MATCHING OF COMPONENTS OF JET ENGINES

A. W. Goldstein

Increased efficiency and increased power output of gas turbines are major objectives of NACA research on this type of engine. Two methods of attaining these objectives are first increasing our understanding of the internal aerodynamics of these machines and developing methods of design to obtain the best internal flow, and second by developing methods for operating turbines at higher gas temperatures. Internal aerodynamics will be discussed first by me and then by Mr. English, while some phases of the program of research or high temperature gas turbines will be described first by Mr. Ellerbrock and then by Mr. Sheflin.

The problem in internal aerodynamics which I will discuss here today is that of matching compressor and turbine components for operation in an engine. We all recognize the temperature of attaining high efficiency in the compressor and turbine components of a gas turbine. We must also recognize the importance of insuring that the good efficiency characteristics of the turbine and compressor components are utilized to their utmost by having both components operate at their maximum efficiency simultaneously in the engine at the desired engine power and temperature. For example the turbine power required to drive the compressor in a jet engine is roughly twice the jet power. If turbine and compressor are mismatched to the extent of causing one of them to operate at a point on its efficiency curve at which the efficiency is three percent lower than the peak value, then there is available a potential increase of 6 percent in engine thrust and efficiency by adjustments which will cause this one component to operate at its best efficiency.

A study of the matching of engine components was made and one result of this study was the development of a method of charting engine and component performance so as to give an over-all view of the operation and interaction and the components over the entire range of engine performance, to show how well these components are matched, and to indicate some of the limitations on the engine operation.

Such a chart is the first figure (fig. 20) which shows operation of the turbine component in a research jet engine designed and built at this laboratory. The ordinate is the shaft torque and the abscissa--the gas flow parameter--is the product of air flow by rotative speed. The blue lines are turbine performance in terms of these variables for various turbine speeds and the green lines are contours of turbine efficiency. The red lines are turbine operating conditions for various ratios of the turbine inlet temperature to the compressor inlet temperature. The white line is the the turbine operating conditions for first appearance of compressor surge--the region below the line being the region for normal compressor operation while the region above is the region for compressor surge in which the compressor efficiency is very low and the engine cannot be operated. This chart employs the usual corrected or generalized variables so that it is applicable for all flight altitudes, ram pressures, jet nozzle settings, fuel inputs, and engine speeds. For a compressor inlet temperature of 500° absolute and a turbine inlet temperature of 2000° absolute the engine temperature ratio is 4:1. At low speeds the engine is inoperative at this temperature ratio because the compressor is in surge, but as the engine speed is increased, the compressor passes out of surge and the turbine operation approaches the region of best turbine efficiency. At highest engine speed for this temperature ratio the turbine is operating at 85 percent efficiency which is about 2-1/2 percent below the peak value possible for the turbine. To reach this point of engine operation it would be necessary to bring the engine up to speed at a lower temperature and then increase the fuel input at or near full speed.

Because the compressor efficiency is just as important in affecting engine performance as the turbine efficiency we examine the compressor performance in the engine as shown by the next figure (fig. 21). Here the compressor pressure ratio is plotted against the air-flow parameter--product of air flow by engine speed--with lines of constant compressor speed, lines of constant compressor efficiency, the compressor surge line and symbols to indicate various engine temperature ratios. The high speed operation point at a temperature ratio of 4:1 has the compressor operating at an efficiency of 86 percent--only 1/2 percent lower than the peak efficiency available. Thus, although in this engine the high efficiency region of the compressor and turbine are fairly well matched, some improvement in turbine operating condition is possible. By replacement of the burner and bearings with known improved types, gains from these components compounded with gains from improved matching were shown by an analysis such as this to result in an increase in thrust of 9 percent and a decrease in specific fuel consumption of 21 percent.

Mr. English will now discuss some other experimental phases of this fundamental research on internal aerodynamics.

