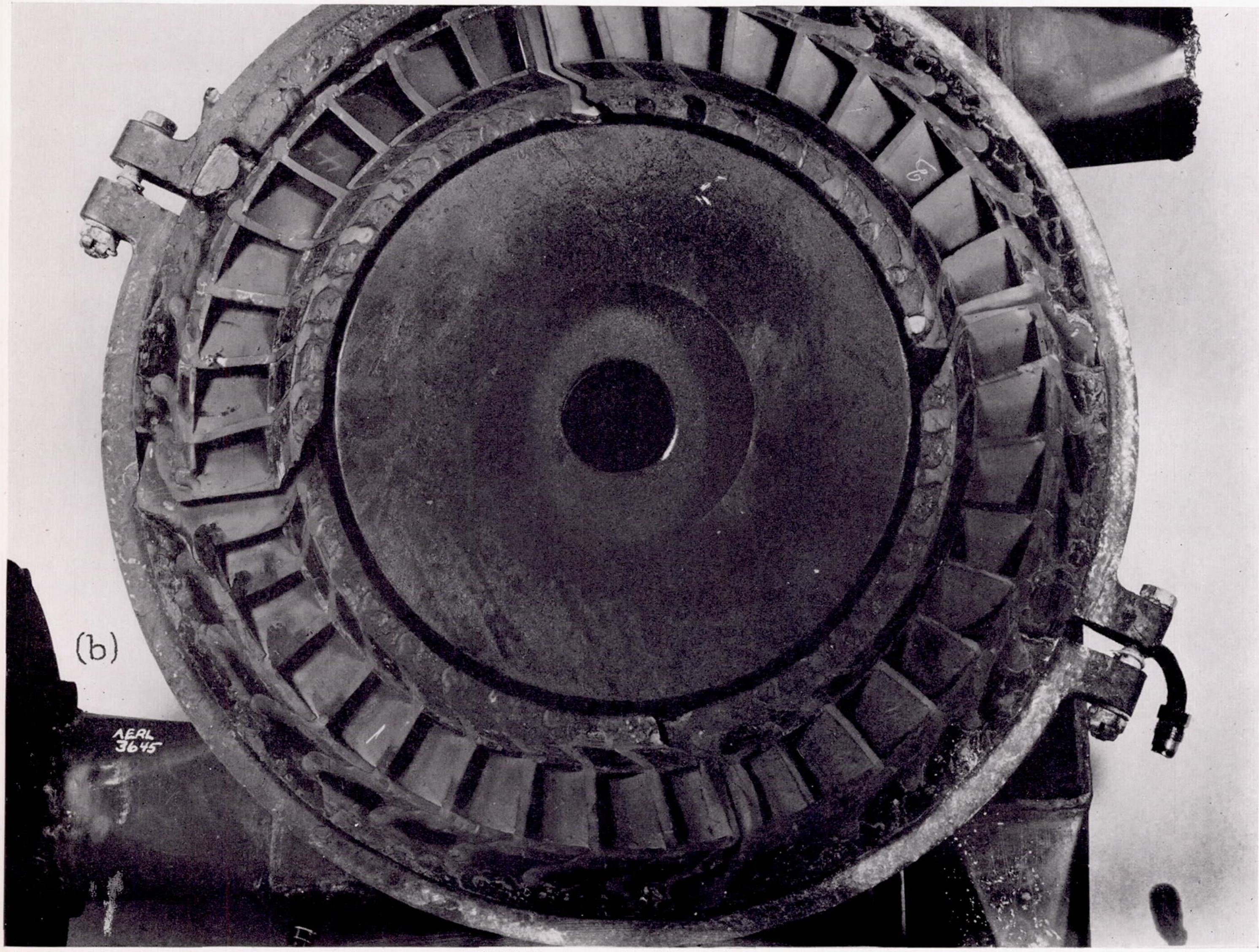


FIGURE 2.—Arrangement of guide vanes in blowdown-turbine nozzle box.



(a) Single nozzle box.



(b) Diaphragm assembly of four nozzle boxes.

FIGURE 3.—Nozzle-box assembly of blowdown turbine.

evacuated fore chamber. Leakage of air through this gland was reduced to a negligible amount by adjusting the pressure difference between the labyrinth stages to 0±0.1 millimeter of water by means of an air-operated jet pump in the line connecting the evacuated fore chamber to the laboratory altitude-exhaust system.

Setup.—The blowdown turbine was connected to eight of the nine cylinders of an R–1340–12 engine by means of four pipes having Y-shaped branches connected to adjacent cylinders. The gas from the turbine discharged to the laboratory altitude-exhaust system. The gas from the ninth cylinder discharged directly to the altitude-exhaust system. The engine air was supplied directly from the room to the carburetor through a duct provided with a measuring orifice.

The turbine power was absorbed by a water-brake dynamometer. The turbine torque was measured by a spring scale; the turbine speed was measured with a condenser-type tachometer. The accuracy of the turbine-power measurements was within ±1.5 percent. The temperature of the gas at the turbine outlet was measured with a quadruple-shielded chromel-alumel thermocouple.

The power of the engine was absorbed by a separate water-brake dynamometer. Engine torque was measured with a balanced-diaphragm torquemeter of the type described in reference 2. Engine speed was measured with a magnetic-drag type of aircraft tachometer. Measurements of engine power are estimated to be accurate within ±1.5 percent.

Engine air flow was measured by a head meter with a thin-plate orifice installed according to A.S.M.E. specifications. Engine fuel flow was measured with a sharp-edged-diaphragm density-compensated rotameter. Air-flow and fuel-flow measurements are estimated to be accurate within ±1 percent. Temperatures of engine air and carburetor air were measured with iron-constantan thermocouples. Pressures at the engine inlet and the turbine outlet were measured with mercury manometers. Pressures in the air-flow metering system were measured with water manometers.

Experimental procedure.—The runs were made at an engine speed of 2000 rpm. The investigation consisted of (a) calibrating the engine equipped with an exhaust collector ring and (b) measuring the engine power and the turbine power with the blowdown turbine in place.

For the engine calibration and for the majority of the measurements of turbine power, the engine was operated at full engine throttle at an inlet-manifold pressure of approximately 34 inches of mercury absolute. In each set of measurements, the exhaust pressure (the collector pressure or the turbine-outlet pressure) was varied from 7.5 to 29 inches of mercury absolute. In the turbine-power runs the turbine speed was varied.

