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RESEARCH MEMORANDUM

DETERMINATION AND USE OF THE LOCAL RECOVERY FACTOR

FOR CALCULATING THE EFFECTIVE GAS TEMPERATURE

FOR TURBINE BLADES

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NATIONAL ADVISORY COMMITTEE
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DETERMINATION AND USE OF THE LOCAL RECOVERY FACTOR FOR CALCULATING THE EFFECTIVE GAS TEMPERATURE FOR TURBINE BLADES

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SUMMARY

An investigation was conducted to determine local recovery factors for a Lucite blade having a velocity distribution about it similar to that of a typical reaction-type gas-turbine blade for subsonic flow. Local recovery-factor data were previously available on simple geometric shapes such as axial probes, cylinders, and the inside of tubes; but little was known concerning the effects of blade configuration, pressure gradients, and Reynolds number on local values of recovery factor for gas-turbine blades.

The local recovery factors were essentially independent of Mach number, Reynolds number, pressure gradient, and position on the blade except for regions where the boundary-layer flow was probably in the transition range from laminar to turbulent. The recovery factors obtained were somewhat higher than indicated by theory for turbulent boundary-layer flow but were within the range of values obtained by other investigators on bodies of various shapes.

Variations in the value of the recovery factor and errors in the calculated Mach number distribution around turbine blades result in small error in the calculation of the effective gas temperature; the greatest uncertainty is in the determination of the total temperature of the gas relative to the turbine blade. It is believed that further research on recovery factors for subsonic flow over gas-turbine blades is unnecessary.

INTRODUCTION

Eckert and Drewitz (reference 1) demonstrated in 1940 that the fluid temperature affecting heat transfer to a body in a high-velocity gas stream was the adiabatic body temperature, which is the temperature a body in the stream would assume at steady-state conditions in the absence of heat transfer. Pohlhausen had previously derived an expression in 1921 for the adiabatic wall temperature of a thin flat plate with no pressure gradient in a high-velocity gas stream for the case where the boundary layer is laminar (reference 2). This expression related the adiabatic wall temperature to the total and static stream temperatures by a temperature-difference ratio, which he found to be a function of the Prandtl number. The same temperature-difference ratio used by Pohlhausen to define the recovery factor of a body can also be used to determine the effective fluid temperature that Eckert and Drewitz found to be necessary for heat-transfer calculations where the same heat-transfer-coefficient equation can be used for both high- and low-velocity streams. If some fluid temperature other than the effective fluid temperature were used in the heat-transfer calculations for high-velocity fluid flow, the heat-transfer coefficient may take on values that are negative, zero, or infinite when the stream temperature approaches the wall temperature as explained in reference 3.

Local and average recovery factors for bodies of various geometric shapes have been determined by a number of investigators. A survey of the literature on recovery factors (reference 4) presents values of the average recovery factor for flat plates, wedges, cones, and cylinders. Average recovery factors for turbine blades are presented by Eckert and Weise in reference 5. Generally the values of average recovery factors obtained were in the range from 0.70 to 0.95; however, the values of the average recovery factor for cylinders are in some cases lower. Local recovery factors have been obtained for the trailing edge of a reaction-type turbine blade (reference 5), cylinders (reference 6), cylindrical axial probes (references 7 and 8), and inside tubes (reference 3). The values of the local recovery factor also lie in the range from 0.70 to 0.95.

Eckert and Weise (reference 7) have shown, in experiments conducted with an axial probe, an increase in the recovery factor from 0.84 to about 0.89 as the Reynolds number was increased from about 5×10^5 to about 16×10^5 because of transition from laminar to turbulent boundary-layer flow. This trend has been substantiated by analyses. For laminar boundary-layer flow, the analysis of Pohlhausen (reference 2) shows the recovery factor to be approximately equal to the square root of the Prandtl number for fluid Prandtl numbers less than 10. In air at 80° F, the laminar boundary-layer recovery factor would therefore be about 0.84. A recent theoretical analysis presented in reference 9 resulted in a calculated turbulent boundary-layer recovery factor of approximately 0.88 for subsonic flow of air at a temperature of about 80° F.

Because most previous investigations have been conducted on simple geometric shapes and no information was available on the local recovery-factor variation around gas-turbine blades, where there is a relatively high pressure gradient, an investigation was conducted at the NACA Lewis laboratory to determine local recovery factors around the periphery of a symmetrical blade with a pressure gradient typical of that for a reaction-type turbine blade. For gas-turbine application, the fluid stream is a gas with a Prandtl number very nearly equal to that of air and the velocities of the stream relative to the turbine and nozzle blades are subsonic or low supersonic; consequently, the investigation was limited to subsonic flows with air as the working fluid. Local recovery factors were obtained for a range of local Mach numbers from 0.3 to 1.0 and over a range of local Reynolds numbers from about 10^5 to 3×10^6. The total air temperature during the investigation varied from about 70° to 80° F.

SYMBOLS

The following symbols are used in this report:

A	area, (sq ft)
Eu	Euler number, $-\frac{dp}{dx}\frac{x}{\rho V^2}$
H	heat-transfer coefficient, Btu/(sec)(sq ft)($^\circ$F)
l	chordwise length of blade, (ft)
M	local Mach number
p	local static pressure, (lb/sq ft)
p'	total pressure, (lb/sq ft)
Pr	Prandtl number
Q	heat-transfer rate, Btu/(sec)
R	gas constant, (ft-lb/(lb)($^\circ$R))
T	static temperature, ($^\circ$R)
T'	total temperature, ($^\circ$R)
$T_{ad,w}$	local adiabatic wall temperature, ($^\circ$R)
T_e	local effective gas temperature, ($^\circ$R)
T_w	local wall temperature, ($^\circ$R)

V	local gas velocity, (ft/sec)
v	specific volume, (cu ft/lb)
x	distance from stagnation point, (ft)
γ	ratio of specific heats
Λ	local recovery factor
ρ	density, (slugs/cu ft)

STATEMENT OF PROBLEM

The recovery factor is defined as the ratio of the excess of the adiabatic wall temperature over the static stream temperature to the excess of the stagnation, or total, temperature over the static stream temperature for a gas having the equation of state $pv = RT$; that is,

$$\Lambda = \frac{T_{ad,w} - T}{T' - T} \tag{1}$$

Because the effective gas temperature is taken as the adiabatic wall temperature, equation (1) can be written

$$\Lambda = \frac{T_e - T}{T' - T} \tag{2}$$

In general, the static stream temperature cannot be measured directly, but it is calculated from measurements of the total temperature and total and static pressures. By use of the isentropic temperature and pressure relations, the expression for recovery factor can be written

$$\Lambda = 1 - \frac{T' - T_e}{T'\left[1 - \left(\frac{p}{p'}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{3}$$

In order to determine the effective gas temperature from known values of total and static pressures, the total temperature, and the recovery factor, equation (3) can be solved for the effective gas temperature:

$$T_e = T'\left\{1 - (1-\Lambda)\left[1 - \left(\frac{p}{p'}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\} \tag{4}$$

Equation (4) can also be written to give the effective gas temperature as a function of the Mach number for a perfect gas

$$T_e = T'\left\{1 - (1-\Lambda)\left[1 - \frac{1}{1 + \frac{\gamma-1}{2}M^2}\right]\right\} \tag{5}$$

Local recovery factors are determined experimentally from local measurements of temperatures and pressures. In many cases, however, an average recovery factor is determined where an average adiabatic temperature is measured and the static temperature may or may not correspond to the average conditions around the body. For example, average recovery factors that are determined for cylinders, cones, and wedges are usually based on an undisturbed free-stream static temperature. Because there is a relation between the local static temperatures at these surfaces and the free-stream static temperature, these recovery factors are applicable to other cylinders, cones, and wedges. Conversely for turbine blades, the relation between the local static temperature at some point on the blade surface and the undisturbed static stream temperature at the inlet or outlet of the blade row is usually complex and is different for every blade profile, angle of attack, and angle of stagger so that a recovery factor based on an inlet or outlet static temperature is applicable only to the turbine-blade arrangement investigated. Another average recovery factor that is sometimes determined and is of more general value for turbine blades is one based on an average static gas temperature and an average adiabatic blade temperature for the blade periphery. The average gas temperature can be determined from static-pressure measurements around the blade periphery. In this report, however, only local recovery factors will be considered for turbine blades.

APPARATUS AND INSTRUMENTATION

Local recovery factors were determined on a symmetrical Lucite blade with a pressure gradient approximating that of a reaction-type turbine blade. The recovery factor of a thermocouple probe was also determined to investigate the effects of air moisture content on the determination of the recovery factors obtained from the Lucite blade at the higher Mach numbers.

Lucite Blade

A symmetrical Lucite blade having a 6-inch chord and a 6-inch span was mounted in a tunnel with contoured walls to provide a pressure distribution similar to that for a typical reaction-type turbine blade.

The tunnel, as shown by the sketch in figure 1, was one previously designed for a liquid-cooling investigation. Three vanes were inserted in the diffuser downstream of the blade to improve the pressure recovery by effectively decreasing the cone angle of the diffuser. For this investigation, the liquid-cooled blade shown in the tunnel was removed and a Lucite blade (fig. 2) was installed. The blade conformed to a NACA 66_4-021 airfoil for the first quarter chord and the remainder of the blade was formed by an arc of 8.65-inch radius with a 0.030-inch radius at the trailing edge.

