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RESEARCH MEMORANDUM

COMPARISON OF CALCULATED AND EXPERIMENTAL TEMPERATURES OF WATER-COOLED TURBINE BLADES

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RESEARCH MEMORANDUM

COMPARISON OF CALCULATED AND EXPERIMENTAL TEMPERATURES OF WATER-COOLED TURBINE BLADES

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SUMMARY

Analytical methods were used to calculate average and local turbine-blade temperatures. These temperatures were compared with experimental data obtained with a forced-convection, water-cooled aluminum turbine over a range of turbine-inlet-gas temperatures from 400° to 1600° F and coolant-mass velocities from 24 to 280 pounds per second - square foot. A stationary water-cooled low-conductivity-material (stainless steel) blade with a high-conductivity material (copper) inserted in a portion of the trailing edge was also investigated in order to determine the cooling effectiveness obtained by use of the insert and to provide data for comparison with calculated trailing-edge temperatures. A gas-temperature range from 400° to 900° F and a coolant-mass velocity range from 485 to 1080 pounds per second - square foot were covered in the stationary-blade investigation.

Calculation of high-conductivity-material turbine-blade average temperatures and low-conductivity-material stationary-blade temperatures resulted in generally good agreement with experimental data. Comparison of calculated and experimental turbine-blade trailing-edge temperatures also resulted in good agreement. Calculated leading-edge temperatures, however, are higher than experimental values, and the degree of variation increased with increasing blade temperature. Maximum allowable turbine-inlet-gas temperatures computed for the water-cooled aluminum turbine for coolant-to-gas flow ratios from 0.05 to 0.40 and a nominal design turbine-inlet-gas mass velocity of 12 pounds per second - square foot resulted in values ranging from 1800° to 2400° F, respectively. Calculated stationary water-cooled-blade trailing-edge temperatures are approximately 15° F less than experimental values for both the trailing-edge section with the copper insert and the section without the copper insert.

Insertion of a high-conductivity material (copper) in the trailing edge provides an effective method for reducing the trailing-edge temperature of a water-cooled blade of low-conductivity material (stainless steel). Over the range of operating conditions investigated with the stationary water-cooled blade, a reduction of more than 50 percent in required coolant flow was achieved in maintaining a given trailing-edge temperature. Calculations indicate that use of a copper insert permits a reduction of 375° F in the stationary-blade trailing-edge temperature with a nominal coolant flow at the design conditions of a current aircraft turbine.

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INTRODUCTION

Design of cooled turbines necessitates the calculation of blade temperatures under desired turbine operating conditions. In order to calculate these temperatures, the gas-to-blade and blade-to-coolant heat-transfer coefficients must be known. In an earlier investigation of a forced-convection, water-cooled aluminum turbine (reference 1), it was shown that the theoretical average gas-to-blade heat-transfer coefficients, calculated according to methods derived in reference 2, agreed within 3 percent with the curve representing turbine experimental data. Another investigation with this turbine (reference 3) demonstrated that over the major portion of the coolant-flow range investigated, blade-to-coolant heat-transfer data agreed within 17 percent with the curve representing heat-transfer data for heated liquids in stationary tubes. The investigation of reference 3 also utilized theoretical gas-to-blade and stationary-tube blade-to-coolant heat-transfer coefficients to calculate average blade-midspan temperatures by analytical methods derived in reference 4 and modified in reference 3. The maximum deviation of calculated average blade-midspan temperatures for the limited number of data points calculated in reference 3 was 19° F at an experimental blade temperature of 165° F. These results suggest that adequate agreement may be expected if analytical methods (references 2 to 4) are applied to the calculation of local blade temperatures; however, verification is necessary. Whether these methods can be applied successfully to water-cooled blades of low-conductivity material must also be determined because future water-cooled turbine applications will primarily involve high-strength, low-conductivity materials. 2554

It has been shown (reference 5) that use of high-conductivity-material (copper) inserts in the leading and trailing edges of air-cooled turbine blades fabricated of low-conductivity material (X-40) substantially reduces the leading- and trailing-edge temperatures. If similar reductions can be achieved with water-cooled blades, the high chordwise temperature gradients can be reduced, thereby decreasing the thermal stresses encountered and effecting important increases in blade life.

The investigation described herein was conducted at the NACA Lewis laboratory in order (1) to provide additional applications and verification of existing analytical methods for calculating temperatures of water-cooled blades fabricated of high- and low-conductivity material, (2) to obtain data for determination of maximum allowable gas temperatures for the forced-convection, water-cooled aluminum turbine, and

The investigation described herein was conducted at the NACA Lewis laboratory in order (1) to provide additional applications and verification of existing analytical methods for calculating temperatures of water-cooled blades fabricated of high- and low-conductivity material, (2) to obtain data for determination of maximum allowable gas temperatures for the forced-convection, water-cooled aluminum turbine, and
2554 (3) to determine the cooling effectiveness of a high-conductivity-material trailing-edge insert when applied to a water-cooled blade. The aluminum turbine was operated over an extended range of gas- and coolant-flow conditions in order to obtain maximum allowable gas-temperature data as well as additional data to that given in references 1 and 3 for use in calculating blade temperatures. A stationary, water-cooled, stainless-steel blade with a high-conductivity-material trailing-edge insert was investigated in a hot gas stream over a range of gas temperatures and coolant flows, and analytical methods were applied in calculating the blade trailing-edge temperatures.

Average turbine-blade-midspan temperatures as well as average temperatures at the blade root and blade tip were calculated for the aluminum turbine by experimentally substantiated heat-transfer-coefficient analysis methods. Although the high conductivity of aluminum prevented large chordwise temperature gradients between various peripheral blade locations such as those that occur in cooled blades of low-conductivity material (reference 6), temperatures at specific blade locations such as the leading and trailing edges were also calculated. Analytical methods of calculating blade temperatures were also used to calculate the maximum allowable turbine-inlet-gas temperature for several coolant-to-gas flow ratios. For the stationary, water-cooled, stainless-steel blade, the trailing-edge temperature of the portion of the blade with an insert was calculated for comparison with measured temperatures, and an average value of thermal conductivity for the trailing-edge section was used in the analytical temperature calculation method. The trailing-edge temperature was also calculated for the blade trailing-edge portion without the high-conductivity insert and compared with experimental data.

In these investigations, the turbine was operated over a range of gas temperatures from 400° to 1600° F, over a range of gas mass velocities from 7.2 to 17.4 pounds per second - square foot, and over a range of coolant mass velocities from 24 to 280 pounds per second - square foot. The stationary water-cooled blade was operated over a range of gas temperatures from 400° to 900° F and over a range of coolant mass velocities from 485 to 1080 pounds per second - square foot at a constant gas mass velocity of 3.8 pounds per second - square foot.

APPARATUS

Descriptions of the water-cooled turbine and the stationary water-cooled blade used in these investigations are presented in the following paragraphs.

Water-Cooled Turbine

Turbine. - The forced-convection, water-cooled, single-stage aluminum turbine used in this investigation is fully described in reference 7. Sectional views illustrating blade-construction details and the coolant-flow path are shown in figure 1(a). The rotor consists of two disks machined from 14ST aluminum. Fifty impulse-type blades of constant cross section with no twist are machined integrally with one of the disks. The turbine rotor has a tip diameter of 12.062 inches. The blade span is 1.15 inches and the blade chord is 0.744 inch. Coolant passages near the blade leading and trailing edges have 0.062-inch diameters and the passages near the blade center have 0.099-inch diameters. The cross-over passage near the blade tip connecting the four radial coolant passages is 0.062 inch in diameter. The turbine installation and the coolant-flow path through the entire turbine are shown in figure 1(b). Hot gases for driving the turbine were supplied by two modified jet-engine burners. Turbine power was absorbed by a water brake.

Instrumentation. - The planes of instrumentation through the turbine installation are shown in figure 1(b). Turbine-blade temperatures were measured at the locations shown in figure 1(a). The blade temperatures were measured at the midspan position on the leading and trailing edges, on the pressure and suction surfaces at points approximately midway between the leading and trailing edges, on the pressure surface at the blade tip, and on the suction surface at the blade root. A thermocouple pickup consisting of a slip-ring and brush system was used to obtain temperature measurements on the rotating elements. Coolant-inlet temperature was measured by a thermocouple located in the stationary coolant-supply tube. Coolant-outlet temperature was measured on the water-outlet side of the baffle plate immediately prior to coolant discharge from the rotor (fig. 1(a)). Total and static gas pressure, gas temperature, gas and coolant flow, and turbine speed were measured in the manner described in reference 7.

Stationary Water-Cooled Blade

Blade fabrication and installation. - The stationary water-cooled AISI type 403 stainless-steel blade is shown in figure 2. The blade was installed in the 10-inch combustion-gas-inlet duct of the aluminum turbine at a position where gas-flow conditions were most uniform (see fig. 1(b)). The blade trailing edge was divided into two spanwise sections, one containing a copper insert to increase the average conductivity of the section and one without the insert. A saw cut separated these sections to eliminate spanwise conduction between them. The copper insert measuring 1.25 by 0.24 by 0.032 inches was brazed in a slot machined to the same length and depth but to a 0.036-inch width in order to accommodate the braze material. The copper insert extended from the trailing edge to the 0.070-inch-diameter coolant passage that was drilled spanwise through the entire blade. A leading-edge section was provided in order to simulate, as far as possible, gas-flow conditions and resulting heat-transfer rates encountered over the trailing-edge section of turbine blades. In order to minimize conduction from the blade leading-edge section, a series of 0.090-inch-diameter holes was drilled through the blade immediately upstream of the coolant passage and filled with a low-conductivity ceramic cement.

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Instrumentation. - Thermocouple locations on the stationary blade are shown in figure 2(a). The temperature of the blade trailing-edge section with the copper insert and that of the section without the copper insert were measured at the midspan trailing-edge point of each section. Coolant-inlet and -discharge temperatures were measured by thermocouples located in the coolant-supply and -discharge tubes at the points of coolant inlet and discharge from the blade. Coolant flows were measured by a rotameter. Total gas temperature and pressure were measured by means of a thermocouple and pressure-tube rake extending across the duct in a plane 6 inches downstream of the blade. From the center of the gas-flow duct, the thermocouples were located at zero radius and at each of three radii, approximately 3/8, 5/8, and 7/8 of the duct radius. The pressure probes were located at each of three radii, approximately 1/4, 1/2, and 3/4 of the duct radius. Static-pressure taps were provided in the same plane at 90° intervals around the duct.

PROCEDURE

Water-Cooled Turbine Investigation

Analytical methods were used to calculate blade temperatures for comparison with data obtained from the forced-convection, water-cooled aluminum turbine. These data covered a wide range of coolant-flow and gas-flow conditions and were obtained at the design turbine-gas-flow inlet angle of 37°. In order to cover as complete a range of turbine operating conditions as possible, data from references 1 and 3 were also included in these calculations. The entire range of turbine operating conditions covered is given in table I.