TURBINE AERODYNAMICS RESEARCH

R. E. English

From the NACA's program of objective research on turbine aerodynamics the results of an investigation of the effect of two design variables on turbine performance will be presented.

A good understanding of the internal aerodynamics of turbines is necessary in order to design efficient, high-performance turbines. We want turbines that in addition to having high peak efficiencies produce their peak efficiencies at their design points. The importance of obtaining the peak turbine efficiency and the peak compressor efficiency at the design point of the engine was discussed by Mr. Goldstein as part of the problem of matching compressors and turbines. In order to obtain a better understanding of the turbine aerodynamics we have been investigating a series of blade designs in a single-stage, cold-air turbine. This is one of the die-cast aluminum blades from this turbine. A wheel from this turbine and some more blades are displayed here (See fig. 22.). In these designs several design variables have been systematically altered to determine the effect of these variables on turbine performance and to indicate problems on which intensive research may most profitably be concentrated.

Our research on turbine aerodynamics has been broken down into two problems: (1) the selection of a set of velocity diagrams that will permit the turbine to pass the design mass flow and produce the required power, and (2) the selection of a set of blade profiles that will produce the desired velocity diagrams. Our general approach to the problem is to theoretically predict the flow conditions in a turbine and then to experimentally check the theoretical flow. The turbine performance is also determined in order to relate design changes to the over-all turbine performance.

From the 10 sets of blades we have so far designed, constructed, and investigated in the cold-air turbine the results from five of the designs will be presented to show the effect of the amount of reaction and of the suction surface curvature. This (cooled blade No. 1) is a scaled-up model of a typical turbine blade. This concave surface is called the pressure surface. This convex surface is called the suction surface. The suction surface curvature is critical in turbine blade design. To investigate the effect of suction surface curvature and the amount of reaction on turbine performance a series of blades was designed with various amounts of reaction and one of two suction surface curvatures, either an arc of a circle or an involute of a circle with the radius of curvature increasing toward the trailing edge. The effect of these variables on turbine efficiency is shown by the following chart (fig. 23).

This chart shows the variation of the turbine efficiency with the amount of reaction for the two suction surface curvatures. Changing the reaction from 0 to 0.40 increased the efficiency by

0.02 from 0.84 to 0.86. Changing the suction surface from an arc of a circle to an involute increased the efficiency by 0.025 to 0.03. These efficiencies are all at the design point; the over-all performance of this design (0.40 reaction, involute) is shown in the following chart (fig. 24).

This chart presents the turbine work as a function of the ratio of the blade speed to the weight flow of gas through the turbine. The green lines are lines of constant pressure ratio, the ratio of inlet total pressure to outlet total pressure, the orange lines are lines of constant blade speed, and the blue lines are the efficiency contours. This design produced an efficiency of 0.86 at its design point, right here, as was pointed out on the previous chart. In addition, an efficiency of 0.88 was observed over the entire range of pressure ratios from 1.5 to 4.0. The peak efficiency was 0.885, 0.025 higher than the 0.86 at the design point. If this turbine were to be used in an engine, the 0.025 difference between the peak efficiency and the efficiency at the design point might justify modifying the engine components in order to improve the engine performance, like the modifications Mr. Goldstein described.

From investigations such as these we will obtain a better understanding of the flow phenomena in turbines and this will in turn permit better turbines to be designed. Paralleling over work on turbine aerodynamics an attempt is being made to raise the operating temperatures of our hot-gas turbines. A portion of this work will be described by Mr. Ellerbrock. Mr. Ellerbrock --

IMPROVEMENT OF PERFORMANCE BY INCREASE OF TURBINE INLET-GAS TEMPERATURE

H. Ellerbrock

In the never ceasing search for methods of improving gas-turbine engine performance, analyses made by the NACA show that increasing the gas temperature at the turbine inlet promises great returns, as illustrated by some results given in the next chart (fig. 25).