Lucite was chosen as the material for the blade primarily because of its extremely low thermal conductivity and secondarily because of the ease of its fabrication and its transparency so that location of thermocouples and pressure orifices could be determined easily. The thermal conductivity of Lucite is given as ranging from 0.1 to 0.14 (Btu/(ft)(hr)($^{\circ}$F)) by the manufacturer. This is an important characteristic for recovery-factor determination because heat conduction within the blade should be an absolute minimum in order to obtain true local adiabatic temperatures. In order to further minimize heat conduction, air spaces were provided within the blade by drilled holes and saw cuts in the blade interior as shown by figure 2.

Air for the recovery-factor tests was drawn from the room through a surge tank, a bellmouth, the test section, and then into the laboratory altitude-exhaust system.

A total of 23 iron-constantan thermocouples was installed in the blade to measure local temperatures for recovery-factor determination and to determine if any temperature gradients existed in a spanwise direction. The blade thermocouples were all connected differentially with a thermocouple that read total temperature in a large surge chamber. The temperatures and temperature differences were measured with a potentiometer with a sensibility of 0.002 millivolts.

Static-pressure orifices (13) were located around the periphery of the blade to measure local static pressures at the same chordwise locations as the blade thermocouples. The total pressure in the surge chamber upstream of the test section was read on a mercury manometer and all the pressure differences between the total pressure and the local static pressures on the blade periphery were measured with water manometers connected differentially.

Thermocouple Probe for Humidity Investigation

A thermocouple probe (fig. 3) was used to determine the effect of air humidity on the determination of recovery factors. The apparatus and instrumentation for this investigation are described in reference 10.

PROCEDURE

Lucite Blade Investigation

The investigation of the Lucite blade to determine local recovery factors was conducted using air drawn from the test cell. In this way it was possible to maintain the total temperature and pressure as well as the total flow rate at constant values. In addition, the blade temperature was very near the temperature of the room so that heat losses were minimized.

It is shown in the section "Effective-Gas-Temperature Determination" that for Mach numbers less than 0.3 the effective gas temperature is at least 99.5 percent of the total temperature, so that values of recovery factor at these low Mach numbers are of no practical use; consequently, thermocouple readings at locations on the blade where local Mach numbers were less than 0.3 were not used to calculate local recovery factors. At the leading and trailing edges of the blade, the velocities on opposite sides of the blade were greatly different. This difference caused variations in the adiabatic temperatures of the blade surfaces. The blade was thin in these regions and heat conduction could easily cause errors in the recovery-factor data; therefore, data from these regions were not used in the calculation of local recovery factors. For these reasons, only the six thermocouples in the locations shown in figure 2(b) were used in the local-recovery-factor determination. In order to eliminate the possibility of constant temperature-difference errors, the zero on the potentiometer was checked periodically at zero air flow. At this condition, the temperature differences between all blade thermocouples and the thermocouple reading total air temperature were zero.

Local Mach numbers were calculated from measurements of the total pressure in the surge chamber upstream of the test section and from the static-pressure measurements on the blade. The local recovery factor was calculated by use of equation (3) where $T' - T_e$ was taken as the differential temperature measurement between the total temperature in the surge chamber upstream of the blade and the local blade temperature. The total temperature and pressure of the air were assumed to remain constant throughout the test section.

In order to determine the possibility of boundary-layer transition from laminar to turbulent flow, it was necessary to evaluate the Euler number variation around the blade. The Euler number is defined as

$$Eu = -\frac{dp}{dx}\frac{x}{\rho V^2}$$

and was calculated using plots of the ratio of total pressure to local static pressure against the distance from the stagnation point to evaluate dp/dx. The density ρ was calculated from the measured local static pressure and the calculated local static temperature (from total- and static-pressure measurements and total-temperature measurement). The local velocity V was calculated from the local static temperature, the local static pressure, and the total pressure.

Humidity Investigation

If air used in the experimental determination of recovery factors has a relatively high moisture content, the static temperature of the air is reduced below the dew point at high Mach numbers and can possibly cause condensation of the moisture in the air. The air temperature would then be increased by the release of the heat of vaporization. If this condition occurs, the measured total temperatures and the calculated static temperatures are in error and therefore the calculated recovery factor would be in error.

A separate investigation was conducted on a thermocouple probe to determine if this effect occurs in the experimental determination of recovery factors. The investigation was conducted over a range of Mach numbers from 0.2 to 1.0 using air having two different dew points, namely 470.5° R, which is the static temperature that was obtained at a calculated Mach number of 0.822 for the inlet total-air temperature of 534° R in this investigation, and 415° R, which was below the static temperature at any of the Mach numbers investigated. The recovery factors were calculated in the same manner as explained for the Lucite blade.

ACCURACY CONSIDERATIONS

Recovery-Factor Determination

Recovery factors are usually determined experimentally at approximately ambient-air conditions in order to reduce conduction heat losses to a minimum. At these temperatures the differences between total, static, and effective temperatures are quite small, particularly for Mach numbers less than 0.3, so that extreme care is required in the temperature and pressure measurements in order to minimize errors in the recovery factor. The effects of errors in these measurements of the approximate magnitude encountered in this investigation are shown in figure 4 for the following assumed conditions: true recovery factor, 0.89; total pressure, 30 inches of mercury absolute; total temperature, 540° R. On figure 4 the maximum error in temperature measurement is assumed to be ±0.1° F and the maximum error in static-pressure measurement is ±0.1 inches of mercury. The effects of these small errors are almost negligible for Mach numbers greater than 0.45; however, at lower Mach numbers, these errors may cause large variations in the value of the calculated recovery factor, particularly if the errors are accumulative.

With proper instrumentation, temperatures can be read to within ±0.1° F without great difficulty; but if care is not used to guard against conduction within the body itself, the temperatures in the blade can be affected enough to cause large errors in the recovery-factor determination.

Effective-Gas-Temperature Determination

In calculating heat-transfer rate from the equation

$$Q = HA(T_e - T_w) \tag{6}$$

it can be seen that the magnitude of the temperature difference $T_e - T_w$ governs the required accuracy in determining the effective gas temperature T_e. For very small temperature differences, T_e will have to be determined accurately, whereas for larger temperature differences, such as those that will probably be obtained on cooled turbines, a greater tolerance in the accuracy of determining T_e would be acceptable.

From the nondimensional temperature plot in figure 5, the effect of Mach number on the recovery factor can be determined. For Mach numbers less than 1, the effective gas temperature will be at least 95 percent and probably more than 97.5 percent of the total temperature; for low Mach numbers, the value of the recovery factor has little effect on the calculated effective gas temperature, but at higher Mach numbers the effect is more pronounced. In the experimental determination of recovery factors, the recovery factors can be determined quite accurately at high Mach numbers, but the accuracy is considerably poorer at low Mach numbers. Because these effects are compensating, the over-all result is that little difficulty is experienced in calculating the effective gas temperature for Mach numbers in the subsonic range.

As mentioned previously, there is evidence that indicates a change in recovery factor as the boundary-layer flow changes from laminar to turbulent. It is probable that the recovery factor, for most bodies, will be in the range between 0.85 and 0.90 for subsonic flow whether the boundary layer is laminar or turbulent.

If the true recovery factor is 0.89 and a recovery factor of 0.85 is used for calculation instead, the maximum error at a Mach number of 1 will be 0.66 percent of the total temperature (fig. 5). At a relative total gas temperature of 1500° F (1960° R), 0.66 percent would amount to an error of less than 13° F which is probably smaller than the error that would be obtained in the total-temperature measurement of a high-velocity gas stream at this temperature.

Effect of Errors in Experimental Measurements

In order to determine the accuracy of the recovery factors obtained in this investigation, an analysis was made of the possible errors involved in the experimental measurements.

Errors in total-temperature measurement. - The total gas temperature was the only temperature that was measured absolutely. All other temperatures were measured differentially with this total temperature. The estimated accuracy of the total-temperature measurement was within ±2° R. Small errors in total-temperature measurement are of little importance so long as all other temperature measurements are based on the total temperature. For example, an error of 10° F in the measurement of the total temperature at 80° F would cause a maximum error of 0.2 percent in the recovery factor at Mach numbers from 0.3 to 1.0.

Errors in temperature-difference measurements. - Periodic checks at zero air flow were made to determine if the difference between the total temperature and the local adiabatic blade temperatures was zero. These checks eliminated the possibility of constant temperature-difference errors. In addition, such an error would cause a variation of recovery factor with Mach number; such a variation was not observed.

The accuracy of small temperature-difference measurement is primarily dependent upon the sensibility of the potentiometer and is affected little by the absolute calibration of the thermocouple wire because the variation in electromotive force per degree Fahrenheit for different batches of wire is so small that temperature-difference errors become significant at large temperature differences only. The potentiometer had a sensibility of 0.002 millivolts, which resulted in a maximum estimated error in the temperature-difference measurements of 0.07° F. This estimated error would have a negligible effect on the recovery factors obtained at high Mach numbers and would cause a maximum error of only ±0.9 percent at a Mach number of 0.3.

Errors in pressure measurement. - Errors in pressure measurement would affect the evaluation of the local recovery factor because the static-temperature values used in the calculation of recovery factors were based on the total- and static-pressure measurements. The static pressures were measured differentially with the total pressure measured in a duct upstream of the blade. Water manometers were used for the differential measurements and the estimated accuracy of the pressure-difference measurements was 0.2 inch of water. Six total-pressure probes were installed in the duct upstream of the blade and the readings from the probes agreed within 0.1 inch of mercury. The recovery factors obtained at different locations on the blade were consistent, indicating that there were no faulty static-pressure readings because of burrs or other faults in the pressure orifices.

