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Kinetic Temperature of Propeller Blades in Conditions of Icing

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COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR), MINISTRY OF SUPPLY

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Summary.—The kinetic temperature of a section of a propeller blade has been calculated for a blade with high thermal conductivity, and also for a blade which is non-conducting. Calculations have been made for clear air, and for conditions of icing to find the extent to which kinetic heating is effective against ice. On a non-conducting blade the temperature is lowest at the position, on the cambered face, where the velocity of the air is greatest. At this position there is practically no protection from kinetic heating. In the case of a blade which is a good conductor, the average temperature is calculated by balancing the flow of heat by convection to and from the blade. The average temperature is substantially above the minimum temperature on a non-conducting blade. The average temperature has been calculated for a range both of conditions of icing and of operation.

Introduction.—Turbine engines, and engine cooling fans and propellers also, are protected against ice, to some extent, by the action of kinetic heating. It is important to know the extent of this protection, and how it may vary with design and with conditions of operation. The particular object of this Note is to show, in the case of solid metal blades, the extent to which the kinetic temperature of the blade is modified by the conduction of heat through the blade, and the advantage to be gained by using a material which is a good conductor of heat.

If there is no conduction of heat through the material of the blade, the kinetic temperature at any position on the surface may be calculated from the equations given in Ref. 1. In conditions of icing, the surface of the blade is assumed to be completely wetted with water, and the temperature of the blade at each position is such that there is equilibrium between the heat received by convection from the air and that lost by evaporation. The rate of evaporation varies with pressure and with temperature, so the increase in temperature from kinetic heating is not dependent only on velocity, as it is in clear air. The kinetic temperature is a maximum at stagnation, and a minimum at the position where the local velocity of the air is greatest.

If the blade is of material of high thermal conductivity, there will be a flow of heat through the blade from the parts where the kinetic temperature is high to the parts where it is low. In clear air, the flow of heat is maintained by the transfer of heat by convection from the air to the surface where the kinetic temperature is high, and from the surface to the air where the kinetic temperature is low. In wet air, as in conditions of icing, this process is complicated by the dissipation of heat by evaporation from the surface. In either case the coefficients of transfer of heat round the surface must be known before the average kinetic temperature of the blade can be calculated.

* R.A.E. Report. Mech. Eng. 2, received 16th July, 1947.

The thermal resistance of the material of the blade, in the case of a solid blade of light alloy, is so much less than the resistance to the transfer of heat from blade to air that an elementary section of the blade will be practically at a uniform temperature. This temperature will be called the average kinetic temperature. The thermal resistance of the blade has not been taken into account in the calculations which form the subject of this Note.

Calculations have been made of the average kinetic temperature of a section of a blade to show the effect of speed, height, and temperature, and to find if the average temperature is related in any simple way with the stagnation temperature. These calculations have been made for a typical propeller section, NACA 2409. This was chosen because the data required are available, and because the temperatures as calculated can be compared with those deduced from observations of the formation of ice on propellers.

Analysis.—Average Kinetic Temperature in Clear Air.—In the absence of conduction of heat through the blade the kinetic temperature at any point on the surface, when the flow is laminar, is

$$t'_s = t_0 + \frac{V_0}{2gJC_p}\left[1 - \frac{V_1^2}{V_0^2}(1 - Pr^{1/2})\right] . \qquad \ldots \quad \ldots \quad \ldots \quad (1)$$

The equation for turbulent flow is similar but with the index of Pr, Prandtl's number, changed to $\frac{1}{3}$. These equations give the kinetic temperature in clear air.

If the conductance of heat through the material of the blade is such that the whole of an elementary section is at a uniform temperature, t'_b, the rate of convection of heat at any position round the section is

$$H = k_h \rho'_0 V_0 C_p (t'_s - t'_b)\, ds . \qquad \ldots \quad \ldots \quad \ldots \quad (2)$$

The values of k_h and t'_s in this equation are those appropriate to each particular position.