The turbine was also operated in order to obtain an indication of the maximum allowable gas temperature for constant coolant-to-gas flow ratios of 0.05, 0.10, 0.20, 0.30, and 0.40. These data were also included in the blade-temperature calculations. A constant gas mass velocity of 12 pounds per second - square foot and the design gas-flow inlet angle of 37° were maintained during these runs. Turbine operation at a constant gas-flow inlet angle was achieved by setting the inlet-gas temperature, the pressure ratio, and the turbine speed according to previously calculated values. The turbine speed was adjusted by means of a water brake to the proper calculated value in order to maintain the desired inlet angle for any condition of pressure ratio and inlet-gas temperature. In view of the approximately 800 hours already logged, turbine operation was maintained at reasonable rotor stress levels by not exceeding 15,500 revolutions per minute. This speed represents approximately two-thirds of the design centrifugal loading. 2554

Stationary Water-Cooled Blade Investigation

The investigation of the water-cooled, stainless-steel blade was conducted simultaneously with the turbine maximum allowable gas-temperature investigation. Test conditions were, consequently, limited to a constant gas mass flow and the various gas temperatures were set while turbine maximum allowable gas-temperature data were being obtained. The complete range of gas temperatures and coolant-flow conditions covered in the stationary-blade investigation is also given in table I. In order to eliminate the possibility of damage to the turbine, the stationary blade was removed from the turbine combustion-gas inlet duct at gas temperatures above 900° F.

METHODS OF CALCULATION

Calculation of Aluminum-Turbine Average Blade Temperatures

Analytical methods derived in references 2 to 4 were used to calculate water-cooled aluminum turbine blade and stationary water-cooled stainless-steel blade temperatures. Modifications of these basic methods were sometimes required to suit the specific application reported herein. For the sake of brevity, reference is made wherever possible to published sources in describing the detailed calculation procedures.

Determination of heat-transfer coefficients. - Calculation of turbine-blade temperatures requires knowledge of gas-to-blade and blade-to-coolant heat-transfer rates or coefficients. In order to obtain average temperatures around the blade periphery, average convection gas-to-blade heat-transfer coefficients were used. For the design gas-flow inlet angle and any given set of gas-flow conditions these coefficients were obtained by applying boundary-layer heat-transfer theory in the manner described in appendix B of reference 2. Application of boundary-layer theory requires knowledge of the chordwise velocity distribution around the turbine blades. Stream-filament theory derived for compressible flow around impulse-type blades (reference 8) was used to obtain the required chordwise velocity distributions. For any given coolant flow, average blade-to-coolant heat-transfer coefficients were obtained from a mean curve through the heat-transfer data of several investigators for the laminar flow of heated-liquids through stationary tubes (fig. 5, reference 3). These correlation methods were verified experimentally with this turbine in earlier investigations (references 1 and 3).

<u>Average blade-midspan temperature</u>. - The average temperature at the blade midspan was calculated from equation (B2) in appendix B of reference 3.

$$T_{B,2} = T_{B,p} + C_3 e^{\alpha x_2} + C_4 e^{-\alpha x_2} \tag{1}$$

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(All symbols are defined in appendix A.) This is the radial-temperature-distribution equation for the cooled portion of the blade (section 2 of fig. 3) and was used in order to account for the effect of radial conduction, which should be considered for a turbine with short blades of high-conductivity material as indicated in reference 4. The terms C_3 and C_4 were calculated as described in appendix B of reference 3. The values of $T_{B,p}$ and α were evaluated from the definitions given in appendix A. The value substituted for x_2 is equivalent to one-half of the length of the cooled blade portion. Values of the cooled blade length and additional geometric factors used in these and subsequent turbine-blade calculations are given in table II.

<u>Average blade-tip temperature</u>. - The average temperature at the blade tip (section 1 of fig. 3) was calculated from equation (B1) in appendix B of reference 3.

$$T_{B,1} = T_{g,e} + C_1 e^{ax_1} + C_2 e^{-ax_1} \tag{2}$$

The terms C_1 and C_2 were evaluated as described in the reference. Since the value of x_1 is equal to zero and since the term a is always finite, equation (2) reduces to

$$T_{B,1} = T_{g,e} + C_1 + C_2 \tag{3}$$

The effective gas temperature $T_{g,e}$ was calculated from equation (4) (equation 3, reference 7) and the nozzle survey data cited in reference 7 for this turbine.

$$T_{g,e} = T_g + \Lambda \frac{W^2}{2gJc_p} \tag{4}$$

<u>Average blade-root temperature</u>. - The average temperature at the blade root was calculated from equation (1). The term x_2 was given a value equivalent to the length of the cooled portion of the blade (see fig. 3). The terms α, $T_{B,p}$, C_3, and C_4 have the same values as those used in the calculation of the average midspan-blade temperature.

Calculation of Specific Blade Temperatures of Aluminum Turbine

Determination of heat-transfer coefficients. - Specific leading- and trailing-edge blade temperatures were calculated by use of local gas-to-blade heat-transfer coefficients averaged over the midspan portions of the leading and trailing edges, respectively (see fig. 3). Local gas-to-blade coefficients over the blade section affecting the trailing-edge temperatures were calculated from the turbulent-boundary-layer heat-transfer equation (equation (26), reference 2) which, according to the notation reported herein, is represented by

$$Nu_o = 0.0296\ (Re_g)^{0.8}\ (Pr_g)^{1/3} \tag{5}$$

In equation (5) physical properties of the gas were evaluated at the wall temperature. The turbulent-flow equation was used because velocity-distribution calculations by stream-filament theory (reference 8) indicated that turbulent flow existed over the blade trailing-edge section for the turbine operating range covered. In order to obtain local coefficients around the leading edge, the velocity distribution in the channel portion of the blade was first calculated according to the method described in reference 8. A velocity profile over the leading edge was then assumed and substantiated by circulation checks made over the blade leading edge. Over the section of the leading edge where the velocity profile was laminar, the local coefficients were calculated from the laminar heat-transfer equation (equation (19), reference 2). According to the notation employed herein, this equation is expressed as

$$Nu_o = \overline{F}_{lam}\ (Re_g)^{1/2}\ (Pr_g)^{1/3} \tag{6}$$

Properties of the gases used in equation (6) were evaluated at the wall temperature. The local coefficients in the turbulent-flow region around the blade leading edge were calculated from the turbulent-flow equation (equation (5)). Integrated averages of the local leading- and trailing-edge coefficients were obtained from a plot of local coefficients against distance along the leading- and trailing-edge blade surfaces, respectively. Because the flow rate through the individual passages in the blades could not be measured or calculated with certainty, average blade-to-coolant coefficients, as described previously, were used in the specific blade-temperature calculations.

Blade-midspan trailing-edge temperature. - Inasmuch as radial conduction from blade to rim has a pronounced effect upon trailing-edge temperature, as shown for a typical water-cooled blade in figure 10(b) of reference 4, it was necessary to account for conduction by approximating the blade trailing-edge section with a rectangular parallelepiped. The trailing-edge temperature was obtained from a series solution (equation (12), reference 4) which may be written as

$$T_{B,TE} = T_{g,e} - \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left(\mathscr{K}_{m,n} \cos \mathscr{L}_n x' \cosh \mathscr{M}_{m,n} y' \cos \mathscr{N}_m z + \mathscr{O}_{m,n} \cosh \mathscr{P}_{m,n} x' \cos \mathscr{Q}_n y' \cos \mathscr{N}_m z \right) \tag{7}$$

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In this equation the terms x', y', and z represent geometric dimensions of the parallelepiped and the integration constants $\mathscr{K}_{m,n}$, $\mathscr{L}_n$, $\mathscr{M}_{m,n}$, $\mathscr{N}_m$, $\mathscr{O}_{m,n}$, $\mathscr{P}_{m,n}$, and $\mathscr{Q}_n$ are evaluated as described in reference 4. The values obtained by use of this equation were corrected to account for inaccuracies introduced by simulating the trailing-edge section with a rectangular parallelepiped. Reference 4 indicates that a more accurate determination of the trailing-edge temperature can probably be obtained by simulating the trailing edge with a wedge-shaped prism. Because of the complexity of the mathematical solution for such a geometric shape, however, the simpler rectangular parallelepiped was used, and corrections obtained in the following manner were applied. For each data point considered, the trailing-edge temperature was separately determined with radial conduction neglected. The trailing-edge section was approximated first with a wedge and then with a rectangle, and the temperature was determined by use of equations (21) and (19) of reference 4. These equations may be expressed as

$$T_{B,TE} = T_{g,e} - \frac{\dfrac{H_i \zeta_2}{2K^2 k_B} (T_{g,e} - T_l) J_o(i\zeta)}{\dfrac{H_i \zeta_2}{2K^2 k_B} J_o(i\zeta_2) - iJ_1(i\zeta_2)} \tag{8}$$

and

$$T_{B,TE} = T_{g,e} - \frac{\dfrac{H_i}{k_B} (T_{g,e} - T_l) \cosh \Phi y'}{\Phi \sinh \Phi j' + \dfrac{H_i}{k_B} \cosh \Phi j'} \tag{9}$$

Geometric factors incorporated in the terms K, ζ, and ζ_2, were evaluated from the definitions given in appendix A and from blade dimensions given in table II and figure 1(a). The difference between the results obtained from equations (8) and (9) provides an indication of the effect of the trailing-edge geometric factor. However, this effect varies with position along the blade span. The following equation expresses a correction, which when subtracted from the trailing-edge temperature calculated by equation (7) provides the final corrected trailing-edge temperature,

$$\Delta T_{TE} = \left(\frac{T_{TE,P} - T_{r,exp}}{T_{TE,R} - T_{r,exp}}\right)\left(T_{TE,R} - T_{TE,W}\right) \tag{10}$$

Midspan leading-edge temperature. - Blade leading-edge temperatures 2554
were calculated by the same method as the trailing-edge temperature by use of equations (7) to (9) except that gas-to-blade coefficients for the leading edge, evaluated as previously described, were used. A simpler procedure of approximating the leading-edge section by concentric circles (equation (23), reference 4) was not employed because the effect of radial conduction is not considered in this equation.

Calculation of Stationary Stainless-Steel Blade Temperatures

Determination of heat-transfer coefficients. - Trailing-edge temperatures were calculated by use of local gas-to-blade heat-transfer coefficients, averaged over the portion of the trailing-edge section indicated in figure 2(a). Local gas-to-blade coefficients were calculated by equation (5). Because the pressure gradient over the surface of this configuration approaches zero, a turbulent boundary layer will ensue according to reference 2. Consequently, the turbulent-flow heat-transfer equation was used. The coolant flows used resulted in coolant-flow Reynolds numbers greater than the critical value of 2300 and, therefore, blade-to-coolant coefficients were obtained from equation 4(c), reference 9. This equation represents a mean curve through the heat-transfer data obtained by several investigators for turbulent flow of liquids through stationary tubes and is written in the notation employed herein

$$Nu_i = 0.023(Re_l)^{0.8}\ (Pr_l)^{0.4} \tag{11}$$

The properties of the coolant were evaluated at the arithmetic average of the coolant-inlet and -discharge temperatures.