Error due to conduction of heat in the blade. - Conduction of heat in the blade was reduced to a minimum by fabricating the blade from a material having an extremely low thermal conductivity, and heat-flow paths were interrupted by removal of material from the blade interior as shown in figure 2. In addition, recovery-factor data were not used from regions of the blade such as the leading and trailing edges where it was thought that conduction might interfere with accuracy. No conduction occurred in the spanwise direction as shown by the thermocouples used for indicating heat flow in this direction. Consistent recovery factors obtained at adjacent locations along the blade gave further evidence that there was no transfer of heat between the adjacent stations.

PRELIMINARY INVESTIGATION ON EFFECT OF AIR HUMIDITY

The air used in the determination of the local recovery factors for the symmetrical Lucite blade had a relatively high moisture content. As mentioned previously, this condition could possibly cause an error in the calculation of the local recovery factors. A preliminary investigation was therefore conducted to determine if humidity would cause an error in the determination of recovery factors when the thermocouple probe shown in figure 3 is used. The recovery factors obtained for the probe for air at two dew points are shown in figure 6. If moisture condensation were to affect the evaluation of the recovery factor, it would be noticeable at the right of the vertical line at a Mach number of 0.822 in figure 6. At this Mach number, the static air temperature is the same as the dew point for the higher dew-point air. Because no divergence occurred between the data above a Mach number of 0.822 for air at two dew points, it can be concluded that humidity had no effect on the determination of recovery factors.

The Lucite blade investigation was conducted over a period of time and as a result there was a considerable variation in the humidity of the air used. No discrepancy occurred in the local recovery factors obtained at different times, indicating no effect of humidity in this investigation also. In no case, for the Lucite blade investigation, was the humidity high enough that the static temperature was less than the dew point for Mach numbers less than 0.733 and there was no reason to believe that humidity caused any error at higher Mach numbers.

RESULTS AND DISCUSSION OF BLADE RECOVERY-FACTOR INVESTIGATION

Effects of Reynolds Number and Boundary-Layer Transition

The local recovery factors obtained at positions 1 to 6 on the Lucite blade (fig. 2(b)) are shown plotted against the local Reynolds number for four small ranges of Mach number in figure 7 and for each of the six locations on the blade surface in figure 8. The characteristic dimension in the Reynolds number was the distance from the stagnation point to the position on the blade where the local recovery factor was determined. The velocity and the density were measured at the same location. There was no apparent effect of Reynolds number shown in the plots in figure 7.

As mentioned previously, it is shown in reference 7 that for an axial probe the recovery factor increased in the Reynolds number range from approximately 5×10^5 to 16×10^5 presumable because the boundary-layer flow changed from laminar to turbulent. Such an effect was not observed in the data shown in figure 7. The transition from laminar to turbulent boundary-layer flow, however, would undoubtedly be different for various bodies because transition is influenced by a number of factors in addition to Reynolds number; for example, pressure gradient (reference 11), surface curvature (reference 12), and gas-to-surface temperature ratio (reference 13). For recovery-factor investigations, the temperature-ratio effect would be practically nonexistent, and little quantitative information is available concerning the effect of surface curvature. Transition for turbine blades probably takes place when a pressure minimum occurs on the surface, that is, when the Euler number is equal to zero (reference 11).

The ratio of total pressure to local static pressure and the Euler number are plotted against the distance from the stagnation point for various inlet Mach numbers in figures 9 and 10. The slopes of the lines from figure 9 were used to determine the Euler numbers in figure 10. For all values of inlet Mach number, an Euler number of zero is obtained near the leading edge on the suction surface of the blade, but zero Euler number is never obtained on the pressure surface (fig. 10). This indicates that on the greater portion of the suction surface turbulent boundary-layer flow occurs and that on the pressure surface laminar boundary-layer flow occurs; consequently, the recovery factors should be lower on the pressure surface than on the suction surface. This trend is exhibited in figure 8. Stations 5 and 6 are on the pressure surface and the recovery factors for these two stations are lower than for the other four stations, which are on the suction surface. The recovery factors for stations 5 and 6 are above the theoretical value of 0.84 for laminar flow in air probably because the stations are located on a portion of the blade that is in the transition range, regardless of the fact that a steadily decreasing pressure exists on this surface of the blade. Reliable recovery factors at locations nearer the stagnation point on this surface could not be obtained because of the low Mach numbers over that portion of the blade. Reynolds numbers over the range investigated apparently had little or no effect on transition.

Effect of Pressure Gradient

Throughout the tests to determine the local recovery factors on the Lucite blade, the pressure gradient at a given station was varied from low to high values by varying the inlet Mach number. In addition, because of the configuration of the Lucite blade and the walls of the tunnel, the pressure gradient at a given station was different from the pressure gradient at any other station. The pressure-gradient variation is represented by the Euler number variation with distance from the stagnation point in figure 10. The variation in pressure gradient between stations on the blade did not cause a variation in recovery factor between stations (fig. 8). The only variation in local recovery factor between stations along the blade was believed due to transition from laminar to turbulent boundary-layer flow as previously discussed. Mach number, which influences pressure gradient (fig. 10), appears to have little or no effect on the recovery factors at any station on the blade (fig. 7); therefore, it can be concluded that there was no apparent effect of pressure gradient on the recovery factor.

Correlation of Recovery-Factor Data

The local recovery factors obtained for all six stations on the Lucite blade are plotted in figure 11 for a range of Mach numbers from 0.3 to 1.0. The least square of the data was taken and the equation for the mean line was found to be

$$\Lambda = 0.890 + 0.009M \tag{7}$$

The recovery factors according to equation (7) varied from 0.893 to 0.899 for the range of Mach numbers investigated.

In reference 9, an approximate equation for turbulent boundary-layer recovery factors was derived, which represented more accurately computed results within 1 percent. In the analysis of reference 9 the boundary-layer velocity profile was approximated by a power law. For a boundary-layer profile parameter of 7 and a Prandtl number of 0.705 (obtained from reference 14 for an air temperature of 80° F), subsonic turbulent boundary-layer recovery factors were calculated; these factors are plotted in figure 11. The theoretical results are from 1.5 to 2.3 percent lower than the experimental line representing data obtained in this investigation for the Mach number range from 0.3 to 1.0. In both the investigation of reference 9 and the present investigation, very little variation of the recovery factor with Mach number was found.

The maximum scatter in the data of this investigation for all stations on the blade was slightly less than ±4 percent. This scatter was probably due to incomplete temperature equilibrium when the data points were recorded. Attempts were made in all runs to obtain equilibrium or steady-state conditions before recording data points; however, the low thermal conductivity of the blade which was necessary to reduce heat conduction also caused the temperature response of the blade to be very slow. In addition, the temperature differences in recovery-factor investigations are so small that it is often difficult to determine when equilibrium is obtained. It is believed that the scatter of data was random and a mean line through the data should be close to a true value.

USE OF RECOVERY FACTOR IN CALCULATION OF EFFECTIVE GAS TEMPERATURE

The greatest error involved in the calculation of the effective gas temperature for a turbine blade in most cases will be in the measurement or calculation of the total gas temperature relative to the blade. The effective temperature is so near to the relative total temperature that reasonable errors in recovery factor are negligible.

The procedures that can be used for calculating the effective gas temperature for both static cascades and gas-turbine engines will be explained in the following paragraphs.

Static Cascades

Little difficulty is encountered in calculating the effective gas temperature in static cascades. The pressure or Mach number distribution around the turbine blade must be determined either experimentally or analytically and then from a measured total temperature the local effective-gas-temperature distribution can be calculated by means of equation (4) or equation (5). It is recommended that the value of the recovery factor be taken as 0.89. For a ratio of specific heats equal to 1.4, the variation of the effective gas temperature with Mach number can be obtained from the nondimensional temperature plot in figure 5.

The simplest method of determining the pressure distribution around a turbine blade in a cascade is by means of static-pressure measurements on the blade surface. The total pressure is usually assumed to remain constant along the blade chord for subsonic flow. If static pressure measurements are unavailable, the pressure distribution around the blade can be calculated by means of the stream-filament theory given in references 15 and 16 for reaction and impulse blades, respectively.

Turbine Stator Blades

The method for calculating the effective gas temperature for turbine stator blades is essentially the same as for static cascades except that the total-temperature profile upstream of the blades is nonuniform. The velocity profile is probably nonuniform also, but this profile is of secondary importance compared with the temperature. It is therefore necessary to survey the total temperatures upstream of the stator blade before calculating the effective gas temperatures by the method outlined in the preceding section.

Turbine Rotor Blades

The calculation of the effective gas temperature for turbine rotor blades can only be an approximation because of the difficulty in determining the total temperature relative to the rotor blade. The method of determining the average relative total temperature is outlined in reference 17. Briefly, the method consists in measuring the temperature of the gas in the engine tail pipe and calculating the static temperature at the stator outlet by means of a heat balance on the engine. The total temperature relative to the turbine blades is obtained after the gas velocity relative to the turbine blades is calculated by means of velocity vectors. The variation in gas temperature along the span of a turbine blade in an engine may be several hundred degrees; therefore, a relation between the average gas temperature and the temperature profile is also needed in order to determine the local effective temperature. Probably the only way that this relation can be obtained is by means of gas-temperature surveys, preferably from the temperature profile on an uncooled rotor blade in the engine.