It will be assumed that the element does not gain or lose heat by conduction along the blade in a radial direction. The heat gained by convection, then, to those parts of the surface where $t'_s > t'_b$ must exactly balance the heat lost where $t'_s < t'_b$, so that

$$\oint k_h \rho'_0 V_0 C_p (t'_s - t'_b)\, ds = 0 . \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

The process of integration is carried completely round the section in a chordwise direction. This gives the value of t'_b, the average kinetic temperature of the section.

Average Kinetic Temperature in Wet Air.—When droplets of water are carried by the air stream, as is the case when an aircraft passes through cloud, evaporation will occur from the surface of the blade because the vapour pressure at the surface, owing to kinetic heating, is greater than that in the surrounding air. From the evidence available, the surface, at least over the forward part, is completely wetted. In what follows, it will be assumed that the blade is completely wetted. The method of dealing with a surface which is partly wetted is discussed in Ref. 1.

It will be assumed, also, that there is no change of phase from liquid to vapour, or the reverse, in the air outside the boundary layer as it flows round the section. This also, is discussed in Ref. 1. The implication is that, temporarily, the air may be in a state of super- or sub-saturation.

On this assumption, the vapour pressure locally is given by the equation

$$e_1 = e_0 \frac{P_1}{P_0} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

in which e_0 is the vapour pressure and P_0 the barometric pressure in the undisturbed stream. The value of P_1, the barometric pressure locally is given by the equation

$$V_0^2 - V_1^2 = 2gRT_0 \frac{\gamma}{\gamma - 1}\left[\left(\frac{P_1}{P_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] . \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

At any position round the section, the rate of dissipation of heat by evaporation is given by the equation

$$H_2 = k_w \rho'_0 V_0 \left(\frac{e_s - e_1}{P_1}\right) \times 0{\cdot}622 L_s\, ds . \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

If there is no transfer of heat by conduction through the blade, there must, at each point, be a gain of heat by convection which is equal to the loss by evaporation, so that

$$k_h \rho' V_0 C_p (t'_s - t''_s) = k_w \rho' V_0 \left(\frac{e''_s - e_1}{P_1}\right) \times 0{\cdot}622 L_s .$$

In the case of water vapour, the diffusivity of heat is equal to that of vapour so that k_h equals k_w, and the equation reduces to

$$t''_s = t'_s - 0{\cdot}622 \frac{L_s}{C_p} \left(\frac{e''_s - e_1}{P_1}\right) . \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

This equation can be used to determine the distribution of temperature, in wet air, round a blade which is a non-conductor of heat.

If the material is a good conductor so that the whole of an elementary section is at a uniform temperature t''_b, the loss of heat from the whole section by evaporation must be balanced exactly by the heat gained by convection, so that

$$\oint k_h \rho'_0 V_0 C_p (t'_s - t''_b)\, ds - \oint k_w \rho'_0 V_0 \left(\frac{e''_b - e_1}{P_1}\right) \times 0{\cdot}622 L_s\, ds = 0 . \quad \ldots \quad (8)$$

The value of t'_s is given by equation (1), that of e_1 by equation (4), and e''_b is the vapour pressure for saturation at the temperature t''_b. The average kinetic temperature of a section of a blade, in wet air, may be calculated from this equation.

In cloud, the value of e_0, of equation (4), is that for saturation at t_0, the static temperature of the undisturbed air. In an engine, the air may be preheated before it enters the compressor, and the value of e_0 at entry to the compressor will differ from that in the cloud, because water will evaporate both from the wet surfaces of the duct leading to the compressor and from the droplets of water which are in suspension in the air. The method of calculating the rate of evaporation from the droplets is given in R. & M. 2805[2]. It will be found that the amount of water which evaporates from the droplets, whilst in the heated zone is surprisingly small owing to the briefness of exposure consequent upon the high velocity of the air. The method of calculating the rate of evaporation from heated surfaces is given in Chapter 4 of Ref. 3.