Trailing-edge temperature for blade section without copper insert. - The trailing-edge section was simulated by an equivalent wedge, and the trailing-edge temperature was calculated by the one-dimensional chordwise-temperature-distribution equation (equation (8)). Geometric factors incorporated in terms K, ζ_2, and ζ were evaluated from blade dimensions given in table III. The value of thermal conductivity used in the term K is also given in table III. The average coolant temperature was used in equation (8). The effective gas temperature was evaluated from gas conditions measured in the instrumentation plane located 6 inches downstream of the blade and by the use of equation (4).

Trailing-edge temperature for blade section with copper insert. - Trailing-edge temperatures were calculated by the same method used for the blade section without the insert, except that a different value of thermal conductivity was used. A weighted average value of conductivity (tabulated in table III) based on the average thickness t of each
2554 material in the trailing edge was determined from the following equation in which the thickness terms are evaluated at the locations shown in figure 2(b):

$$k_{B,av}\,(t_s + t_c + t_s) = t_s k_s + t_c k_c + t_s k_s \qquad (12)$$

An average value of conductivity $k_{B,av}$ so evaluated was based on the assumption that heat will flow in the direction of the coolant passage through the insert material as well as through the blade material surrounding the insert.

Calculation of Maximum Operating Conditions of Aluminum Turbine

Maximum allowable blade temperature. - Calculation of the maximum allowable turbine-inlet gas temperature for a given coolant flow requires knowledge of the maximum permissible blade-radial-temperature distribution. For this turbine, the maximum blade temperature for a design speed of 19,000 rpm and 1000-hour life was determined as described in reference 10. Briefly, the procedure is as follows: Centrifugal stresses due to the blade material and the coolant head were calculated at several radial blade locations. By use of these stresses and unpublished stress-to-rupture curves obtained at various temperatures for 14ST aluminum, the maximum permissible blade-radial-temperature distribution was evaluated. Calculated blade centrifugal stresses were multiplied by a safety factor of 1.25 in order to account for small superimposed blade stresses due to gas bending, blade-temperature gradients, etc. Induced stresses resulting from temperature gradients are likely to be small for this turbine because of the high conductivity of the blade material; consequently, a small safety factor is adequate.

Maximum allowable turbine-inlet gas temperature. - Maximum allowable turbine-inlet gas temperatures over a range of coolant flows were calculated from equation (1). Of the temperatures measured at the blade root, midspan, and tip, the average midspan temperature was closest to the curve of maximum permissible blade-radial-temperature distribution obtained as described previously. Consequently, the average blade-midspan temperature is considered as the criterion in determining the maximum allowable gas temperature, and equation (1), which expresses a relation between the average midspan-blade temperature and the gas temperature, was used. A method of approximation was used to obtain the maximum allowable gas temperature. The maximum permissible blade-midspan temperature evaluated as described in the previous paragraph was substituted for $T_{B,2}$ in equation (1). An assumed value of effective gas temperature and corresponding average gas-to-blade and average blade-to-coolant coefficients, obtained for this turbine as described previously, were substituted into equation (1). The right side of the equation was then evaluated by the method of appendix B of reference 3 and the result compared with the limiting blade temperature previously substituted for $T_{B,2}$. This procedure was repeated until use of an assumed value of effective gas temperature resulted in the proper value of $T_{B,2}$. The maximum allowable turbine-inlet-gas temperature was then evaluated by both equation (4) and the nozzle box survey data described in reference 7.

RESULTS AND DISCUSSION

Comparison of Calculated and Experimental Aluminum Turbine Blade Temperatures

A direct comparison of experimental blade temperatures obtained over a range of gas temperatures from 400° to 1600° F with values calculated by use of analytical gas-to-blade and blade-to-coolant coefficients (references 2 and 3) is presented and discussed in the following sections.

Average blade-midspan temperature. - A consideration of analytical methods (reference 4) for calculating cooled-blade temperatures indicates that the average blade temperatures are the most readily calculated. The average blade temperature over the midspan portion of the blade is of practical interest in turbine design because it reflects the general blade operating temperature level and, consequently, the blade strength available. A comparison of calculated average blade-midspan temperatures and experimental average blade-midspan temperatures obtained from a plot of blade temperature against blade periphery is shown in figure 4. Calculated values are close to a 1:1 correlation line and lie on both sides of the line over the experimental blade-temperature range investigated from 105° to 299° F. The maximum deviation of calculated from experimental data over this range was 25° F and occurred at an experimental temperature of 264° F. This represents a maximum error of less than 10 percent, which appears adequate for water-cooled-turbine blade design. The minor deviations of calculated from experimental values shown in figure 4 may be attributed to inaccuracies in experimental measurements required to calculate the analytical heat-transfer rates. A similar comparison made in figure 7 of reference 3, for a small number of data points over a limited range of turbine operating conditions, also indicated good agreement between experimental and calculated blade temperatures. The results shown in figure 4 over an extended range of turbine operating conditions provide additional verification of analytical temperature-calculation methods for blades of high-conductivity material. It should be emphasized that for low-conductivity materials the spanwise blade temperature-calculation method used previously is valid only in the region of the coolant passages (reference 4). Therefore, it may be necessary to calculate specific blade temperatures, especially for locations somewhat removed from the water passages, in order to obtain a representative average blade temperature for blades of low-conductivity material.

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<u>Average blade-tip temperature</u>. - Although centrifugal stresses at the blade tip are generally negligible in uncooled turbines, hydraulic stresses near the tip of the coolant passages may be quite high in water-cooled turbines. The effect of thermal stresses combined with such hydraulic stresses may be critical and knowledge of the blade temperature at this location under imposed turbine operating conditions is desirable from a design standpoint. Calculations of specific midchord temperatures for this turbine are complex, involving a relaxation solution for the blade-temperature distribution for varying boundary conditions. Inasmuch as variations among local temperatures around the blade tip are probably small as found at the blade midspan, such a complex procedure is not warranted and consequently average blade-tip temperatures were calculated. Calculated average blade-tip temperatures are compared in figure 5(a) with an experimental blade-tip temperature measured at a point on the pressure surface, approximately midway between the leading and trailing edge. Over the experimental blade-tip temperature range investigated, 120° to 340° F, calculated values are in general higher than experimental data and the deviation appears to increase with increasing blade temperature. The maximum deviation of calculated values from experimental data was 50° F at an experimental blade temperature of 230° F. A factor that may influence the accuracy of these calculations is irregularity in gas flow at the blade tip. Gas-flow irregularities in turn vary the gas-to-blade heat-transfer rates, which affect the experimental blade-tip temperatures.

<u>Average blade-root temperature</u>. - Because blade centrifugal stresses are highest near the blade root, knowledge of the blade temperature at this location is desirable for design purposes. A comparison similar to that made at the blade tip is shown for the blade root in figure 5(b). Failure of the blade-root thermocouple during the latter phase of turbine operation slightly reduced the number of data points available for comparison with calculated average blade-root temperatures. Over the greater portion of the experimental temperature range investigated, 90° to 215° F, the calculated values fall along and on both sides of a 1:1 correlation line. With the exception of several data points approximately at the center of the temperature range investigated, good agreement between

calculated and experimental temperatures was obtained. The maximum deviation of calculated values from experimental data was 22° F at an experimental blade temperature of 140° F.

Blade-midspan trailing-edge temperature. - A comparison of calculated midspan trailing-edge temperatures with experimental values is shown in figure 6(a). Because of the complexity of the calculation procedure involved, the midspan trailing-edge temperatures were calculated for a limited number of data points selected over the entire range of gas-flow and coolant-flow conditions. Six of the seven calculated values agreed within 20° F with the experimental data over an experimental blade-temperature range from 118° to 334° F. The deviation of the seventh point was 31° F at an experimental blade temperature of 268° F. Generally, good agreement resulted when the trailing-edge temperatures were originally calculated by approximating the trailing-edge section with a rectangular parallelepiped; however, use of a correction that accounts for the effect of the trailing-edge geometric factor improved the agreement between calculated and experimental temperatures to that shown in the figure. The magnitude of this correction ranged from 7° F at the lowest blade temperature of 118° F to 44° F at the highest blade temperature of 334° F.

The temperature gradient between the blade trailing edge and the blade metal adjacent to the trailing-edge coolant passage was also determined for the blade-midspan position in addition to the calculation of the temperatures shown in figure 6(a). At a turbine-inlet-gas temperature of 1600° F, the calculated temperature gradient was approximately 40° F for this turbine. Calculations for a similar blade configuration fabricated from a high-temperature, low-conductivity material and for identical gas-flow and coolant-flow conditions result in a temperature gradient of approximately 250° F. Existence of such large temperature gradients in water-cooled blades of low-conductivity material verifies the need for calculating the temperature at specific blade locations in the design of blades of this type.

Blade-midspan leading-edge temperature. - Figure 6(b) shows a comparison of the calculated leading-edge temperatures with experimental values. As in the case of the trailing-edge temperatures, a limited number of data points over the entire range of turbine operating conditions was used because of the complexity of the calculation procedure. For the experimental blade-temperature range investigated, 116° to 315° F, the calculated values are generally higher than the experimental data, and the degree of variation increases with increasing blade temperature. The maximum deviation of computed from experimental values was about 47° F at an experimental blade temperature of 278° F. Although the correction for blade geometry was applied, a larger variation between calculated and experimental temperatures results than at the trailing edge. Conduction in the blade leading-edge section for this turbine apparently is greater than can be accounted for in the calculation procedure employed. The agreement obtained in the leading-edge temperature comparison is less favorable than that obtained for the trailing edge; nevertheless, these results also indicate the usefulness of analytical methods in which experimentally substantiated heat-transfer coefficient analysis procedures were used in computing specific blade temperatures.

Comparison of Calculated and Experimental Stationary-Blade Temperatures

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Calculated stationary-blade trailing-edge temperatures are compared with experimental values obtained over a range of gas temperatures from 400° to 900° F in figure 7 and discussed in the following paragraphs.

Trailing-edge temperature for blade section without copper insert. - It has been shown that analytical methods are generally applicable for calculating temperatures of water-cooled blades fabricated from high-conductivity material. The results of applying these methods to the calculation of the trailing-edge temperatures of the water-cooled blade constructed of low-conductivity material are shown in figure 7(a). Calculated values are displaced below a 1:1 correlation line by a constant value of approximately 15° F over the entire range of experimental blade temperatures from 116° to 272° F. Verification of the applicability of analytical methods of calculating the trailing-edge temperature of water-cooled blades of low-conductivity material is thereby provided.

Trailing-edge temperature for blade section with copper insert. - Figure 7(b) shows a comparison of calculated and experimental trailing-edge temperatures for a section of a stainless-steel water-cooled blade with a high-conductivity-material (copper) trailing-edge insert. Over the entire experimental blade temperature range from 85° to 182° F, the calculated values are approximately 15° F lower than the experimental values. These results apparently substantiate, for design purposes, the calculation procedure in which an average value of thermal conductivity for the trailing-edge section was used.