After determining the relative total-temperature distribution along the blade span, the approximate pressure distribution around the blade can be determined by means of the stream-filament theory (references 15 and 16), but the inaccuracies in the determination of the relative total gas temperature are probably such that an accurate determination of the pressure distribution is unwarranted. For most rotor blades the local Mach numbers will probably range between 0.7 and 1.0. According to figure 5, for a recovery factor of 0.89, if the effective gas temperature is taken as 98.6 percent of the relative total temperature, the maximum error in the calculation of the effective gas temperature for the Mach number range from 0.7 to 1.0 and a relative total gas temperature of 1960° R would be 8.5° R. This error is far less than the errors encountered in the measurement of a gas temperature in a high-velocity gas stream. Therefore, only the approximate pressure or Mach number distribution around a turbine blade is required in order to calculate the effective gas temperature to the accuracy normally required in heat-transfer calculations for cooled gas-turbine blades.

Because of inaccuracies encountered in the determination of total gas temperatures in high-velocity high-temperature gas streams and the small effects of inaccuracies in the recovery factor on the determination of effective gas temperatures, it is believed that further research on the experimental determination of recovery factors for subsonic flow over gas-turbine blades is unnecessary.

SUMMARY OF RESULTS

The results of this investigation on the determination and use of the local recovery factor for determining the effective gas temperature may be summarized as follows:

1. The local recovery factors determined for a Lucite blade that had a pressure distribution similar to that of a reaction-type turbine blade were essentially independent of Mach number, Reynolds number, pressure gradient, and position on the blade except for regions where the boundary-layer flow was thought to be in the transition range from laminar to turbulent.

2. The values of the recovery factor obtained were somewhat higher than indicated by theory for turbulent boundary-layer flow but were within the range of values obtained by other investigators on bodies of various shapes.

3. An analysis of possible errors involved in the determination of recovery factors indicated that the random scatter obtained in the experimental data was probably caused by temperature equilibrium not being completely obtained for all runs.

4. Variations in the value of the recovery factor and errors in the measured pressure or calculated Mach number distribution around turbine blades result in a small error in the calculation of effective gas temperature; however, the greatest uncertainty in the calculation of effective gas temperature in a gas-turbine engine is the determination of the total temperature of the gas relative to the turbine blade.

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REFERENCES

1. Eckert, E., and Drewitz, O.: The Heat Transfer to a Plate in Flow at High Speed. NACA TM 1045, 1943.

2. Pohlhausen, E.: Der Wärmeaustausch zwischen festen Körpern und Flüssigkeiten mit kleiner Reibung und kleiner Wärmeleitung. Z.f.a.M.M., Bd. 1, Heft 2, 1921, S. 115-121.

3. McAdams, William H., Nicolai, Lloyd A., and Keenan, Joseph H.: Measurements of Recovery Factors and Coefficients of Heat Transfer in a Tube for Subsonic Flow of Air. NACA TN 985, 1945.

4. Johnson, H. A., and Rubesin, M. W.: Aerodynamic Heating and Convective Heat Transfer - Summary of Literature Survey. Trans. A.S.M.E., vol. 71, no. 5, July, 1949, pp. 447-456.

5. Eckert, and Weise: The Temperature of Uncooled Turbine Blades in a Fast Stream of Gas. Reps. & Trans. No. 39, British M.A.P., March, 1946. (Distributed in U.S. by J.I.O.A. (Washington, D.C.), June 26, 1946, Available From Navy Dept. as CGD-485.)

6. Eckert, E., and Weise, W.: The Temperature of Unheated Bodies in a High-Speed Gas Stream. NACA TM 1000, 1941.

7. Eckert, E., und Weise, W.: Messungen der Temperaturverteilung auf der Oberfläche schnell angeströmter unbeheizter Körper. Forschung Ing.-Wes., Bd. 13, Heft 6, Nov./Dez. 1942, S. 246-254.

8. Eckert, E., and Weise, W.: The Measurement of Air Temperatures in High-Speed Flight. British R.T.P. Translation No. 2570, Ministry Aircraft Prod.

9. Tucker, Maurice, and Maslen, Stephen H.: Turbulent Boundary-Layer Temperature Recovery Factors in Two-Dimensional Supersonic Flow. NACA TN 2296, 1951.

10. Scadron, Marvin D., Gettelman, Clarence C., and Pack, George J.: Performance of Three High-Recovery-Factor Thermocouple Probes for Room-Temperature Operation. NACA RM E50I29, 1950.

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

12. Liepmann, Hans W.: Investigations on Laminar Boundary-Layer Stability and Transition on Curved Boundaries. NACA ACR 3H30, 1943.

13. Lees, Lester: The Stability of the Laminar Boundary Layer in a Compressible Fluid. NACA Rep. 876, 1947. (Formerly NACA TN 1360.)

14. Keenan, Joseph H., and Kaye, Joseph: Thermodynamic Properties of Air. John Wiley & Sons, Inc., 1945.

15. Huppert, M. C., and MacGregor, Charles: Comparison Between Predicted and Observed Performance of Gas-Turbine Stator Blade Design for Free-Vortex Flow. NACA TN 1810, 1949.

16. 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.

17. Ellerbrock, Herman H., Jr., and Stepka, Francis S.: Experimental Investigation of Air-Cooled Turbine Blades in Turbojet Engine. I - Rotor Blades with 10 Tubes in Cooling-Air Passages. NACA RM E50I04, 1950.