Calculations.—A number of calculations have been made in order to show the effect of changes in the conditions of operation on the extent to which the blade is protected against ice by kinetic heating. These, for most part, are for a blade with thermal conductivity such that a section may be assumed to be at a uniform temperature. A few calculations have been made for a blade of non-conducting material in order to show the variation of temperature round a section, and to show the extent to which thermal conduction affects protection against ice.

The aim, in each case, has been to find the limit of protection against ice by kinetic heating. This is defined as the temperature of the air at which the temperature of the blade is exactly 0 deg C, and will be called the limiting air temperature for protection. It is found by calculating the temperature of the blade for a range of air temperatures and interpolating.

The calculations are all for blades of section NACA 2409. The data required, namely the values of V_1/V_0 and k_h, have been taken from R. & M. 1986[4]. Transition from laminar to turbulent flow have been taken as occurring at 10 per cent chord on both surfaces. This is an arbitrary choice, as it is uncertain to what extent transition may be affected by droplets of water on the surface of the blade.

The calculations have been made for a range of velocity, this being the resultant velocity of the blade. The maximum velocity for which calculations have been made is that at which velocity, locally, on the cambered face, reaches the velocity of sound. There is not the data, at present, to carry the calculations to higher speeds.

Integrations have been made graphically from values taken at 14 positions round the section. These positions, as fractions of the chord measured round the surface, are

$$0,\ 0{\cdot}05,\ 0{\cdot}1,\ 0{\cdot}2,\ 0{\cdot}3,\ 0{\cdot}5,\ 0{\cdot}7,\ 1{\cdot}0,$$

on both cambered and pressure faces.

Range of Calculations and Results.—Non-conducting Blade.—The kinetic temperature in wet air has been calculated from equation (7), for each position round the section, it being assumed that there is no conduction of heat within the blade. This is for a blade velocity of 640 ft/sec, an air temperature of $-$ 15 deg C, an altitude of 20,000 ft, and $C_L = 0{\cdot}8$. The results are shown in Fig. 1, which gives the increase in temperature of the surface of the blade above that of the ambient air. The distribution of velocity round the section is shown in Fig. 2.

The position at which the protection from kinetic heating is a minimum, is the position in which the local velocity is a maximum. The effect of variation in local velocity, the blade velocity being 640 ft/sec, is shown in Fig. 3. This shows the results of calculating the limiting air temperature for protection, namely the air temperature at which the surface temperature is 0 deg C.

Conducting Blade.—The average kinetic temperature of an element of a blade, has been calculated both for clear air and for wet air, on the assumption that the blade is a perfect conductor of heat.

In clear air the average kinetic temperature is given by equation 3. This has been evaluated for a blade velocity of 640 ft/sec, an air temperature of 0 deg C, and $C_L = 0{\cdot}8$. The average kinetic temperature is found to be 16·1 deg C; the increase in temperature is 0·84 of that at stagnation.

In wet air, equation (8) which gives the average kinetic temperature of an element of a blade, has been evaluated for a range of conditions. The effect of variation both in blade velocity and altitude is shown in Fig. 4, the average kinetic temperature having been calculated for air temperature of 0 deg C.

The process by which the limiting air temperature is determined is illustrated in Fig. 5, which shows increase in temperature from kinetic heating in wet air, against air temperature. Figures similar to this have been drawn which give the limiting air temperature for a range of blade velocity. The values so determined are shown in Figs. 6 and 7. The effect of altitude is shown in Fig. 6, and the effect of change in C_L in Fig. 7.

Temperatures Observed on Propeller Blades.—The temperature of the blades of propellers has been measured indirectly by observing the maximum radius to which ice forms on exposure to conditions of icing. The temperature of the blade at the edge of the ice is assumed to be 0 deg C, so the temperature of the ambient air for each observation is the limiting temperature for protection as defined in this Note.

The temperatures observed are shown in Fig. 8, for comparison with the temperatures calculated for NACA 2409 at $C_L = 0 \cdot 8$. Calculated values for both average kinetic temperature and stagnation temperature in wet air are shown. The observed temperatures, which were made both on the ground and in flight, have been reduced to a common level, namely 8000 ft, by using the calculated values for the change of kinetic temperature with altitude.