Another method of calculating the trailing-edge temperature of a water-cooled blade with a high-conductivity trailing-edge insert was suggested in reference 11. The method was based on the assumption that the high-conductivity-material insert could be considered as the primary conductive path surrounded by a low-conductivity-material coating. Less satisfactory results were obtained when this method was applied to the blade under investigation.

Stationary Water-Cooled Blade Operating Data

The stationary water-cooled blade was investigated over a range of coolant-flow conditions comparable to those encountered in small-scale

turbine operation. The variation of measured trailing-edge temperature with coolant flow at a constant gas mass velocity and over a range of gas temperatures from 400° to 900° F is shown in figure 8 for the trailing-edge sections of the stationary blade with and without the high-conductivity-material (copper) insert. For a constant gas temperature and over the entire coolant-flow range investigated, from 0.013 to 0.029 pounds per second, essentially a constant difference in temperature between the two trailing-edge sections occurs. However, this difference between the two sections increases with increasing gas temperature. At the highest gas temperature investigated (900° F), a 90° F 2554
reduction in trailing-edge temperature is effected by use of the copper insert. The curves also show that for the range of conditions investigated, use of this insert permits a reduction of more than 50 percent in the coolant flow required to maintain a given trailing-edge temperature. These results indicate that the copper insert provides an effective method of reducing the trailing-edge temperature of a stainless-steel water-cooled blade.

Although the investigation was limited to gas temperatures up to 900° F, the trend of increased reduction in trailing-edge temperature for increasing gas temperature warranted analytical investigation at higher gas temperature. In order to obtain an indication of the effectiveness of the high-conductivity-material trailing-edge insert under current turbine operating conditions the trailing-edge temperature of each section of the stationary blade was calculated for a 1600° F gas temperature. Use of a gas mass velocity indicative of the flow through the blade passage of a current aircraft turbine engine and a representative coolant flow indicated a reduction in trailing-edge temperature of 375° F. A trailing-edge temperature reduction of this magnitude can greatly reduce the temperature gradients in a water-cooled blade and thereby decrease the thermal stresses encountered and effect an increase in blade life.

Turbine Operating Data

Maximum allowable inlet-gas temperature. - Maximum allowable turbine-inlet-gas temperatures calculated for the aluminum turbine over a range of coolant-to-gas flow ratios are shown in figure 9. For a coolant-to-gas flow ratio range from 0.05 to 0.40 and a constant gas flow of 2.0 pounds per second (gas mass velocity of 12 lb/(sec)(sq ft)), the calculated maximum allowable inlet-gas temperatures ranged from 1800° to 2400° F, respectively. Figure 9 also indicates that for the experimental range of gas temperatures investigated (400° to 1600° F) a marked decrease in average blade-midspan temperature resulted for this turbine when the coolant-to-gas flow ratio was increased from 0.05 to 0.20. However, further increases in coolant-to-gas flow ratios from 0.20 to 0.40 had little effect on the average blade-midspan temperature. For example, at a gas temperature of 900° F, a 65° F decrease in average blade-midspan temperature results from increasing the coolant-to-gas flow ratio from 0.05 to 0.20. A 17° F decrease in blade temperature results from further increasing the coolant-to-gas flow ratio from 0.20 to 0.40. This trend verifies an analysis for a typical forced-convection, water-cooled turbine blade (reference 4, fig. 9), which showed that the rate of decrease in blade temperature diminishes as the coolant flow increases.

2554 In order that the favorable allowable gas temperatures calculated for the aluminum turbine will not be misleading, it should be emphasized that this turbine could not be tested under conditions indicative of current aircraft turbine engine operation because of imposed rig limitations. Although design conditions for the aluminum turbine are severe, the rate of gas-to-blade heat transfer is approximately two-thirds as great as that which occurs at the design conditions for a current aircraft turbine. Calculations made at the design conditions of a current aircraft turbine, assuming the blades were made from aluminum and assuming a nominal water flow, indicated the maximum blade temperature would exceed 400° F. Because the tensile strength of aluminum decreases rapidly at temperatures above 400° F, this is the maximum temperature at which aluminum can be considered for such high-stress application. From these calculations the application of aluminum to a full-scale jet-engine turbine apparently is not feasible. However, these calculations of maximum turbine operating conditions illustrate another useful application of the analytical methods under investigation.

Water-cooled turbine design factors. - The possibility of steam formation inside the rotor is an important factor in the design of water-cooled turbines. It is shown in figure 9 that for a 0.05 coolant-to-gas flow ratio, runs were terminated at approximately a 950° F gas temperature. Operation of this turbine at these conditions resulted in a rotor coolant-discharge temperature near the boiling temperature of water. Turbine operation at this coolant-to-gas flow ratio and higher gas temperatures would have resulted in partial steam formation at the free surface of the coolant in the coolant reservoir and a pressure increase within the rotor. Rather than endanger the turbine rotor by the added stresses induced, further operation at a 0.05 coolant-to-gas flow ratio was curtailed. Although steam formation during turbine operation may not be undesirable on the basis of cooling because of the high latent heat of vaporization of water, steam formation may be undesirable with respect to rotor stress because of possible pressure buildups. The latter possibility should be considered in design-stress calculations.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the application of analytical methods to the calculation of water-cooled blade temperatures:

1. Comparisons of calculated and experimental turbine and stationary-blade temperatures provided additional verification of analytical temperature calculation methods when experimentally substantiated heat-transfer coefficient analysis methods were used.

2. Calculated average turbine blade-midspan temperatures were compared with average midspan experimental temperatures and the results lie close to and on both sides of a 1:1 correlation line over the entire range investigated. The maximum deviation was 25° F over an experimental temperature range from 105° to 299° F.

3. Average blade temperatures calculated for the blade tip and blade root were compared with a specific temperature obtained experimentally at each of these blade positions. Generally good agreement was obtained at the blade root; at the blade tip, calculated values were generally higher than experimental values and the variation increased with increasing blade temperature.

4. Specific turbine-blade temperatures were calculated for the trailing and leading edges. Comparison with specific experimental values resulted in good agreement at the trailing edge, and the results lie close to and on both sides of a 1:1 correlation line. At the leading edge, calculated temperatures were higher than experimental values and the degree of variation increased with increasing blade temperature.

5. The maximum allowable turbine-inlet-gas temperatures computed for the forced-convection, water-cooled aluminum turbine for coolant-to-gas flow ratios from 0.05 to 0.40 and a nominal design gas mass flow of 2.0 pounds per second (turbine-inlet-gas mass velocity of 12 lb/(sec)(sq ft)) resulted in values ranging from 1800° to 2400° F, respectively.

6. Stationary water-cooled-blade trailing-edge temperature calculations showed equally good agreement with experimental values for the section with a high-conductivity-material insert as well as for the section without the insert. In both cases the calculated values were approximately 15° F below the experimental values over the investigated temperature ranges that extended from 85° to 182° F for the section with copper insert and from 116° to 272° F for the section without a copper insert.

7. Insertion of a high-conductivity material (copper) in the trailing edge provided an effective method for reducing the trailing-edge temperature of a water-cooled blade of low-conductivity material (stainless steel). Over the range of conditions investigated, a reduction of more than 50 percent was obtained in the coolant flow required to maintain a given trailing-edge temperature. Calculations indicated a possible reduction of 375° F in the stationary-blade trailing-edge temperature

with a nominal coolant flow at the design conditions of a current aircraft turbine.

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APPENDIX - SYMBOLS

The following symbols are used in this report:

A	area normal to radial heat conduction path in blade, sq ft
a	$(H_o l_o / k_B A_1)^{\frac{1}{2}}$, ft^{-1}
C_1 to C_4	constants
c_p	specific heat of gas at constant pressure unless otherwise indicated by subscripts, Btu/(lb)(^{o}F)
D	hydraulic diameter of coolant passage in stationary blade, ft
$\overline{F}_{lam}$	variable, evaluated in figure 8, reference 2
g	acceleration due to gravity, (ft/sec^2), or ratio of absolute to gravitational unit of mass, (lb/slug)
H	heat-transfer coefficient, Btu/(^{o}F)(sq ft)(sec)
J	mechanical equivalent of heat, 778.3 (ft-lb)/Btu
J_o, iJ_1	Bessel functions
j	chordwise distance from blade trailing or leading edge to coolant passage, ft
K	$\left(\frac{H_o}{k_B \sin\psi}\right)^{\frac{1}{2}}$, ft$^{-\frac{1}{2}}$
k	thermal conductivity of gas unless otherwise indicated by subscripts, Btu/(^{o}F)(ft)(sec)
l	perimeter, ft
Nu_l	blade-to-coolant Nusselt number, $\frac{H_l D}{k_l}$, (thermal conductivity evaluated at average coolant temperature)
Nu_o	gas-to-blade Nusselt number, $\frac{H_{o,v} v}{k_w}$
Pr_g	Prandtl number of gas, $\frac{c_{p,w} \mu_w g}{k_w}$

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Pr_l	Prandtl number of coolant, $\frac{c_{p,l}\mu_l g}{k_l}$, (properties evaluated at average coolant temperature)
Re_g	gas-flow Reynolds number, $\frac{\rho_w W_v v}{\mu_w}$
Re_l	coolant-flow Reynolds number, $\frac{\rho_l W_l D}{\mu_l}$, (properties evaluated at average coolant temperature)
T	temperature, or gas static temperature, °F
$T_{B,p}$	$(H_o l_o T_{g,e} + H_i l_i T_l)/(H_o l_o + H_i l_i)$, °F
t	average thickness of material, ft
v	peripheral distance measured from leading edge, ft
W	gas velocity relative to blade unless otherwise indicated by subscripts, ft/sec
W_v	gas velocity relative to blade at edge of boundary layer and at local position v, ft/sec
x	radial distance along blade span defined in figure 3, or spanwise distance from blade tip to blade element, ft
y	chordwise distance from trailing or leading edge to blade element, ft
z	distance from median plane of section to blade element, ft
$\mathscr{K}_{m,n}, \mathscr{L}_n, \mathscr{M}_{m,n}, \mathscr{N}_m, \mathscr{O}_{m,n}, \mathscr{P}_{m,n}, \mathscr{Q}_n$	integration constants defined by equations 13 to 18, reference 4
α	$\left[(H_o l_o + H_i l_i)/(k_B A_2)\right]^{\frac{1}{2}}$, ft^{-1}
ζ	$2K\left[y' + \frac{\tau_4(1 - \tan\psi)}{2\tan\psi}\right]^{\frac{1}{2}}$
ζ_2	$2K\left[j' + \frac{\tau_4(1 - \tan\psi)}{2\tan\psi}\right]^{\frac{1}{2}}$

Λ recovery factor

μ absolute viscosity of gas unless otherwise indicated by subscripts, slugs/(ft)(sec) or (lb)(sec)/sq ft

ρ mass density of gas unless otherwise indicated by subscripts, slugs/cu ft

τ thickness of trailing- or leading-edge section, ft 2554

Φ $(2H_o/k_B\tau)^{\frac{1}{2}}$, ft^{-1}

ψ $\tan^{-1} \dfrac{\tau_5 - \tau_4}{2j}$

Subscripts:

1,2,3 rotor sections illustrated in figure 3

4 evaluated at trailing or leading edge

5 evaluated at coolant passage

av average

B blade

c copper

e effective

exp experimental

g gas

i inside blade surface

l coolant, or average coolant when used with temperature

o outside blade surface

P evaluated by equation for rectangular parallelepiped, (equation 7)

p prevalent (see symbol $T_{B,p}$ for definition)

R evaluated by equation for rectangle, (equation 9)

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r	blade root
s	stainless steel
TE	trailing edge
v	at local position v
W	evaluated by equation for wedge, (equation 8)
w	evaluated at wall temperature

Superscript:

prime	linear dimension increased by $\tau_4/2$

REFERENCES

1. Freche, John C., and Schum, Eugene F.: Determination of Gas-to-Blade Convection Heat-Transfer Coefficients on a Forced-Convection Water-Cooled Single-Stage Aluminum Turbine. NACA RM E50J23, 1951.