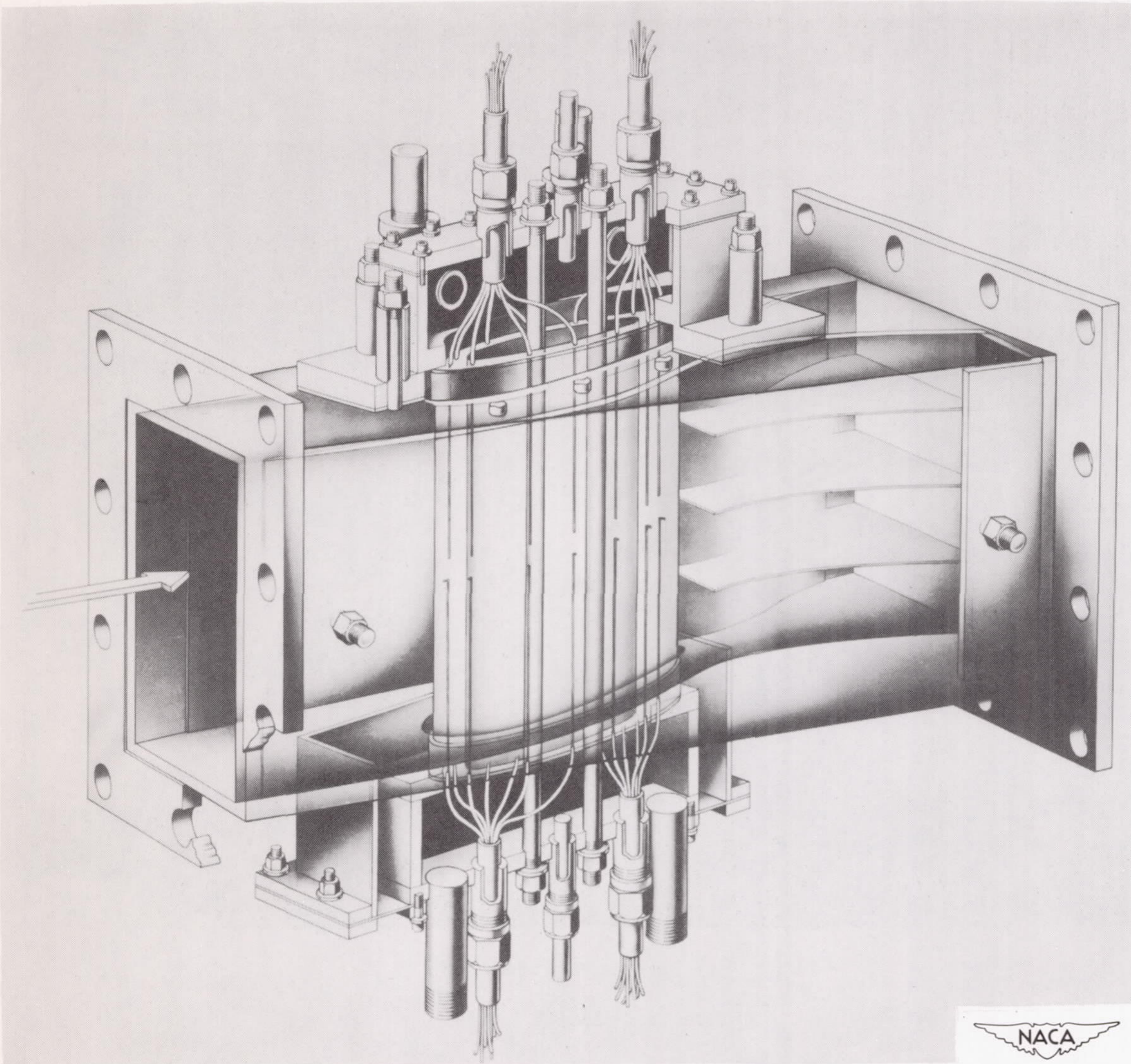
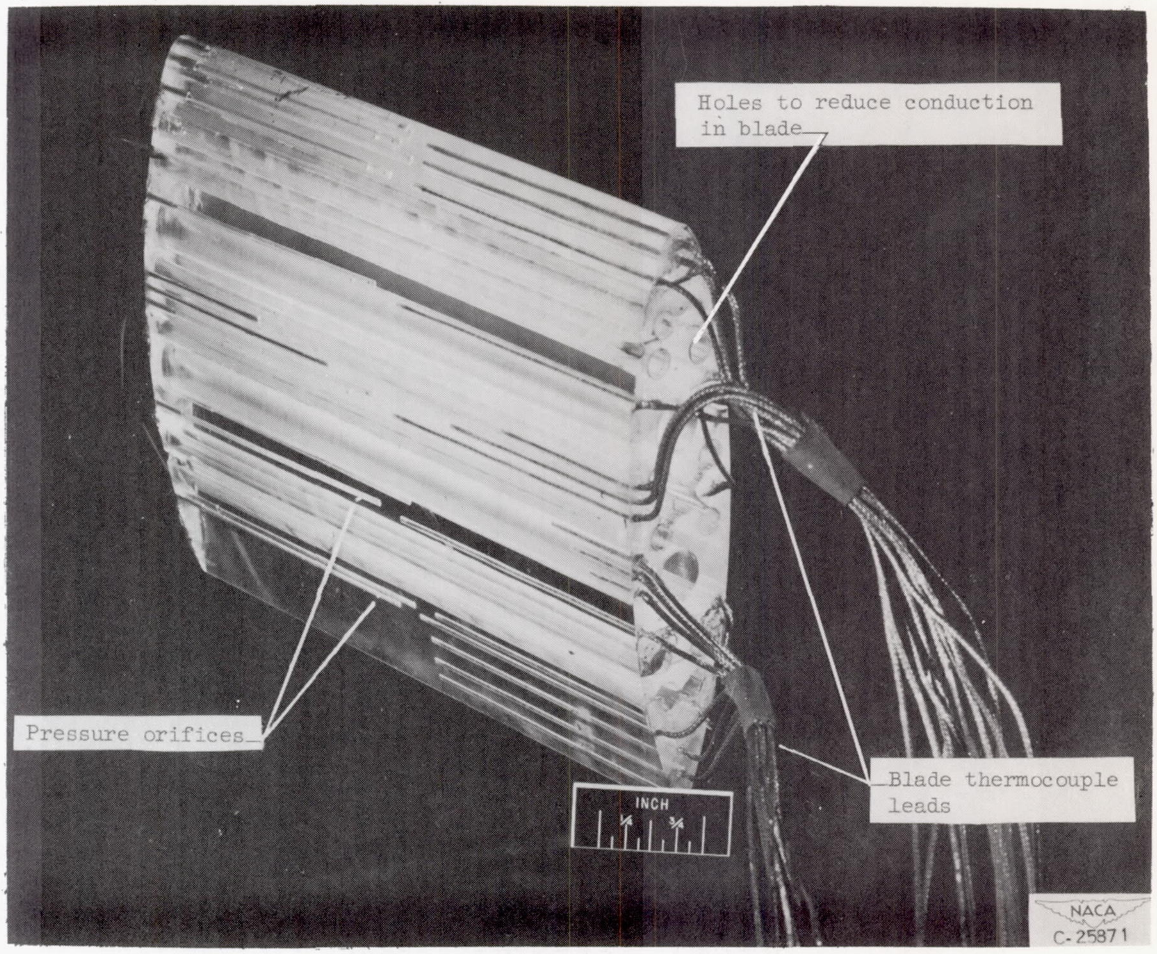
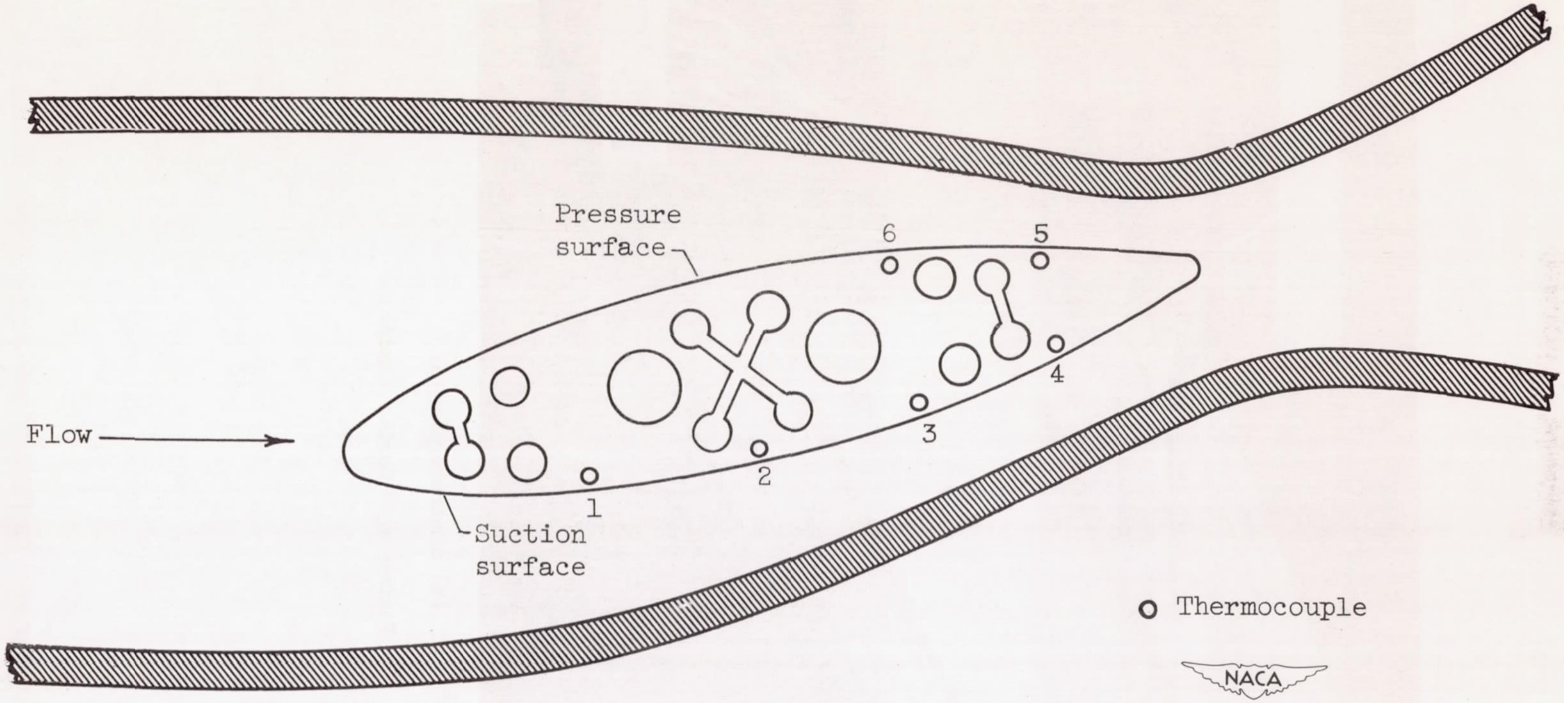


Figure 1. - Apparatus used for determination of Lucite-blade recovery factors.



(a) Instrumentation.

Figure 2. - Lucite blade.



(b) Location of thermocouples.

Figure 2. - Concluded. Lucite blade.

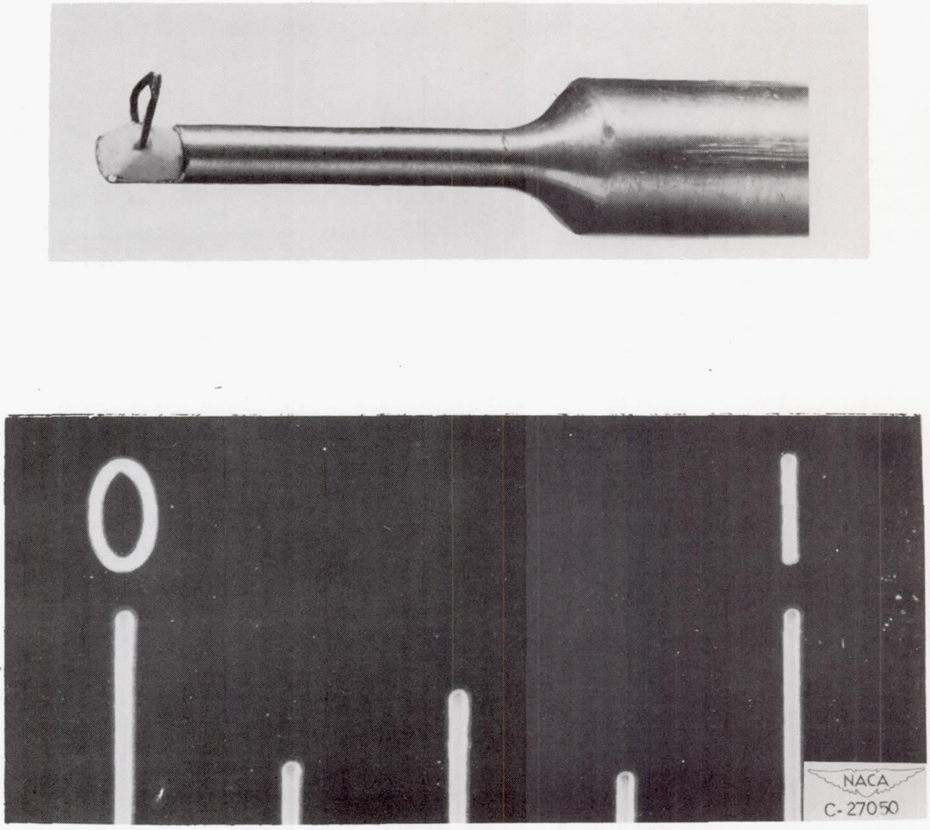


Figure 3. - Probe used for determination of effect of humidity on recovery factors.