Additional runs with the turbine were made at part engine throttle, with engine inlet-manifold pressures of 24 to 19 inches of mercury absolute, a turbine-outlet pressure of 7.5 inches of mercury absolute, and with variable turbine speed.

Method of reducing data.—In an ideal turbine engine, the power recoverable by the turbine would be the actual kinetic energy of the jet, which could be described in terms of the mean-square velocity $\overline{V^2}$ defined by the relation

$$\overline{V^2}=\frac{\int V^2Mdt}{\int Mdt} \tag{1}$$

where

V instantaneous velocity

M instantaneous rate of mass flow

t time

In the strictest sense the term $\frac{1}{2}M\overline{V^2}$ should be used as a basis in defining the efficiency of the blowdown turbine. A preliminary analysis of the operation of a blowdown turbine, however, predicted that, when the speed of the turbine is considered as the only variable, the maximum power output of the turbine P_{max} is given by the relation

$$550\ P_{max}=\frac{1}{2}M_t\overline{V}_e^2\eta_{max} \tag{2}$$

where

M_t mass flow of exhaust gas to turbine, slugs per second

$\overline{V}_e$ mean jet velocity at turbine-nozzle exit, feet per second, which is defined by the relation

$$\frac{\int VMdt}{\int Mdt} \tag{3}$$

η_{max} efficiency of turbine (including bucket losses but excluding nozzle losses) at optimum blade-to-jet speed ratio

Equation (2) was obtained by assuming that the instantaneous turbine-bucket efficiency is a parabolic function of the instantaneous blade-to-jet speed ratio and is independent of the Mach number. The analysis (as shown by equation (2)) indicates that the term $\frac{1}{2}M_t\overline{V}_e^2$ is a measure of the power available to the turbine. The conditions are almost exactly satisfied by single-stage impulse turbines unless the inlet Mach number relative to the buckets becomes too high, at which time the buckets choke and the instantaneous efficiency is reduced. The mean velocity $\overline{V}_e$ has the further advantage as the basis for a definition of a performance parameter that it can be easily measured, as, for example, by means of a thrust target whereas $\overline{V^2}$ is difficult or impossible to measure. The mean efficiency $\overline{\eta}_t$ of the blowdown turbine with any operating conditions has therefore been defined as the ratio of the turbine-power output P_t to the available power by means of the equation

$$\overline{\eta}_t=\frac{1100\ P_t}{M_t\overline{V}_e^2} \tag{4}$$

Because the turbine was connected to eight of the nine cylinders of the test engine, the mass flow of gas through the turbine M_t was therefore assumed to be eight-ninths of the total mass flow of exhaust gas M_e.

In the absence of mean-jet-velocity data for the R–1340–12 engine, the value of $\overline{V}_e$ was computed for an R–1820–G single-cylinder engine with a 25-inch straight stack (fig. 10 of reference 1) as a function of p_eA/M_t where p_e is the turbine-outlet pressure in pounds per square foot and A is the effective nozzle area in square feet. The effective nozzle area to be used for calculating p_eA/M_t for branched stacks is determined by multiplying the area per stack by the number of cylinders connected to the turbine. The effective nozzle area of the stacks used was 16.88 square inches.

RESULTS AND DISCUSSION

Effect of turbine on engine power.—The power delivered by the engine discharging its exhaust to a standard collector ring and the power delivered by the engine discharging its exhaust to the blowdown turbine are shown in figure 4 together with the maximum turbine power, which was obtained at the optimum permissible turbine speed.

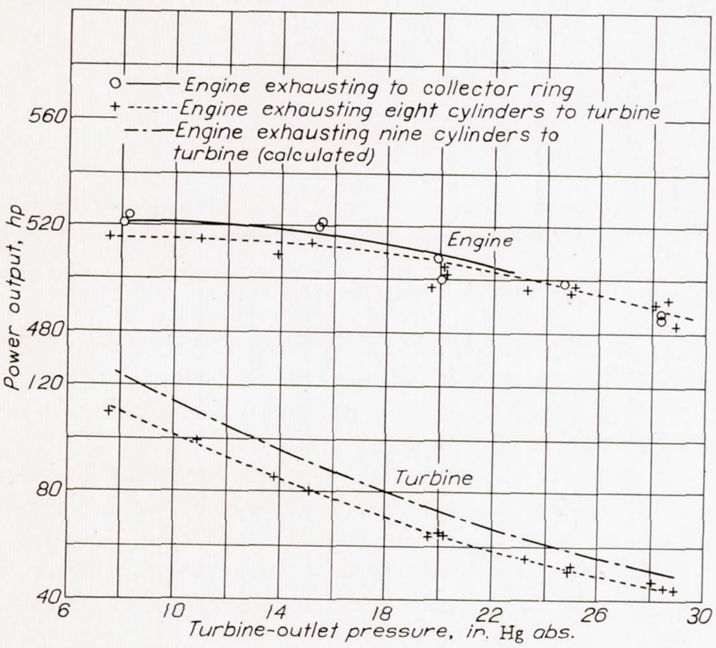


FIGURE 4.—Power output of engine and blowdown turbine. Engine speed, 2000 rpm. Data corrected to carburetor-air temperature of 90° F and inlet-manifold pressure of 33.5 inches of mercury absolute.

The power-output data for the engine and the turbine shown in figure 4 were corrected for small variations in the operating variables to constant carburetor-air temperature and engine inlet-manifold pressure. Engine power and mass flow of combustion air were assumed to vary inversely as the square root of the absolute carburetor-air temperature and directly as the first power of the inlet-manifold pressure. At the lowest turbine-outlet pressure, the power of the engine exhausting to the blowdown turbine was slightly smaller (1 percent) than the power of the engine discharging to a standard collector at a pressure equal to the turbine-outlet pressure. As the exhaust pressure increased, the power loss with the turbine operating decreased. For exhaust pressures greater than 20 inches of mercury absolute there was no measurable power loss. No measurable change in engine-air weight flow was caused by the presence of the turbine. The engine power shown in figure 4 was obtained with the carburetor air supplied directly from the room. The pressure drop through the air-measuring orifice and the duct was 3 inches of mercury and the carburetor pressure was 26 inches of mercury absolute. In order to determine the net power at altitude, it is necessary to subtract the supercharger power required to obtain a carburetor-inlet pressure of 26 inches of mercury. Because this power would be the same for the two cases in figure 4 at any given exhaust-outlet pressure, it does not affect the comparison, which reveals the negligible effect of the presence of the turbine on the engine power.