2. Brown, W. Byron, and Donoughe, Patrick L.: Extension of Boundary-Layer Heat-Transfer Theory to Cooled Turbine Blades. NACA RM E50F02, 1950. 2554

3. Freche, John C., and Schum, Eugene F.: Determination of Blade-to-Coolant Heat-Transfer Coefficients on a Forced-Convection, Water-Cooled, Single-Stage Turbine. NACA RM E51E18, 1951.

4. Livingood, John N. B., and Brown, W. Byron: Analysis of Temperature Distribution in Liquid-Cooled Turbine Blades. NACA TN 2321, 1951.

5. Ellerbrock, Herman H., Jr., Zalabak, Charles F., and Smith, Gordon T.: Experimental Investigation of Air-Cooled Turbine Blades in Turbojet Engine. IV - Effects of Special Leading- and Trailing-Edge Modifications on Blade Temperature. NACA RM E51A19, 1951.

6. Diaguila, Anthony J., and Freche, John C.: Blade-to-Coolant Heat-Transfer Results and Operating Data from a Natural-Convection Water-Cooled Single-Stage Turbine. NACA RM E51I17, 1951.

7. Freche, John C., and Diaguila, A. J.: Heat-Transfer and Operating Characteristics of Aluminum Forced-Convection and Stainless-Steel Natural-Convection Water-Cooled Single Stage Turbines. NACA RM E50D03a, 1950.

8. Hubbartt, James E., and Schum, Eugene F.: Average Outside-Surface Heat-Transfer Coefficients and Velocity Distributions for Heated and Cooled Impulse Turbine Blades in Static Cascades. NACA RM E50L20, 1951.

9. McAdams, William H.: Heat Transmission. McGraw-Hill Book Co., Inc., 2d ed., 1942, p. 168.

10. Ellerbrock, Herman H. Jr., and Schafer, Louis J., Jr.: Application of Blade Cooling to Gas Turbines. NACA RM E50A04, 1950.

11. Freche, John C.: A summary of Design Information for Water-Cooled Turbines. NACA RM E51A03, 1951.

TABLE I. - RANGE OF OPERATING CONDITIONS FOR TURBINE AND STATIONARY BLADE

Investigation	Objective	Inlet-gas temperature (°F)	Turbine speed (rpm)	Gas mass velocity lb/(sec)(sq ft)	Coolant mass velocity lb/(sec)(sq ft)
Forced-convection water-cooled turbine	Blade temperature calculations	400 - 1600	3400 - 15,500	7.2 - 17.4	24 - 280
	Maximum allowable gas-temperature operation	400 - 1600	7000 - 15,500	12.0	27 - 216
Stationary water-cooled blade	Temperature calculation and insert-effectiveness determination	400 - 900	--------------	3.8	485 - 1080

TABLE II. - PHYSICAL CONSTANTS USED IN CALCULATION OF TURBINE-BLADE TEMPERATURES

Chordwise blade-surface perimeter, ft	0.1662
Blade cross-sectional area[a], A_1, sq ft/blade	0.001128
Blade cross-sectional area[a], A_2, sq ft/blade	0.000980
Disk rim cross-sectional area[a], A_3, sq ft/blade	0.004040
Distance from blade tip to top of coolant passages[a], x_1, ft	0.00833
Distance from top of coolant passages to blade-root[a], x_2, ft	0.0880
Thickness of rim section[a], x_3, ft	0.0433
Coolant passage surface area inside blade, sq ft/blade.	0.00799
Passage length used in Graetz number, ft	0.0880
Diameter of large coolant passages, ft	0.00825
Diameter of small coolant passages, ft	0.00517
Hydraulic diameter of coolant passages, ft	0.00709
Thermal conductivity of aluminum, Btu/(sec)(ft)(°F)	0.0292

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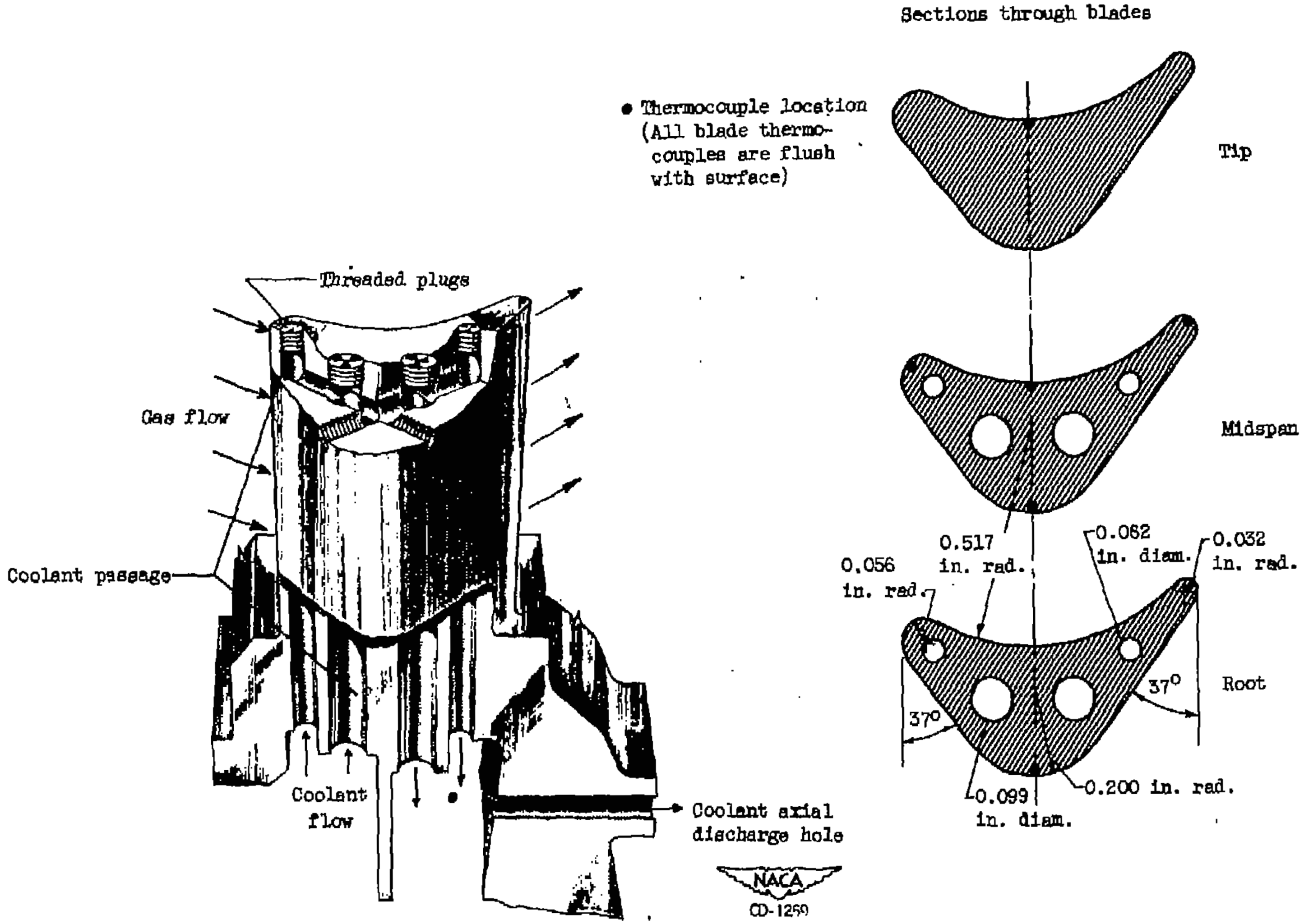
[a]See figure 3.

TABLE III. - PHYSICAL CONSTANTS USED IN CALCULATION OF STATIONARY WATER-COOLED BLADE TEMPERATURES

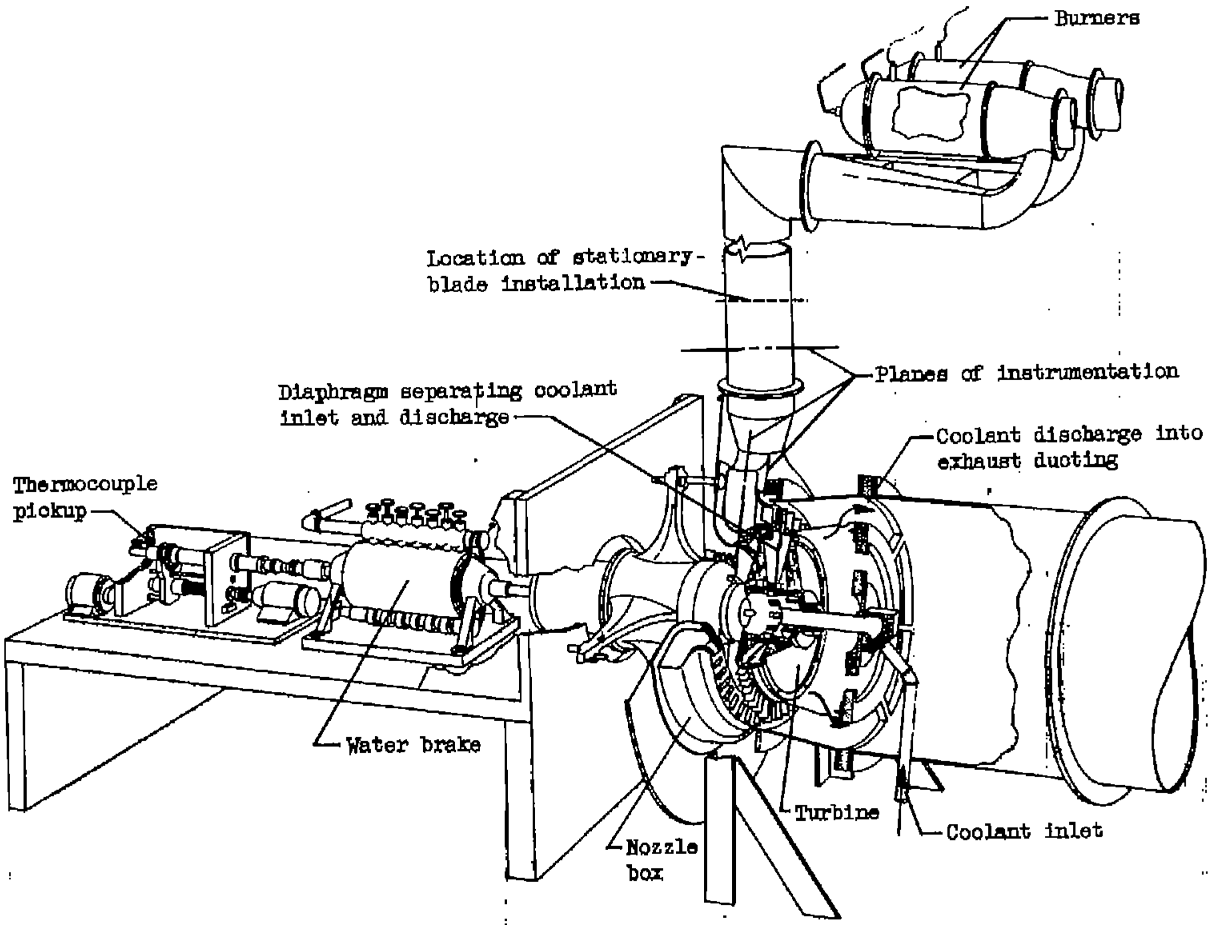
Perimeter of blade[a], ft	0.1628
Span of blade[a], ft	0.2083
Diameter of coolant passage[a], ft	0.0058
Chordwise length of copper insert in trailing-edge section[a], ft	0.0200
Constant thickness of copper insert in trailing-edge section[a], ft	0.0027
Radius of blade leading edge[a], ft	0.0069
Radius of blade trailing edge[a], ft	0.0025
Thermal conductivity of stainless steel, Btu/(sec)(ft)(°F). . .	0.00444
Weighted average thermal conductivity of trailing-edge section with copper insert, Btu/(sec)(ft)(°F)	0.0221