This chart shows turbo-propeller engine performance with cooling losses included for a speed of 500 mph and an altitude of 30,000 feet. The net thrust power and the specific fuel consumption have been plotted against turbine inlet temperature. The curves were calculated for ideal compressor pressure ratio conditions. It is evident from the chart that the power increases rapidly as the turbine inlet temperature increases and also that the specific fuel consumption decreases slightly.

The permissible gas temperature at the inlet at present is limited to approximately 1500° F because of blade metal limitations. The approximate power output of present-day engines at this limiting temperature of 1500° F is indicated by this point. If the gas temperature could be increased to 3500° F, the approximate temperature limit that can be attained with present hydrocarbon fuels, the results on this chart show that the power could be about tripled. Similar calculations at the same airplane speed and altitude have been made for turbojet engines in the range from 1000° F to 2000° F turbine-inlet temperature and show a doubling of power in this temperature range. The specific fuel consumption, however, is adversely affected in the region of 2000° F because of loss of propulsive efficiency at the high relative jet velocities.

In order to increase the permissible gas temperature at the turbine inlet and realize the remarkable performance improvement that is indicated by the analyses, two methods of attack are available: One method is to cool the turbine blades thus permitting an increase in gas temperature at a constant blade temperature. Another very important possibility of this method is that non-strategic metals can be used for the blades. The second method is to improve the blade materials so that higher blade temperatures and consequently higher gas temperatures would be possible.

A brief outline of the NACA program on the first method of attack is illustrated on this chart (fig. 26). A series of analytical studies were made to determine the effect of various possible blade-cooling methods on the permissible gas temperature increase. The complete results of these studies have been published by the NACA in eight Research Memorandum reports. The essential feature of the first method analyzed, rim cooling, is that heat received by a solid blade, such as indicated by model 1, (See fig. 22.), which is a scaled-up section of a typical blade, is conducted through the blade to the cooled rim of the rotor. (Indicate on wheel.) The study showed that inappreciable increases in permissible gas temperature could be obtained with present-day metals, but that blade life could be increased appreciably, in fact doubled, by small decreases in rim temperature. Further studies were made to determine the effects of air and liquid cooling. Some results are shown in the next chart (fig. 27).

The increases in permissible gas temperature when cooling air is passed through a hollow blade made of a high-temperature alloy steel and shaped as indicated by the scaled-up model 2, are shown in this curve for different rates of cooling-air flow expressed here as a fraction of hot-gas flow. The results show that for this case, 12 percent cooling air permits a gas temperature increase of 500° F. The same blade provided with an insert, as shown in model 3, so as to restrict the air to a narrow passage in the blade, permits a higher permissible gas temperature increase with much lower quantities of cooling air than the blade without the insert. For instance, with only 4 percent cooling air, the permissible gas temperature rise is 650° F. If the coolant is water, which must be passed through round holes, as shown in model 4, because of the very high internal pressures, the permissible gas temperature increase becomes very large - more than ten times that with air cooling. A few calculations to determine the effect of putting ceramic coatings around liquid-cooled blades indicates that further significant increases, about 500° F, in permissible gas temperature, over and above that obtained with the cooling alone, are possible if high conductivity metal blades and ceramics with the conductivity of thorium oxide or lower are used. Ceramic coatings also offer the advantage of protecting the blade metal surface from erosion.

Thus the results of studies to date show that moderate increases in permissible gas temperature are possible with air cooling and that with water cooling gas turbines should be able to be operated with present-day high-temperature alloy steels at the limiting temperatures attainable with present hydrocarbon fuels.

The results of the analytical studies were approximate because of limitations in heat-transfer data for cooled turbine blades. Consequently, experimental research has been started to obtain these much needed data to permit more refined analysis and design of cooled turbines using static and rotating cascades of blades. The rigs are constructed in a manner to permit rapid changing of wheels and blades. Because of the very promising results of the analytical studies with water cooling, two turbine wheels have been designed and constructed by the NACA using this method of cooling. The blades and rotor of the first wheel were made of aluminum alloy, in order to determine the performance using a material of high conductivity, a property that analysis showed was important. The blades and rotor of the second wheel were made of stainless steel to obtain experimental information regarding the relative importance of high conductivity and high melting points.