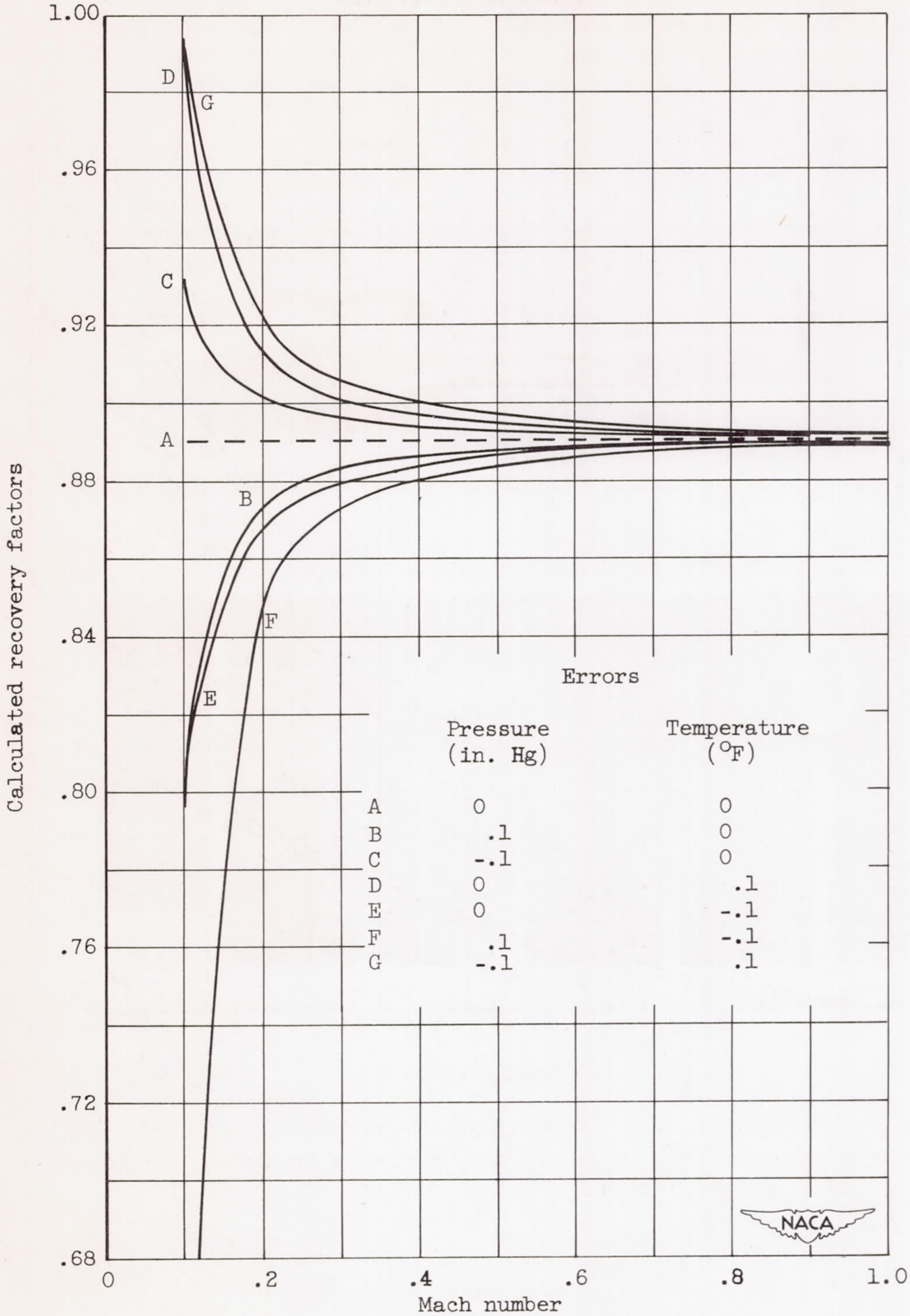


Figure 4. - Effect of errors in pressure and temperature measurements on calculated recovery factors. True recovery factor, 0.89; total pressure, 30 inches mercury absolute; total temperature, 540° R; ratio of specific heats, 1.4.

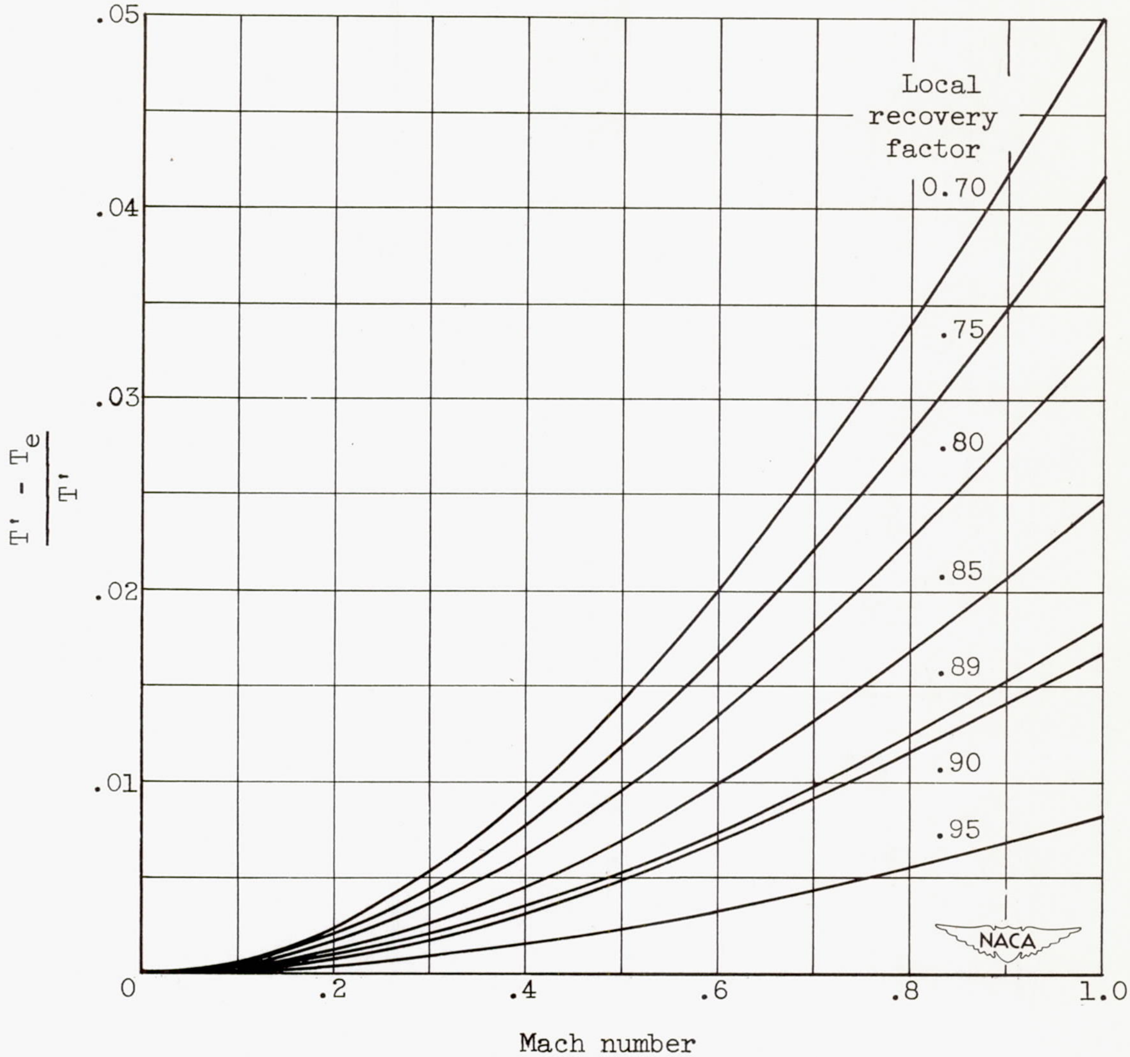


Figure 5. - Curves for determining the effective gas temperature for a range of Mach numbers and recovery factors. Ratio of specific heats, 1.4.

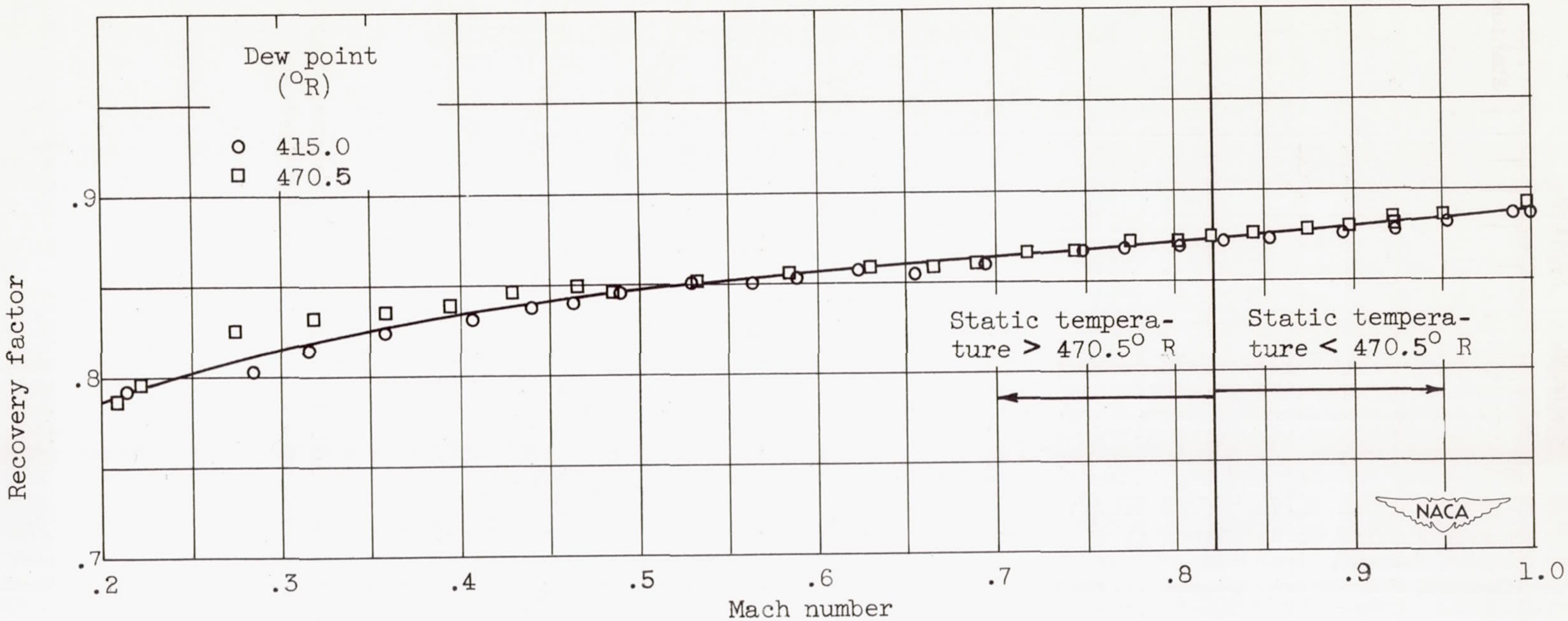


Figure 6. - Effect of air humidity on recovery factor for thermocouple probe. Air inlet temperature, 534° R.