With respect to its effect on engine power, the blowdown turbine is similar to the Büchi exhaust-gas turbine (reference 3). In both systems the exhaust duct is arranged to avoid producing back pressure on the cylinders toward the end of the exhaust stroke and particularly during the valve overlap or scavenging period. No attempt was made in the blowdown turbine to provide a resonant or tuned exhaust-stack system sometimes mentioned in connection with the Büchi system.

References 1 and 4 showed that the effect of an exhaust restriction on engine power is determined by the value of the ratio v_dn/A where v_d is the displacement volume in cubic feet and n is the engine speed in revolutions per second. For this turbine the effective nozzle area was 0.132 square foot (for nine cylinders). At an engine speed of 2000 rpm the value of v_dn/A was therefore 196 feet per second. A loss in engine power from 2 to 3 percent was expected at the lowest exhaust pressure for this value of v_dn/A. (See reference 4.) Because the loss was less than predicted, it must be concluded either that the R–1340–12 engine is slightly less sensitive to exhaust-pipe restriction than the R–1820–G engine used in references 1 and 4 or that the blowdown turbine exerts a favorable suction effect during the last part of the exhaust stroke when the velocity of flow through the exhaust system is small.

Turbine power output and speed characteristics.—The turbine power output (fig. 4), using the exhaust gas from eight of the nine cylinders, varied from about 9 percent of engine power at a turbine-outlet pressure of 28 inches of mercury absolute to about 21 percent of engine power at 7.5 inches of mercury absolute. The turbine data in this figure were corrected to a carburetor-air temperature of 90° F and an engine inlet-manifold pressure of 33.5 inches of mercury absolute by a method derived from the analysis of reference 1. Figure 4 also shows the turbine power that would be expected had all the gas from the engine passed through the turbine, based on the assumption that for use of all the exhaust gas the turbine power would have been one-eighth greater than the measured power.

At the lowest turbine-outlet pressures the turbine speed was limited to the rated speed of 21,300 rpm. A larger power output could have been obtained at a higher turbine speed.

The ratio of maximum turbine power output to engine power output at constant engine speed increases with a decrease in the exhaust pressure. Consideration of dynamic similarity indicates that at constant engine speed the ratio of turbine to engine power is a function of the ratio of exhaust to inlet-manifold pressures p_e/p_m.

At the higher exhaust pressures the blowdown turbine imposed no loss in engine power (fig. 4). At a given set of engine conditions, the mean jet velocity from a single exhaust stack or a branched exhaust stack increases when the exit area is reduced. (See references 1 and 4.) A greater total power output could therefore be obtained from the turbine and the engine by the use of nozzles small enough to produce a small loss in engine power.

The variation of turbine power output with turbine speed for constant engine power output is shown in figure 5.

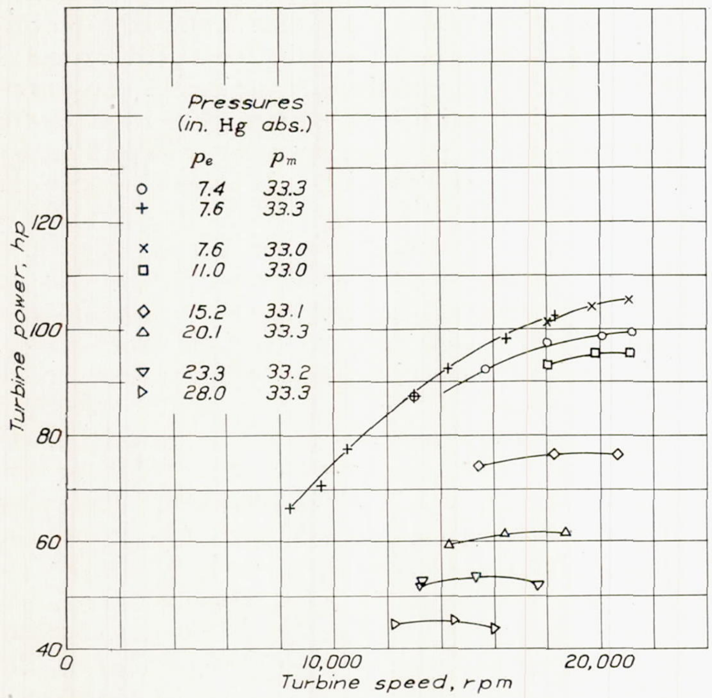


FIGURE 5.—Variation of turbine power with turbine speed. Engine speed, 2000 rpm; full throttle.

These curves are similar in shape to the power-speed curves of single-stage steady-flow impulse turbines. The blowdown-turbine power output is nearly independent of speed near the maximum power output. A deviation in speed of 10 percent from the optimum speed reduces the power output only approximately 1 percent.

At the lowest turbine-outlet pressure, the maximum turbine power output varied between runs through a range of about 9 percent of the turbine power. During the operation of the turbine, the seals around the four intake pipes developed leaks and were replaced several times. As the leaks developed, the turbine power generally decreased. It was also found that the clearance between the turbine wheel and the nozzle box could not be maintained at a constant value. A combination of these factors is believed to have caused the variation in maximum turbine power among the three runs at the exhaust pressure of approximately 7.5 inches of mercury absolute.

Mean turbine efficiency.—The variation of the mean efficiency $\bar{\eta}_t$ of the blowdown turbine, defined by equation (4), with the ratio of blade speed to mean jet speed is shown in figure 6. The maximum turbine efficiency, which is obtained at a turbine pitch-line velocity of approximately $0.4\overline{V}_e$, is approximately 72 percent. This efficiency corresponds to a work recovery by the blowdown turbine approximately equal to 30 percent of the work that is theoretically available in the expansion of the exhaust gas from its pressure in the cylinder at the time of exhaust-valve opening to the prevailing discharge pressure.