[a]See figure 2.



(a) Cutaway section of rotor showing coolant-passage arrangement and instrumentation.

Figure 1. - Forced-convection, water-cooled aluminum turbine.



(b) Sectional view of installation.

Figure 1. - Concluded. Forced-convection, water-cooled aluminum turbine.

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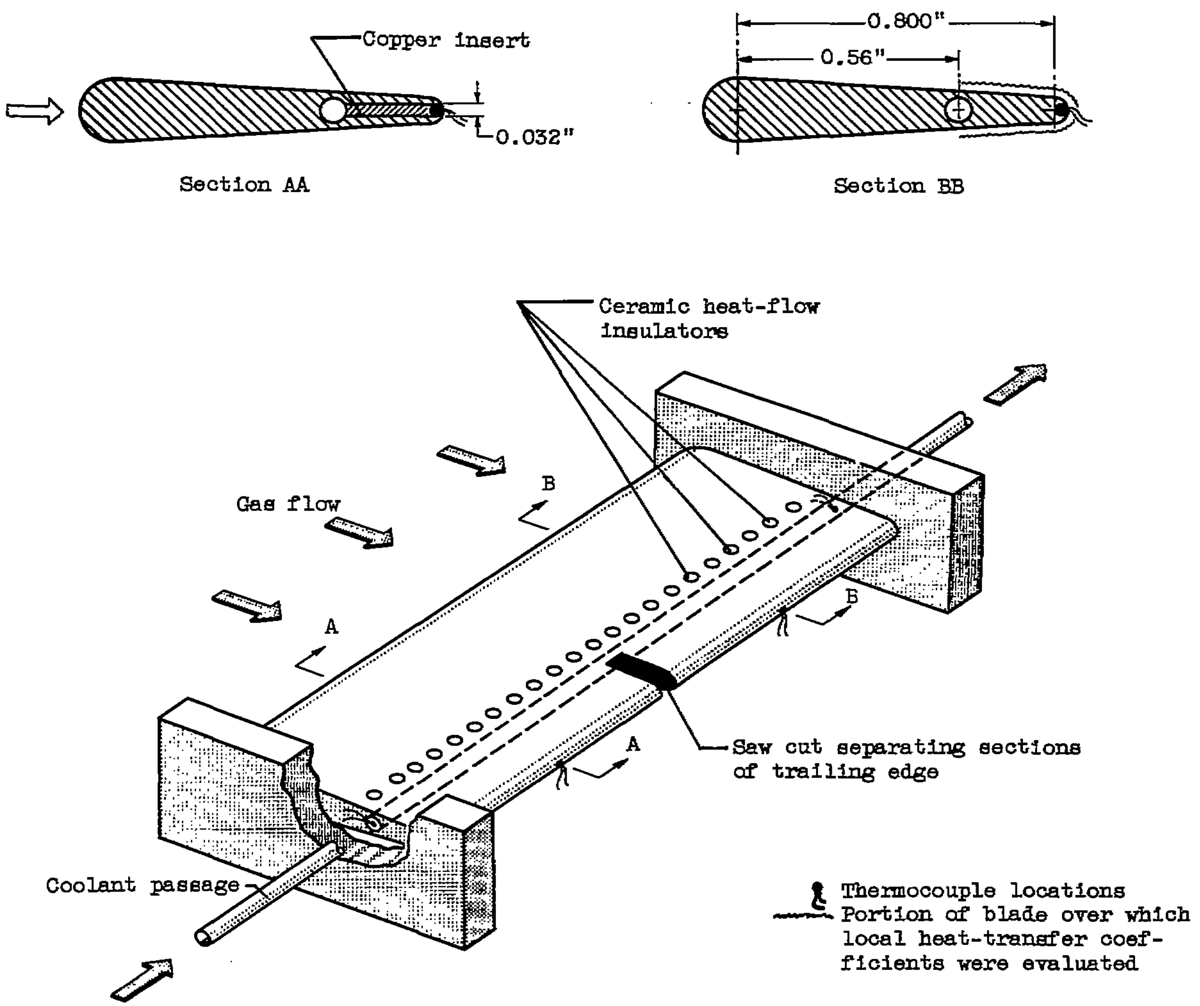
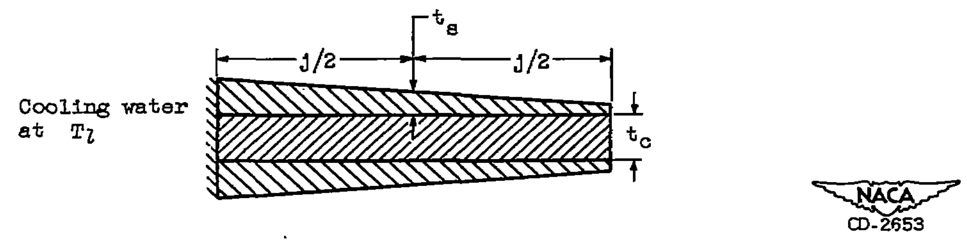


(a) Sectional view of stationary blade.



(b) Approximation of stationary-blade trailing-edge section with copper insert.

Figure 2. - Stationary, stainless-steel, water-cooled blade with high-conductivity (copper) trailing-edge insert.

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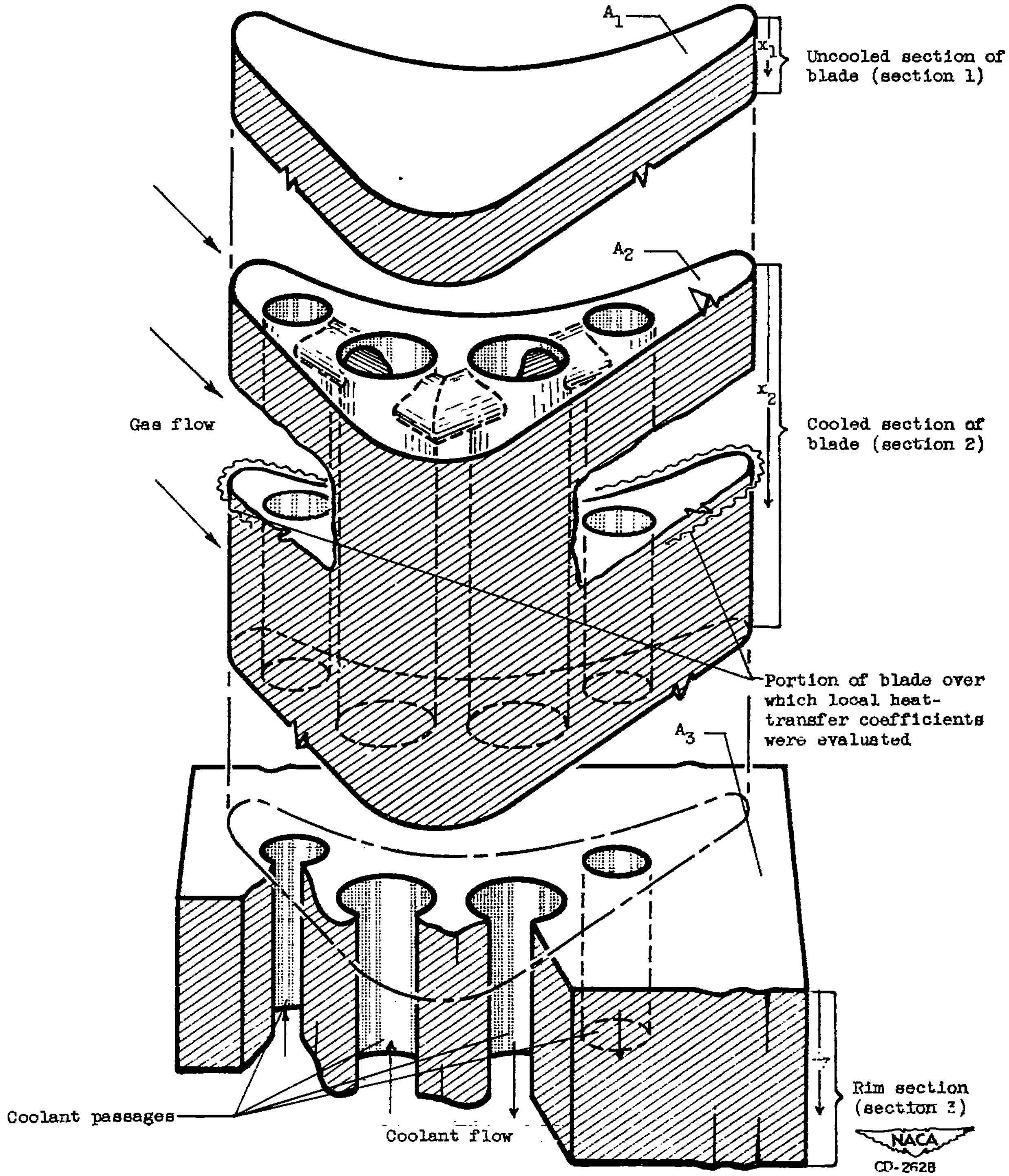

Figure 3. - Exploded view of the forced-convection, water-cooled aluminum turbine showing sectional arrangement used in blade-temperature calculations.