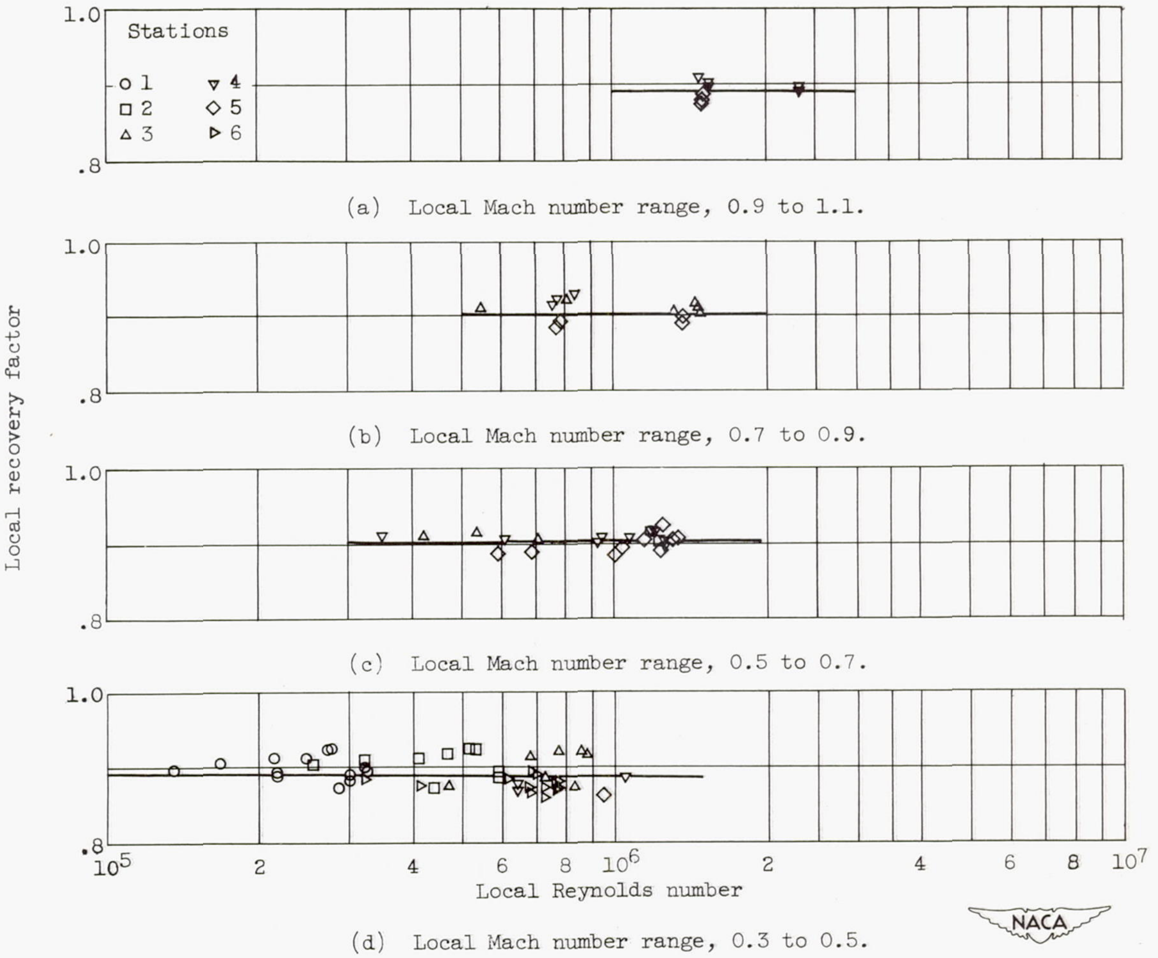
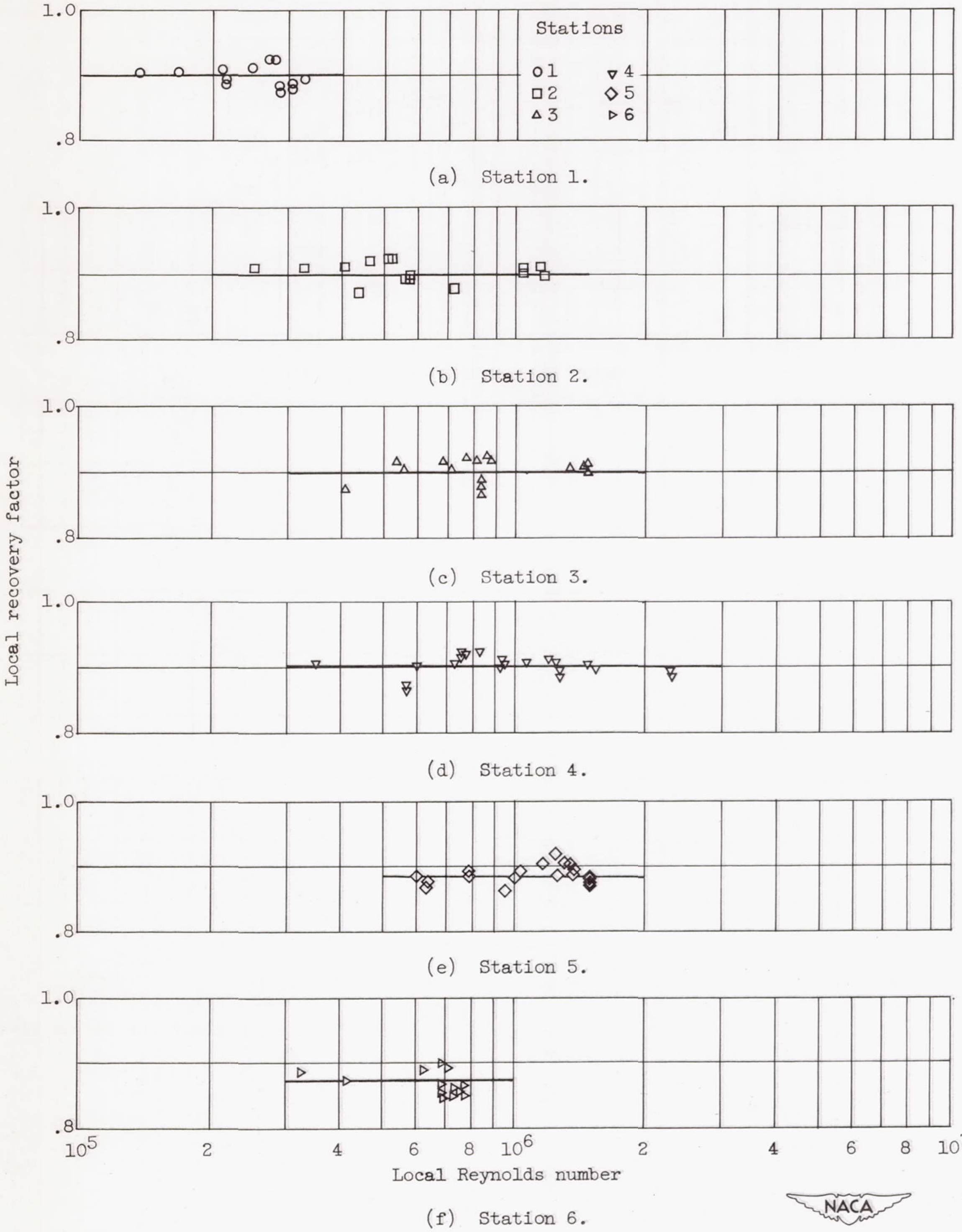


Figure 7. - Effect of local Reynolds number on local recovery factor for Lucite blade over range of local Mach numbers.



(a) Station 1.

(b) Station 2.

(c) Station 3.

(d) Station 4.

(e) Station 5.

(f) Station 6.

Figure 8. - Effect of blade-surface location on local recovery factor for Lucite blade for range of local Reynolds numbers.