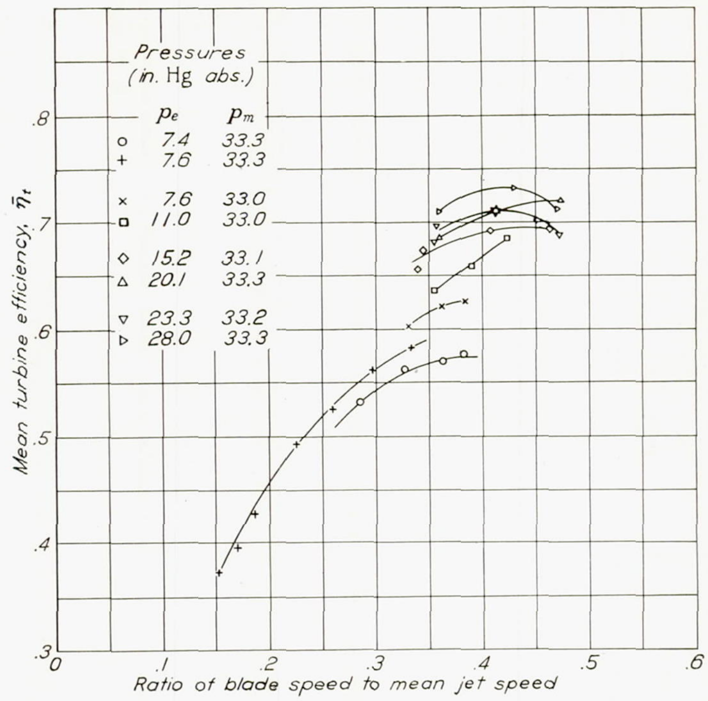


FIGURE 6.—Variation of mean turbine efficiency with ratio of blade speed to mean jet speed. Engine speed, 2000 rpm; full throttle.

For the lower turbine-outlet pressures, the mean efficiency decreases as the exhaust pressure decreases. With a turbine-outlet pressure of 7.5 inches of mercury absolute, the instantaneous peak value of the ratio of the impact pressure in the nozzle to the turbine-outlet pressure may be as great as 7 or 8. (See fig. 12 (b) of reference 1.) As determined by steady-flow measurements the pressure ratio for the greatest efficiency of the experimental turbine wheel is appreciably lower than 7. For pressure ratios lower than that for the greatest efficiency, the bucket efficiency is nearly constant but, for greater pressure ratios, it decreases appreciably. A mean turbine efficiency is therefore expected to decrease at low turbine-outlet pressures.

The value of $\overline{V}_e$ used for the computation of the mean turbine efficiency was that measured for a 25-inch straight stack. (See fig. 10 of reference 1.) A previous investigation with an exhaust stack having a side branch had shown that with restricted nozzles on the ends of the stacks the mean jet velocity $\overline{V}_e$ was smaller than the velocity for a straight stack or a curved stack. (See fig. 4 of reference 4.) The diagram efficiency of the turbine, excluding all losses, is 86 percent and it had been expected that peak mean efficiency of the blowdown turbine would be about 80 percent. The use of the branched-stack jet-velocity data to compute mean turbine efficiency gave mean turbine efficiencies greater than 90 percent. The mean jet velocity for the stack arrangement used in the blowdown turbine is therefore probably greater than the velocity for the branched stack reported in reference 4 but may be less than that for a straight stack.

The variation of the maximum mean turbine efficiency is shown in figure 7 as a function of the jet-velocity parameter p_eA/M_t. The correlation is satisfactory except for the lowest exhaust pressures (low p_eA/M_t). (See the previous discussion of the effects of leakage and variation in wheel clearance in connection with fig. 5.)

The efficiency data obtained at part engine throttle fall below the full-throttle curve. In the initial calculations no allowance was made for effect of variations in exhaust-gas temperature on the mean jet velocity. When the turbine data are corrected for the variation of turbine-inlet gas temperature with engine power, turbine data obtained at part engine throttle and the data obtained at full engine throttle are in good agreement. The details of these corrections are described in the appendix.

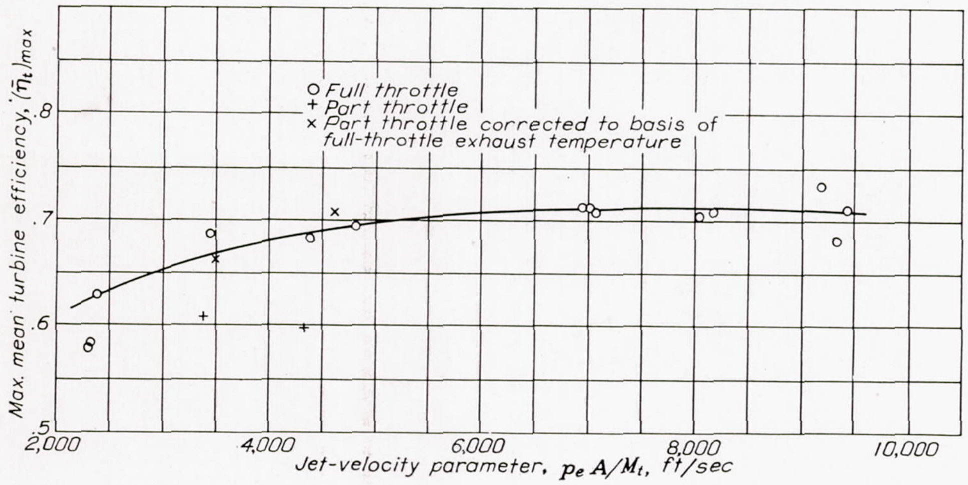


FIGURE 7.—Variation of maximum mean turbine efficiency with jet-velocity parameter p_eA/M_t.