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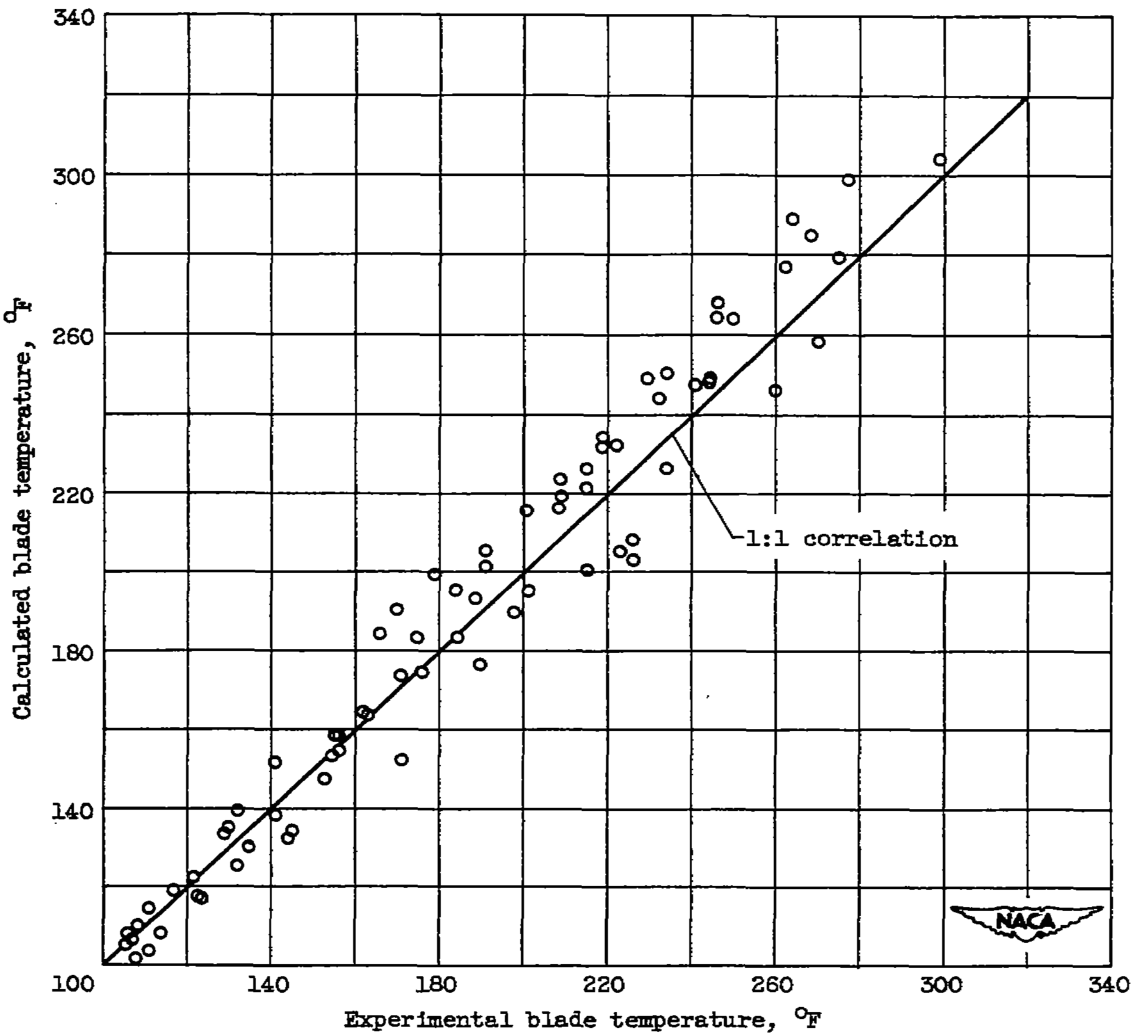

Figure 4. - Comparison of calculated and experimental average blade-midspan temperatures for forced-convection, water-cooled aluminum turbine. Used in calculations were blade-to-coolant heat-transfer coefficients from stationary-tube heated-liquid data (reference 3) and average gas-to-blade heat-transfer coefficients calculated by methods of reference 2.

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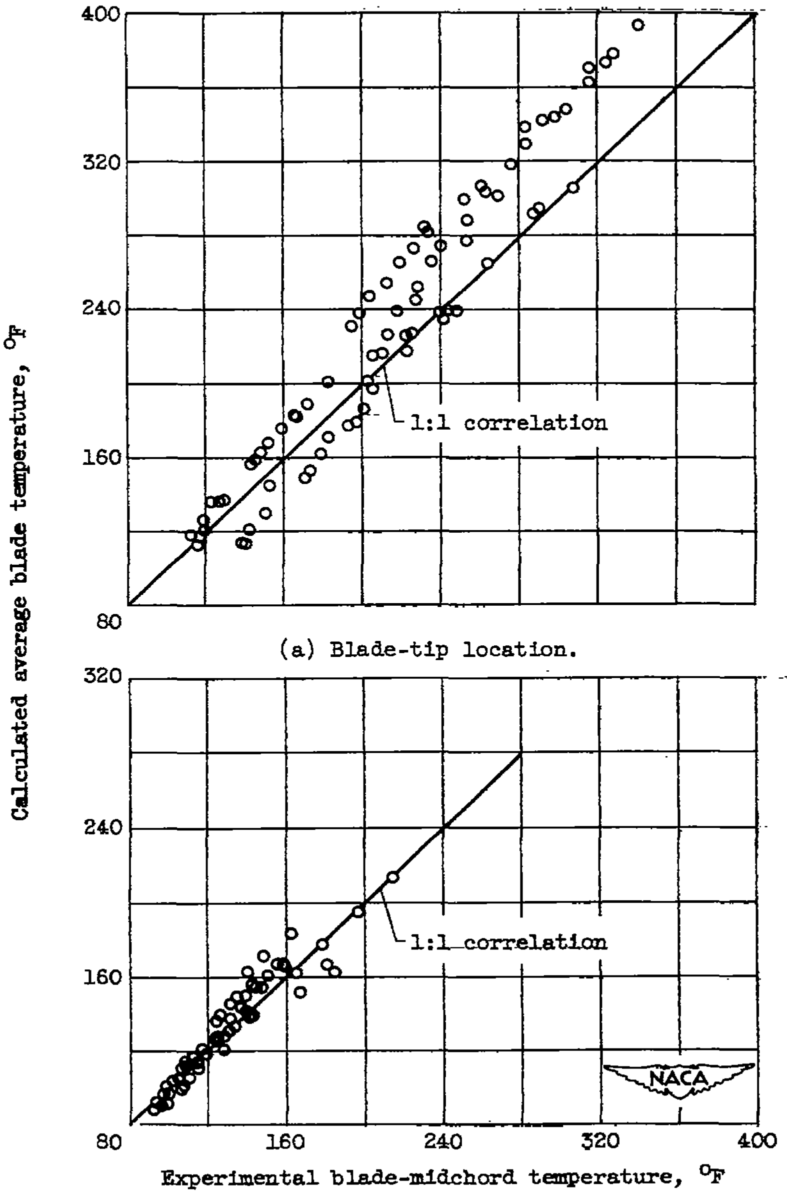
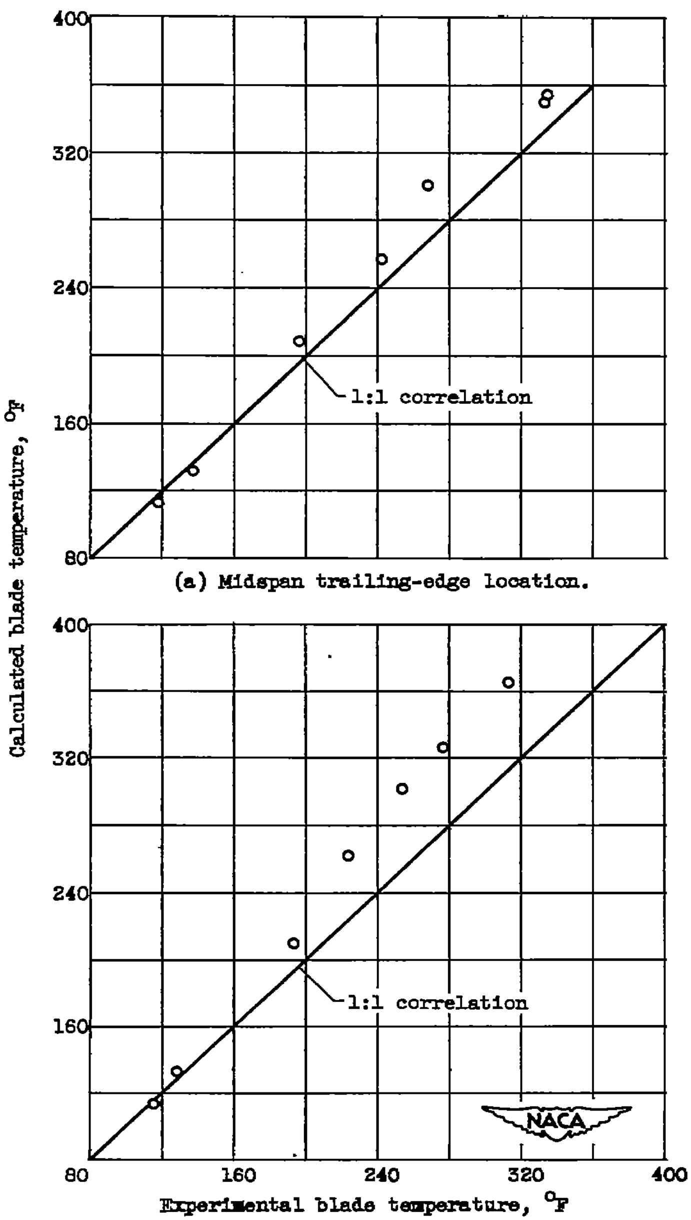


(b) Blade-root location.