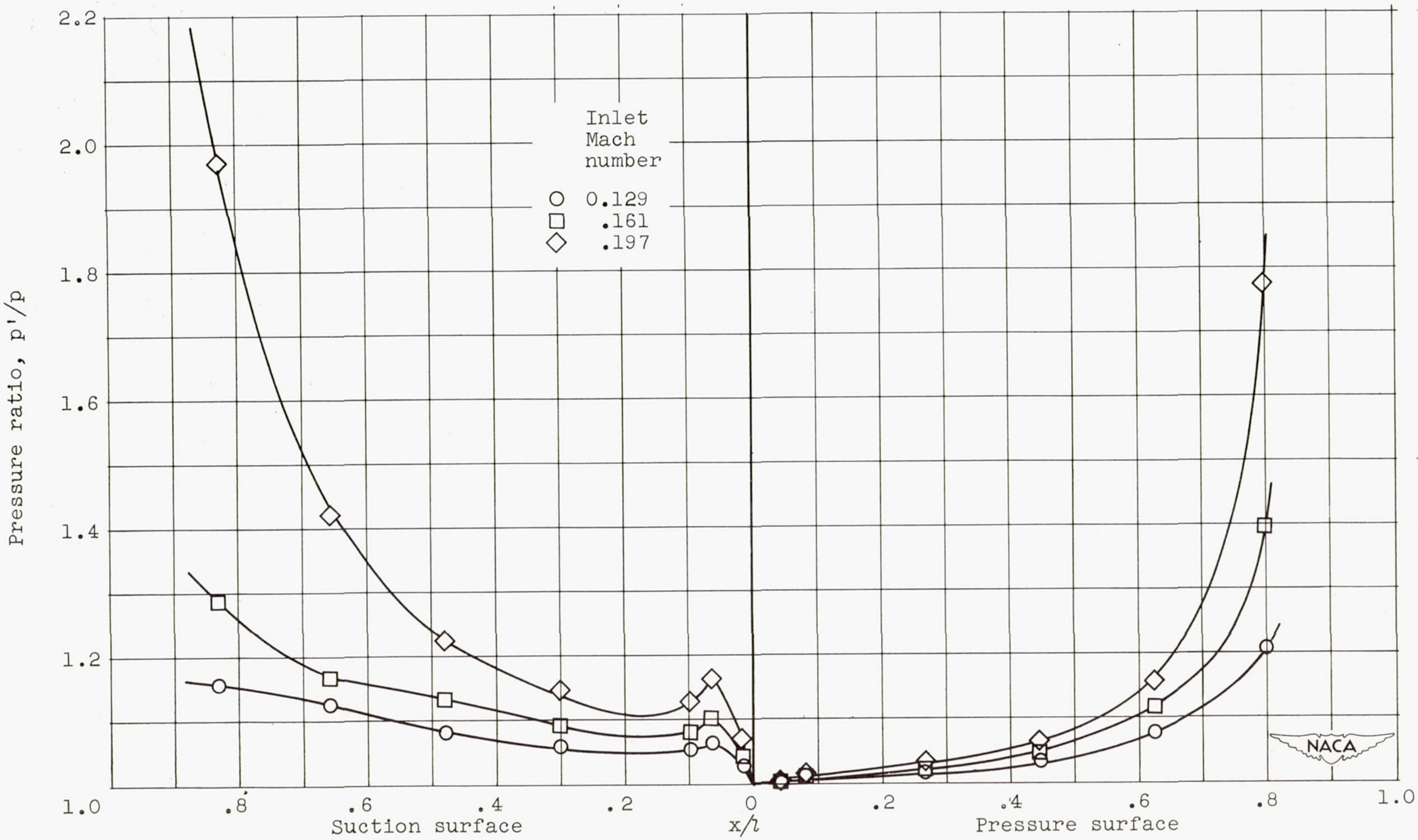


Figure 9. - Pressure-ratio distribution around Lucite blade.

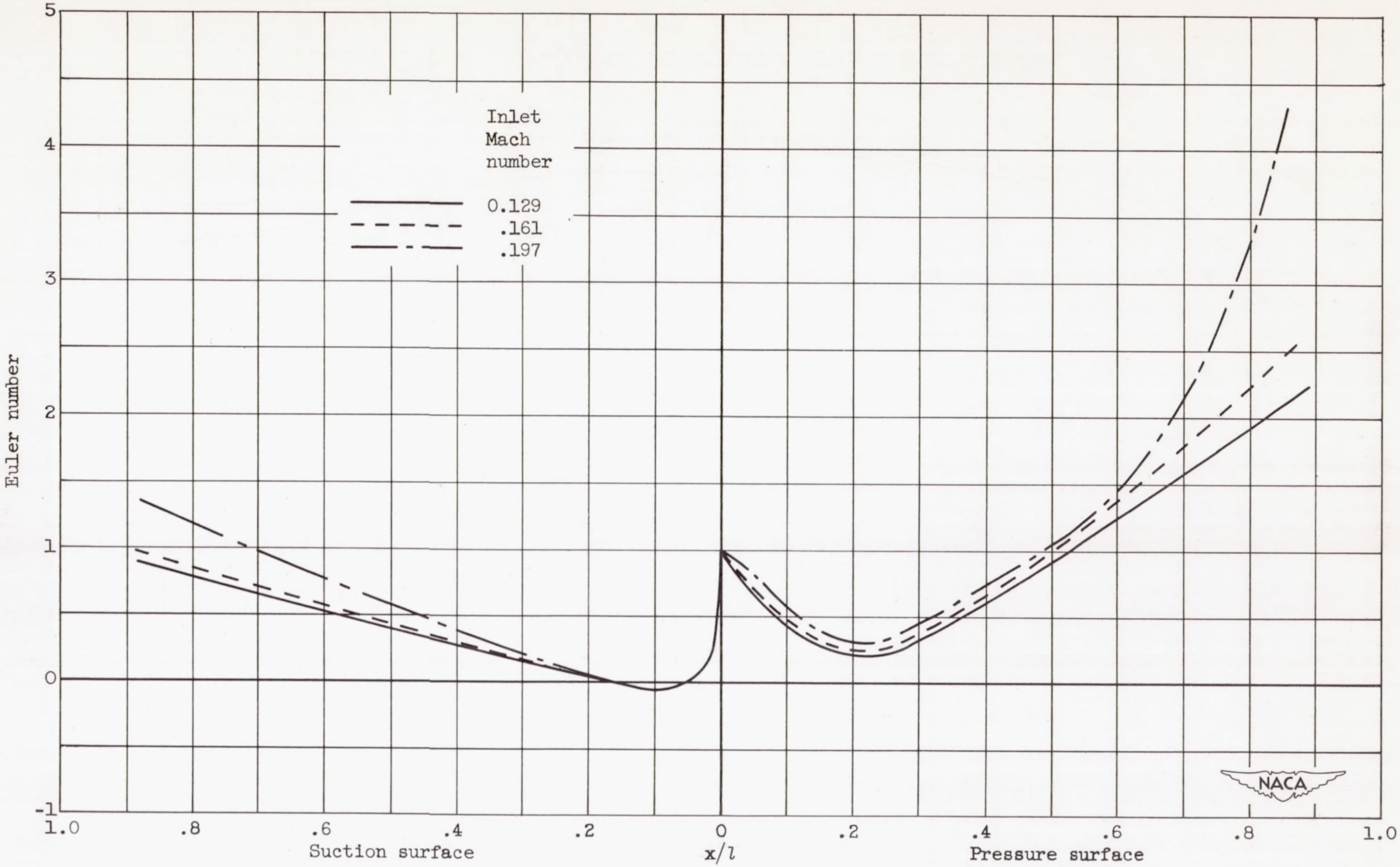


Figure 10. - Euler number distribution around Lucite blade.

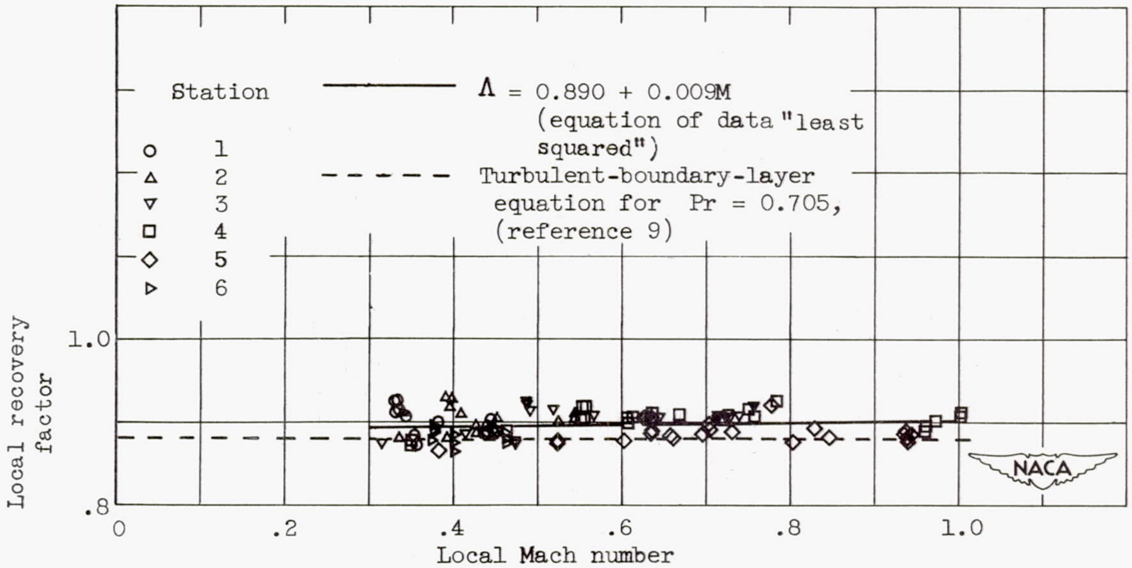


Figure 11. - Effect of local Mach number on local recovery factor.