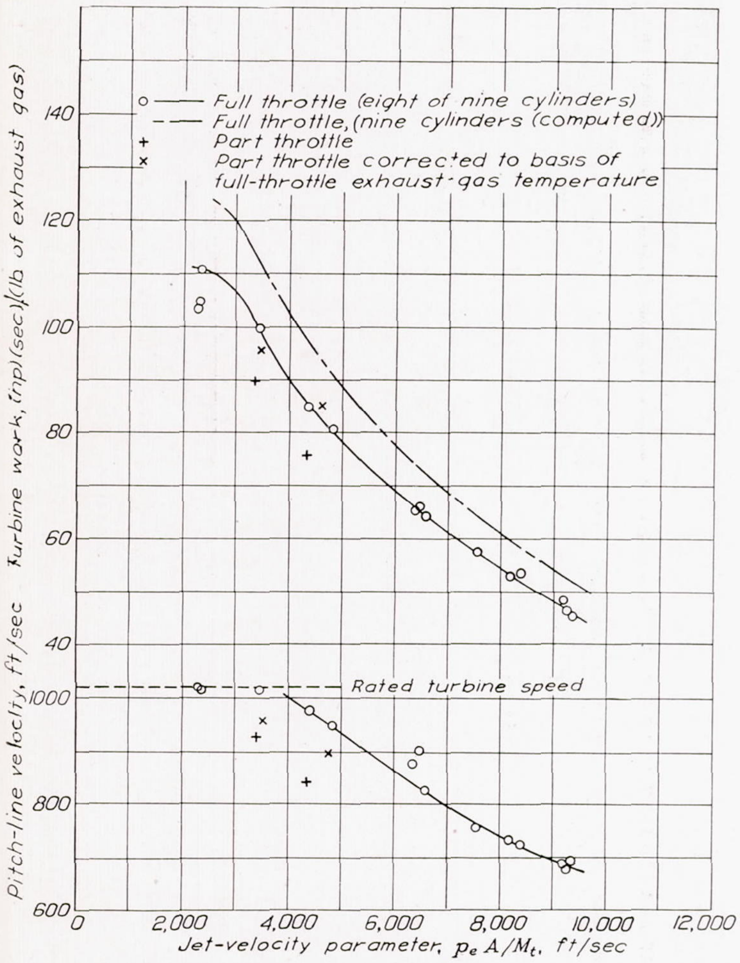


FIGURE 8.—Variation of maximum turbine work output per pound of exhaust gas and optimum turbine speed with jet-velocity parameter p_eA/M_t. Engine speed, 2000 rpm.

The maximum turbine work output per pound of exhaust gas and the estimated optimum turbine pitch-line velocity is shown in figure 8 as a function of p_eA/M_t. At the lowest values of p_eA/M_t, the turbine power is that obtained at rated turbine speed (21,300 rpm) rather than at the optimum speed. The turbine-power data obtained with full-open engine throttle form a smooth curve except for the two points at the lowest value of p_eA/M_t.

Effect of blowdown turbine on exhaust-gas temperatures.—The variation of the exhaust-gas temperature at the turbine outlet with turbine power for an exhaust pressure of 7.5 inches of mercury absolute is shown in figure 9. The temperature measured with a quadruple-shielded thermocouple was assumed to be the total turbine exhaust-gas temperature. The mean total gas temperature at the turbine inlet was computed by adding to the measured turbine-outlet temperature the temperature difference corresponding to the work per pound of gas removed by the turbine. The computed total inlet temperature was not quite constant, apparently varying with small variations of the fuel-air ratio. The effect of fuel-air ratio on total temperature at the turbine inlet is included in figure 9.

The effect of engine power on the total turbine-inlet gas temperature at a fuel-air ratio of 0.075 is shown in figure 10. The exhaust-gas temperature increases with engine power because the heat rejection per pound of exhaust gas from the engine and its exhaust piping to the cooling air is greater at low engine power. The correction of the turbine data obtained with the engine operating at part throttle to the basis

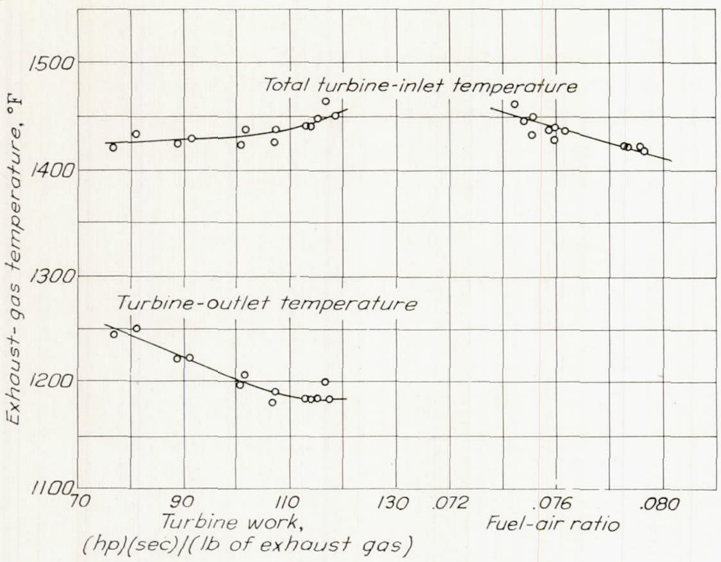


FIGURE 9.—Variation of exhaust-gas temperature with turbine work and fuel-air ratio. Average engine power, 513 horsepower; engine speed, 2000 rpm; exhaust pressure, 7.5 inches of mercury absolute.

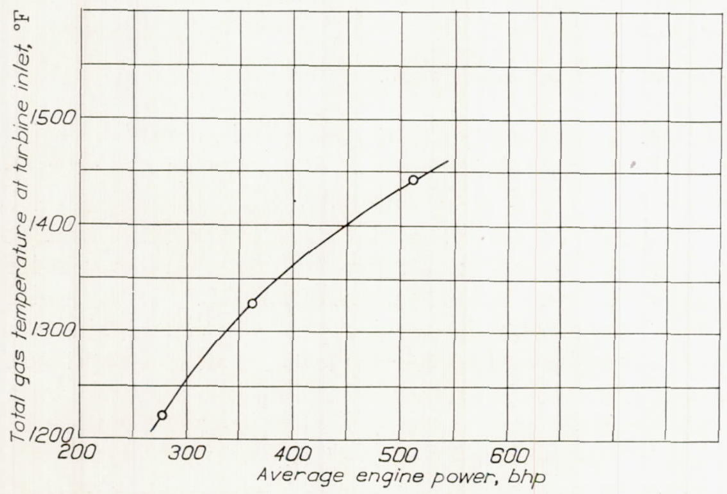


FIGURE 10.—Effect of engine power on exhaust-gas temperature. Engine speed, 2000 rpm; fuel-air ratio, 0.075.

of constant mean exhaust-gas total temperature was made from these data.

Condition of blowdown turbine after tests.—The blowdown turbine was operated for a total time of approximately 24 hours. Although a small stretching of the buckets occurred, the stretching was less than that normally experienced in conventional exhaust-gas turbine operation with the same inlet-gas temperature. One bucket showed a deformation of the shroud due either to bucket vibration or to initial bending stresses.