The second method of attack by the NACA on the problem of increasing the permissible gas temperature, namely, that of improving the blade materials, is described in another part of today's tour. In addition to that work, further research is being conducted on the solution of the problems presented in the application of ceramics to the blades of turbine wheels designed and constructed by the NACA, with the ultimate objective of using such blades in an engine for expendable missiles.

This slide (color photograph of ceramic-bladed turbine wheel) shows the assembly of ceramic blades and the rotor of the latest wheel design. Several materials were used for the blades of the wheels, the most promising being Bureau of Standards body 4811 with a minimum of 80 percent beryllium oxide. This material was developed by the Bureau under the sponsorship of the NACA. A Research Memorandum report has been published giving the design details and some performance results obtained to date with the wheels in a turbine rig. The wheel shown here with the B. of S. body 4811 blades, has completed several runs at a gas temperature of 1800° F reaching speeds up to 13,000 rpm. The wheel has been operated for a total time of 75 hours at speeds above 9000 rpm. The picture here was taken after the runs indicated and close examination would show the greater part of the blades in very good condition. The next slide (color photograph of ceramic turbine in operation) shows the turbine rig in operation; the hottest metal area being the inlet collector which was at a temperature of about 1400° F. The ceramic-bladed wheel is operating at this point, and the degree of heat is well indicated by the metal color.

This concludes the presentation in this room. In the next room, which you will now pass through, the aluminum-bladed turbine wheel is operating and a running commentary of its performance will be given to you by Mr. Sheflin. In addition, the stainless steel wheel that will be water-cooled and the ceramic-bladed wheel are on display. Because of gasoline fumes no smoking is allowed in the next room. This way please.

IV TURBINE RESEARCH - W-7, C&TRFB

NACA LIQUID-COOLED ALUMINUM-BLADED TURBINE

R. Sheflin

Gentlemen -- if you will stand on the white line, not more than three deep everyone will be able to see this presentation.

We are operating here a liquid-cooled gas turbine (See fig. 28.) all of the rotating parts of which, except the shaft, are made of aluminum.

The turbine is operating today with an inlet-gas temperature of 1800° F but at reduced speed in order to keep the noise level down.

Gasoline is burned in a pair of burners, the hot gas is circulated through the turbine and discharged to the laboratory exhaust system. Power is absorbed with a water brake. The device at the end of the water brake is a thermocouple pickup which makes it possible for us to measure blade metal temperatures with the turbine in operation.

This turbine was designed and built at the NACA to investigate the problems involved and the advantages to be gained in the adaptation of liquid cooling and high conductivity material to turbine parts.

I have here a picture of the turbine wheel (fig. 29) before assembly in this rig and a four-times size model of a single blade. The coolant is introduced at the center of the disk and its flow is radially outward through the two holes nearest the leading edge of the blade across the tip of the blade through a pair of intersecting transfer holes and radially inward through the two holes nearest the trailing edge of the blade.

This chart (fig. 30) shows that this turbine has been operated at inlet gas temperatures very near or above the melting point of aluminum for a total of 45 hours, 9 hours of which was at inlet gas temperatures between 1800° and 2110° F. Regular inspections during this operating period revealed no deterioration of the blades due to corrosion or elongation.

Also on display here is a stainless-steel water-cooled turbine wheel on which an investigation of the effect of cooling on performance will be run and the ceramic-bladed turbine wheel which Mr. Ellerbrock told you a little about in the other room.

The turbines we are running here are giving us much needed information in our quest for a low-cost turbine made of non-strategic materials which can be operated with inlet-gas temperatures of from 3 to 4000° F.

(Raise hand -- lights out for 10 seconds.)

Your guide is at the door. Will you please follow him to the next exhibit.