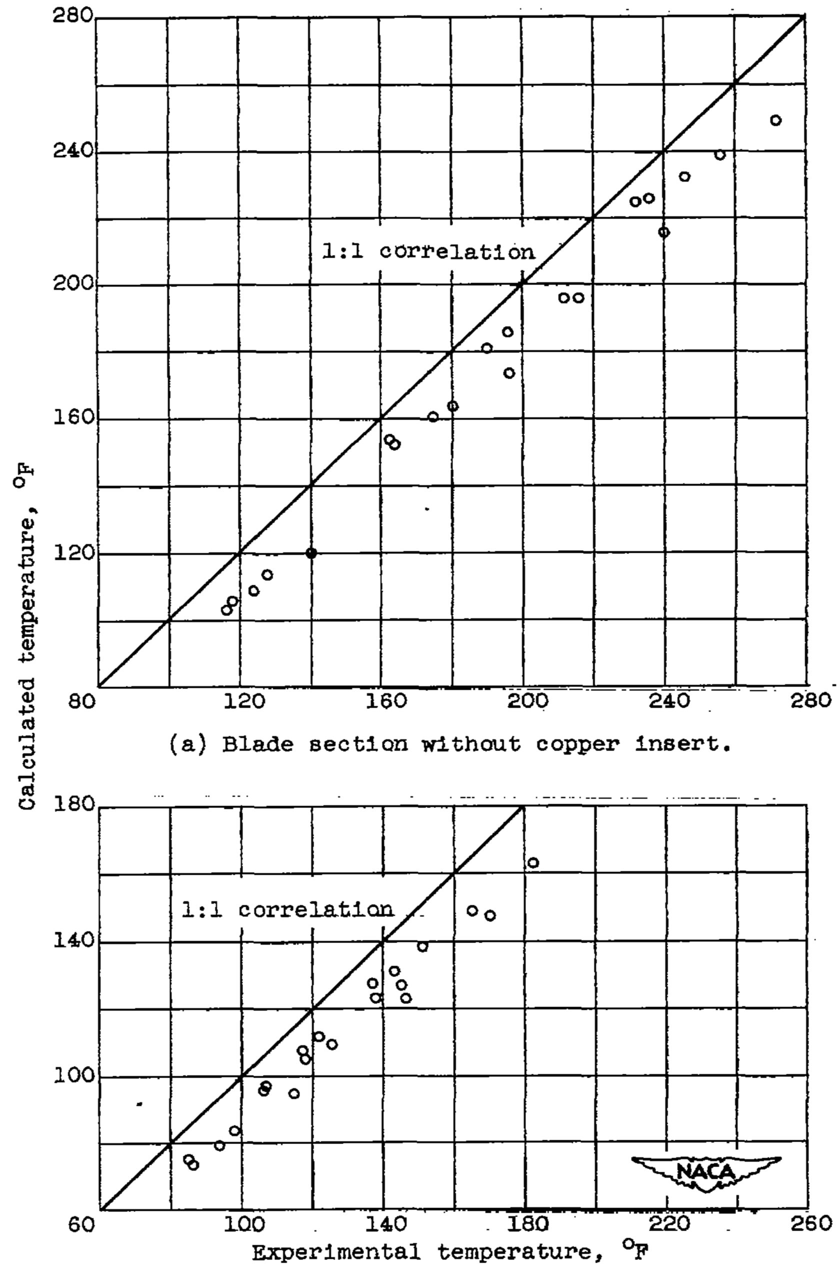
Figure 5. - Comparison of calculated average blade-tip and average blade-root temperatures with a specific experimental blade temperature measured at midchord location at each of these stations on forced-convection, water-cooled aluminum turbine. Used in calculations were blade-to-coolant heat-transfer coefficients from stationary-tube heated-liquid data (reference 3) and average gas-to-blade heat-transfer coefficients calculated by methods of reference 2.



(a) Midspan trailing-edge location.

(b) Midspan leading-edge location.

Figure 6. - Comparison of specific calculated midspan trailing and leading edge temperatures with experimental data obtained at these locations from forced-convection, water-cooled aluminum turbine. Used in calculations were blade-to-coolant heat-transfer coefficients from stationary-tube heated-liquid data (reference 3) and local gas-to-blade heat-transfer coefficients calculated by the methods of reference 2.



(a) Blade section without copper insert.

(b) Blade section with copper insert.

Figure 7. - Comparison of calculated with experimental trailing-edge temperatures for the stationary, stainless-steel, water-cooled blade. Used in calculations were blade-to-coolant heat-transfer coefficients from stationary-tube heated-liquid data (reference 3) and local gas-to-blade heat-transfer coefficients calculated by the methods of reference 2.

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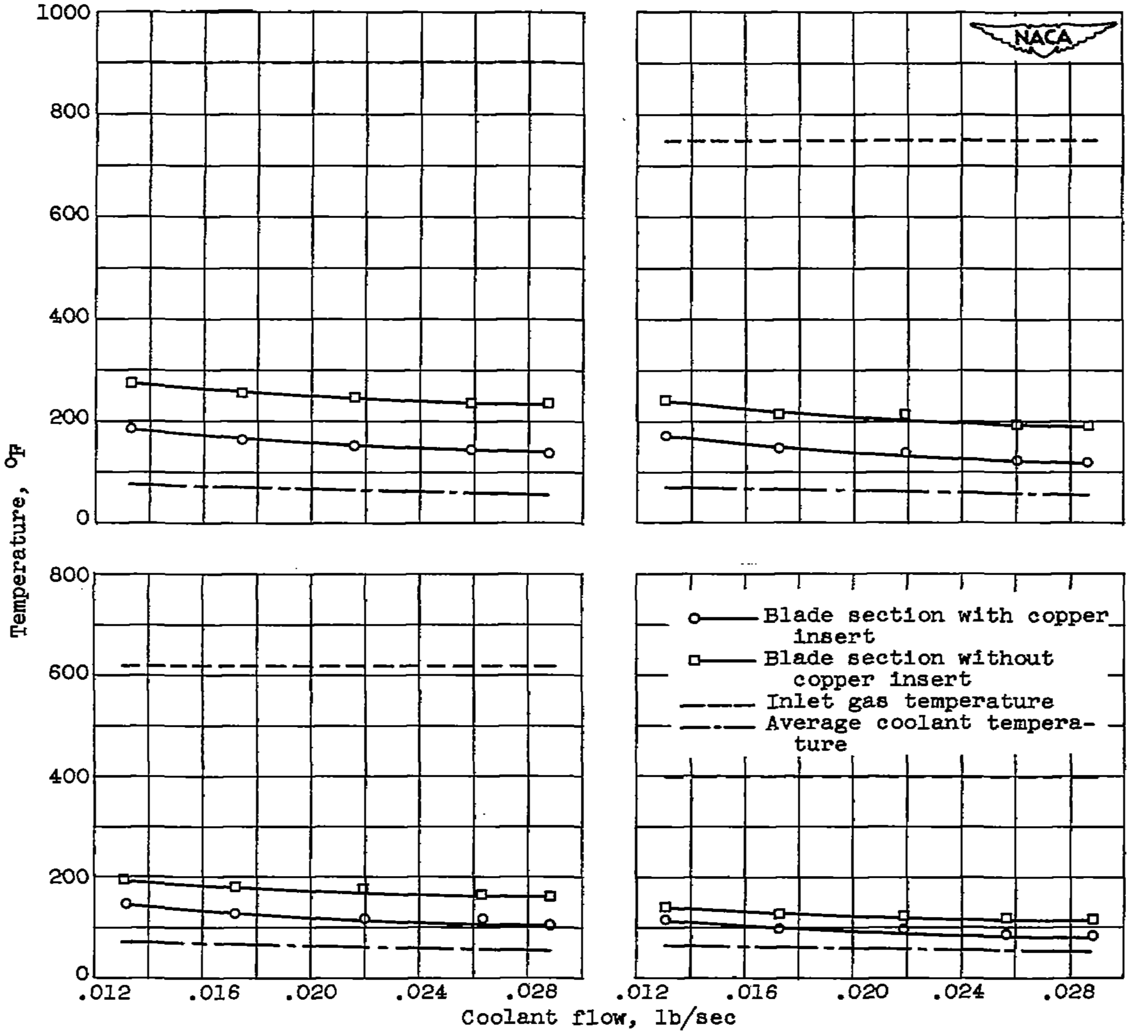

Figure 8. - Effect of high-conductivity insert on the trailing-edge temperature of a stationary, stainless-steel, water-cooled blade. Inlet-gas temperatures that ranged from 400° to 900° F at a constant test-section gas mass velocity of 3.8 pounds per second - square foot and the average coolant temperatures are shown.

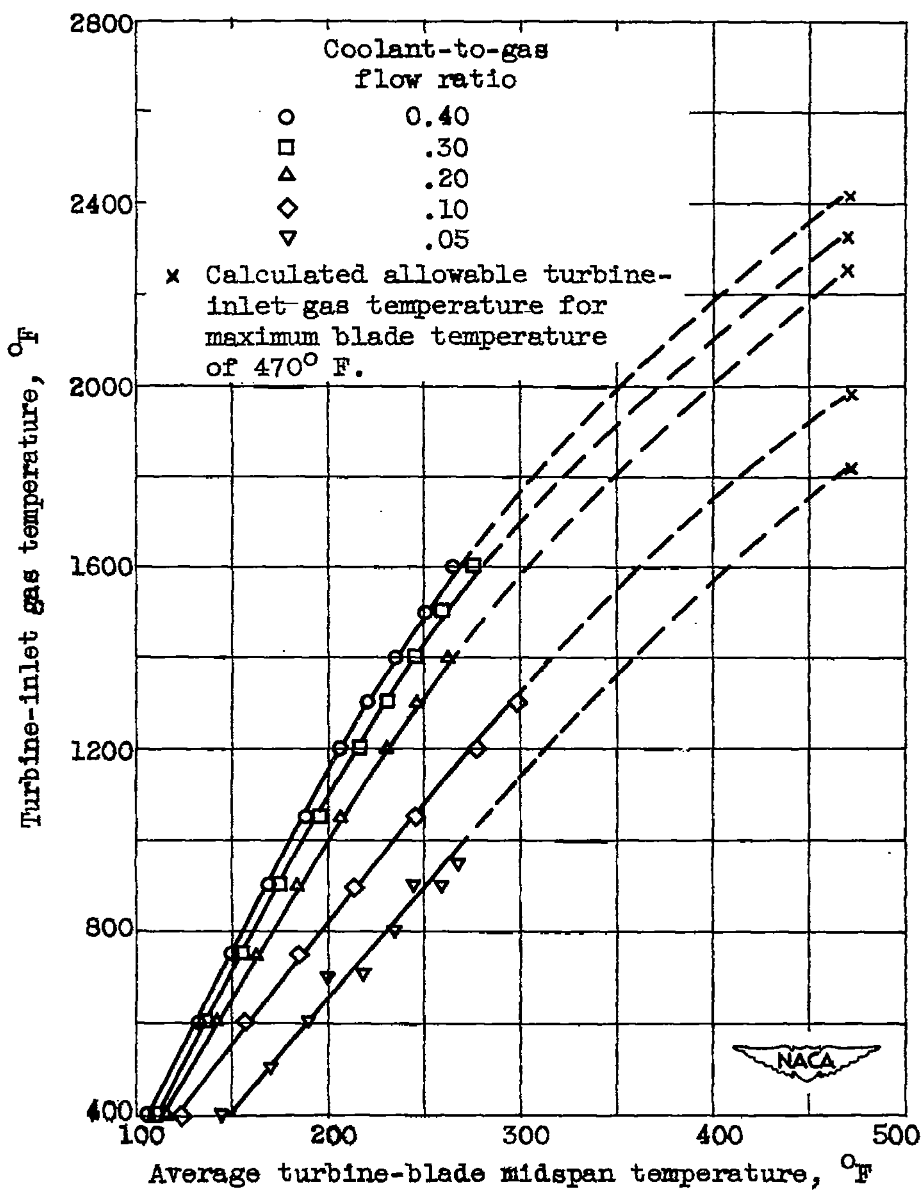

Figure 9. - Effect of coolant flow on average blade-midspan temperature of the forced-convection, water-cooled aluminum turbine. Gas temperatures ranged from 400° to 1600° F at a constant turbine-inlet gas mass velocity of 12 pounds per second - square foot. Curves are extrapolated to calculated maximum turbine-inlet gas temperature.

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