The turbine buckets apparently ran quite cool, as suggested by the appreciable lead deposits found on the exit side of the buckets (fig. 11). Cool running of the buckets was expected because the buckets are exposed to the hottest exhaust gas for a short time and to the coolest exhaust gas for a relatively long time. These lead deposits also serve as an index of flow conditions because solid particles tend to accumulate in regions of separation of flow.

Numerous small local deformations of the leading edges of the buckets (fig. 12) and trailing edges of the nozzle-box guide vanes (figs. 3 (b) and 13) were noted. These deformations apparently resulted from the action of large solid particles in the gas stream. The wheel-nozzle clearance was originally set at 0.11 inch but owing to warping the clearance was not maintained. Actual contact of the wheel and one nozzle occurred at one time during operation, as shown by polished spots on the buckets and the nozzles. The deformation of nozzles caused by thermal expansion is a serious problem because each nozzle must be connected to a separate set of exhaust pipes.

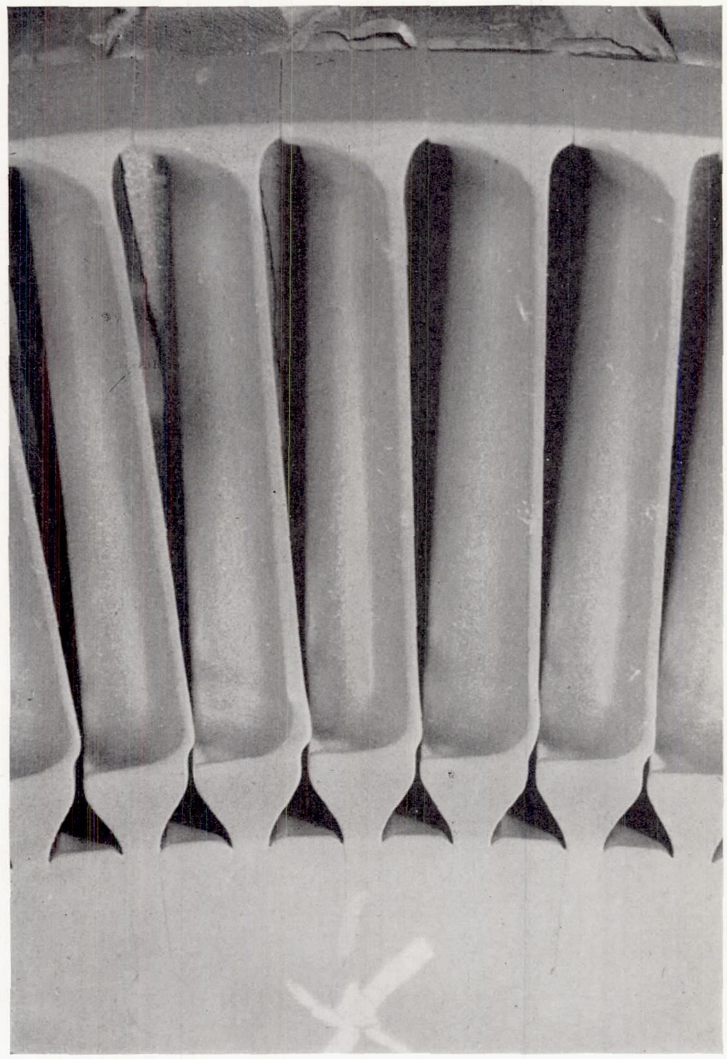


FIGURE 11.—Lead deposits on outlet side of buckets.

The leading edges of the buckets were rounded or eroded more than in previous tests with the same type wheel at approximately the same total turbine-inlet exhaust-gas temperature with steady flow. This rounding could have been caused by mechanical erosion, by solid particles in the gas stream, or, as seems more likely, by thermal erosion caused by the extremely rapid alternate heating and cooling of the bucket leading edges. The flow in a blowdown turbine is similar to that in a Holzwarth explosion turbine; the problems arising from blade vibration and thermal erosion due to the rapidly varying gas temperatures are therefore

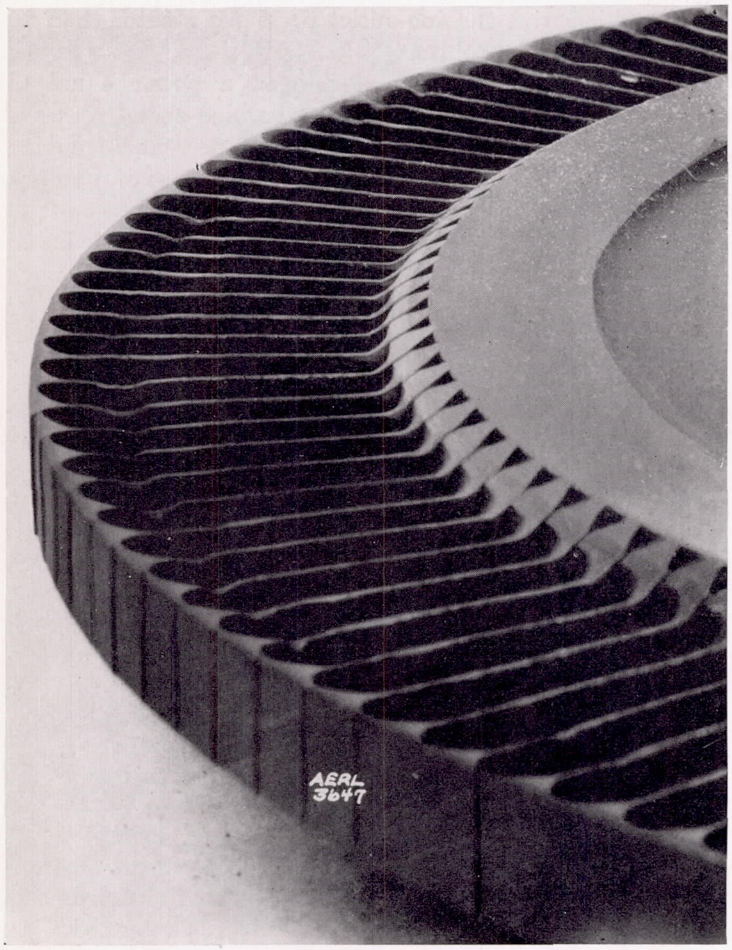


FIGURE 12.—Erosion and bending of leading edges of buckets.

similar. (See reference 5.) Thermal erosion can be reduced by using buckets with slightly rounded noses to increase the ratio of internal heat-transfer area to external heat-transfer area.

The total damage to the turbine was not serious.

Gain in performance with use of blowdown turbine.—Preliminary calculations indicate that the greatest net power output can be obtained in a composite engine using a blowdown turbine when the blowdown turbine is used as a first stage of expansion and is followed by a steady-flow device in which further expansion of the exhaust gas is obtained.

The order of magnitude of the gain in net power output and in economy may be indicated by the following discussion of the use of a blowdown turbine in series with a conventional turbosupercharger.

The carburetor-inlet pressure for these tests averaged 26 inches of mercury absolute. This pressure could be provided at high altitude by passing the gas from the blowdown turbine to a conventional turbosupercharger of proper size operating at a nozzle-box pressure of approximately 26 inches of mercury absolute. The blowdown-turbine power output with a discharge pressure of 26 inches of mercury absolute on the basis of utilizing all the exhaust gas would amount to 11 percent of engine power. It is evident therefore that, even in a power plant equipped with a turbosupercharger, an appreciable gain in power and economy can be obtained by installing a blowdown turbine between the engine and the turbosupercharger.

When the blowdown turbine and a conventional turbosupercharger are used in series, the blowdown turbine may be geared to the engine. Aircraft engines are operated at high speed for emergency power output and at successively reduced speeds for rated-power and cruising-power operation. With approximately constant blowdown-turbine exhaust pressure, the nozzle-jet velocity decreases approximately in the same proportion as the engine speed. A blowdown turbine geared to the engine crankshaft with a fixed-ratio gear train will therefore operate at nearly optimum speed for each engine power output.

It is noted that the speed of the turbine for the maximum output with an exhaust pressure of 26 inches of mercury absolute and an inlet-manifold pressure of 33.5 inches of mercury absolute is approximately 16,000 rpm. (See fig. 7.) This speed is about 75 percent of the rated turbine speed: hence, the centrifugal stress in the buckets is only 56 percent of the centrifugal stress at rated speed. If the inlet-manifold pressure were increased to 52 inches of mercury absolute with the exhaust pressure of 26 inches of mercury absolute, the optimum turbine speed would be approximately the rated speed.

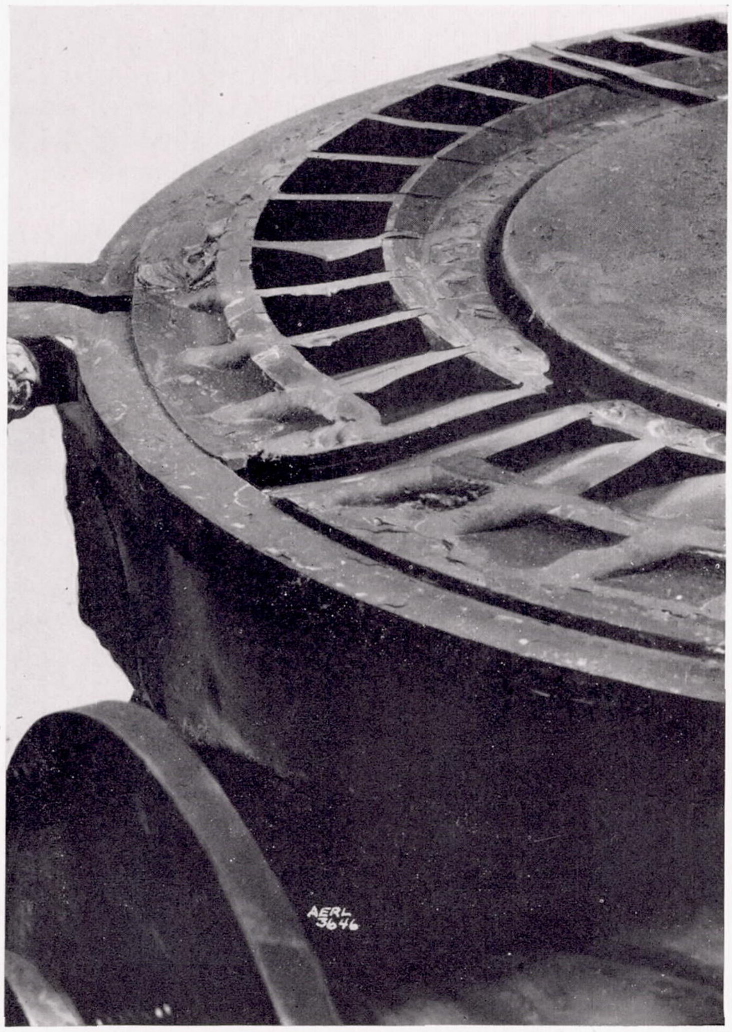


FIGURE 13.—Damage to turbine-nozzle diaphragm.

The use of a blowdown turbine as part of a turbosupercharged engine is only one of a number of possible applications of the blowdown turbine; further study is required to determine the most advantageous application.

CONCLUSIONS

The results of an investigation of a blowdown turbine having four nozzle boxes with an outlet area of 2.11 square inches per nozzle box, each connected to an adjacent pair of eight of the nine cylinders of the engine, showed that at an engine speed of 2000 rpm and at an inlet-manifold pressure of 33.5 inches of mercury absolute:

1. The engine power was decreased a maximum of 1 percent by the presence of the turbine as compared with the conventional exhaust collector ring discharging to an equal pressure. No engine power loss was imposed by the presence of the turbine with turbine-outlet pressures greater than 20 inches of mercury absolute.
2. The blowdown turbine developed a power equal to 9 percent of the engine power with a turbine-outlet pressure of 28 inches of mercury absolute and 21 percent of engine power with a turbine-outlet pressure of 7.5 inches of mercury absolute.
3. After a total operating time of 24 hours no evidence of failure from bucket vibration was observed. Some evidence of erosion of the leading edges of the buckets was noted.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, *December 1, 1944*.

APPENDIX

CORRECTION OF BLOWDOWN-TURBINE POWER FOR VARIATIONS IN ENGINE OPERATING CONDITIONS

The mean turbine efficiency $\bar{\eta}_t$ has been defined by the equation

$$\bar{\eta}_t=\frac{1100\ P_t}{M_t\overline{V}_e^2} \tag{4}$$

where the mean jet velocity $\overline{V}_e$ is a function of the parameter p_eA/M_t. The results of the present investigation showed that the maximum values of $\bar{\eta}_t$ were sufficiently independent of the value of p_eA/M_t within the range of variation required for small corrections that equation (4) may be used to predict the effect of changes in operating conditions on turbine power.

The data on turbine power output (shown in fig. 4) were corrected to the basis of constant carburetor-air temperature and constant inlet-manifold pressure by use of the following steps:

(a) The computation of corrected engine-air and exhaust-gas mass flows

(b) The computation of $\bar{\eta}_t$ from equation (4) using the uncorrected mass flow M_t and $\overline{V}_e$ from figure 10 of reference 1

(c) The computation of $(M_t)_{corr}$ from the equation

$$(M_t)_{corr}=M_t\frac{(M_e)_{corr}}{M_e}$$

where M_e is the total mass of engine exhaust gas

(d) The computation of $(\overline{V}_e)_{corr}$ from figure 10 of reference 1 using the corrected turbine exhaust-gas flow

(e) The computation of $(P_t)_{corr}$ from an inverted form of equation (4)

$$(P_t)_{corr}=\frac{(M_t)_{corr}(\overline{V}_e)^2_{corr}\,\bar{\eta}_t'}{1100} \tag{5}$$

The turbine data obtained with the engine operating at part throttle in figures 7 and 8 have been corrected to the basis of full-throttle exhaust-gas temperature by the following method:

The theory of exhaust stacks developed in reference 1 shows that the mean jet velocity $\overline{V}_e$ is a function of the gas temperature and the parameter p_eA/M_t. The mean jet velocity decreases with a decrease in temperature for constant p_eA/M_t. In the application of a correction to the turbine output and the efficiency for variations in temperature, $\overline{V}_e$ was assumed to vary with temperature according to the relation

$$\frac{\overline{V}_e}{\sqrt{R_e\overline{T}_e}}=f\left(\frac{p_eA/M_t}{\sqrt{R_e\overline{T}_e}}\right) \tag{6}$$

where

R_e gas constant of exhaust gas for actual fuel-air ratio

$\overline{T}_e$ mean exhaust-gas temperature, °R

The relation expressed in equation (6) was inferred from equation (15) of reference 1.

The following steps were involved in the correction of turbine efficiency:

(a) The computation of p_eA/M_t and determination of $\overline{V}_e$ from figure 10 of reference 1

(b) The computation of $(p_eA/M_t)_{corr}$ from the equation

$$\left(\frac{p_eA}{M_t}\right)_{corr}=\frac{p_eA}{M_t}\sqrt{\frac{R_s\overline{T}_s}{R_e\overline{T}_e}}$$

where

$\overline{T}_s$ mean exhaust temperature to which basic data are being corrected, °R

R_s corresponding gas constant

(c) The computation of jet velocity $\overline{V}_e'$ from figure 10 of reference 1 corresponding to $(p_eA/M_t)_{corr}$

(d) The solution of

$$(\overline{V}_e)_{corr}=\overline{V}_e'\sqrt{\frac{R_e\overline{T}_e}{R_s\overline{T}_s}}$$

If the fuel-air ratio is a constant, $R_e = R_s$ and the correction may be based solely on temperature; otherwise the variation in fuel-air ratio should be included.

(e) The computation of corrected efficiency $(\bar{\eta}_t)_{corr}$ from the equation

$$(\bar{\eta}_t)_{corr} = \bar{\eta}_t \left(\frac{\overline{V}_e}{(\overline{V}_e)_{corr}} \right)^2$$

The turbine power and the pitch-line velocity were corrected to the conditions corresponding to $(p_e A/M_t)_{corr}$ for which the mean jet velocity is $\overline{V}_e'$. The following steps were involved in the correction of turbine power:

(a) The computation of $(P_t)_{corr}$ from the equation

$$(P_t)_{corr} = P_t \left(\frac{\overline{V}_e'}{(\overline{V}_e)_{corr}} \right)^2$$

(b) The computation of corrected pitch-line velocity $(u)_{corr}$ from the equation

$$(u)_{corr} = u \frac{\overline{V}_e'}{(\overline{V}_e)_{corr}}$$

where u is the turbine pitch-line velocity, feet per second.

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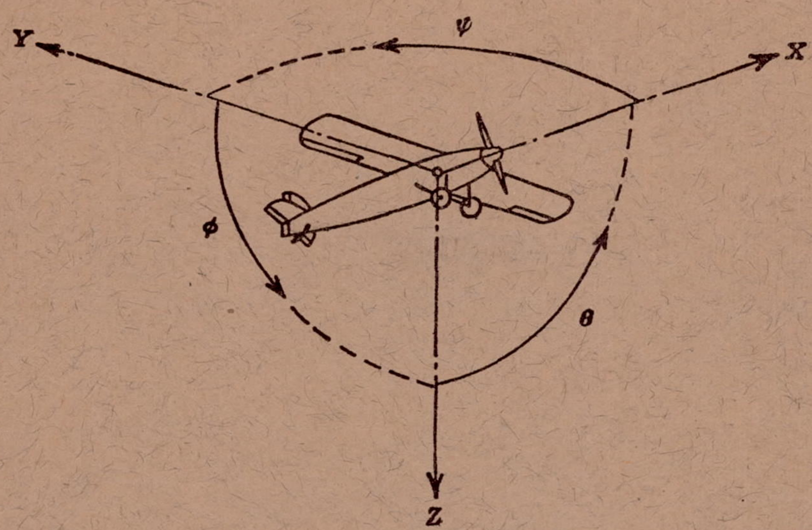

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	φ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter

p Geometric pitch

p/D Pitch ratio

V' Inflow velocity

V_s Slipstream velocity

T Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$

Q Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$

C_s Speed-power coefficient $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$

η Efficiency

n Revolutions per second, rps

Φ Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec

1 metric horsepower=0.9863 hp

1 mph=0.4470 mps

1 mps=2.2369 mph

1 lb=0.4536 kg

1 kg=2.2046 lb

1 mi=1,609.35 m=5,280 ft

1 m=3.2808 ft