The temperatures in Fig. 8 were observed on the ground[5], on the propeller of a Lockheed 12-A with solid metal blades, and in flight, on a propeller with solid metal blades which were covered with rubber.

Discussion.—The thermal conductivity of the material of the blade has a decided effect on the extent to which the blade is protected against ice by kinetic heating. This is shown by comparing Figs. 3 and 5. For the particular conditions, the limiting temperature for a blade of high conductivity is $-8 \cdot 5$ deg C, while for the blade of non-conducting material it is $+1 \cdot 8$ deg C. For the non-conducting blade there is, actually, a refrigerating effect, the temperature of the surface in the zone of maximum velocity being below that of the ambient air. The mechanism by which this effect is produced is the same as that which causes throttle-ice in the induction system of an engine. The area of blade affected is very narrow, and thermal conductance, even though the material of the blade is a poor conductor, will cause the actual temperature at the surface to be somewhat higher than that calculated. Even so, the advantage of the conducting blade is substantial.

The limiting temperature for protection, in the case of a non-conducting blade, is determined by the maximum value of V_1/V_0, and will depend both on the coefficient of lift and the shape of blade. In the case of a conducting blade, the effect of change in C_L is small, as is shown by Fig. 7, and it is probable that shape is not important.

In wet air, the amount by which the average temperature of the conducting blade is increased, above the temperature of the ambient air, is not a fixed fraction of the increase at the stagnation point. This is because the rate of evaporation from the surface of the blade changes with change in the field of pressure round the section. The relation of average to stagnation temperature is shown in the Table below.

TABLE

Comparison between average blade temperature and stagnation temperature in wet air

Height ft	Air Temp. deg C.	Blade Vel. ft/sec	$\frac{\Delta t_{av}}{\Delta t_{stn}}$
20,000 $C_L = 0 \cdot 8$	0	498	0·58
		640	0·52
	-5	498	0·63
		640	0·60
	-10	498	0·66
		640	0·64
8,000 $C_L = 0 \cdot 24$	0	904	0·63
	-10	904	0·71

In clear air, the increase of average temperature by calculation is $0 \cdot 86$ of that at stagnation for $C_L = 0 \cdot 24$, and $0 \cdot 84$ for $C_L = 0 \cdot 8$. This is independent of speed and altitude and varies only with shape of section and incidence. The temperature of the blades of a turbine has been measured, Ref. 6 and the increase was $0 \cdot 85$ of that at stagnation.

In comparing the measured temperatures with those calculated, in Fig. 8, some allowance must be made for the conduction of heat along the blades, and for the conditions of the test. Kinetic temperature increases with radius so that there will be a flow of heat from the outer to the inner parts of a blade. This is not taken into account in the calculations, so that the limiting temperatures, as calculated, will be higher than observed for the inner parts and lower for the outer parts. The radius at which reversal occurs, is calculated to be at two-thirds the radius of the tip of the blade. The method of calculation is given in an Appendix. In Rodert's experiments, the radius of the ice was in all cases greater than the two-thirds radius, so that the measured values of limiting temperature should be somewhat above those calculated. The opposite effect may have been produced by the conditions in which the experiments were made. Conditions of icing were created by spraying water, and, because of the coarseness of the drops, the blades may not have been wetted as completely as they would be in natural conditions.

The observations in flight were made in natural conditions of icing, but the blades of the propeller were rubber covered. Because of the thermal resistance of the covering, the temperatures observed are not strictly comparable with those calculated on the assumption that resistance is negligible.

Though they may have some bias, the measured temperatures are in satisfactory agreement with those calculated. The measurements are not sufficient, either in number or quality, to allow a critical comparison. Further measurements would be useful, particularly at the high velocities which are used in axial-flow compressors.

Conclusion.—Conclusions are as follows:

1. Protection from kinetic heating is more effective if the material of the blades is of high thermal conductivity.

2. Calculated values for the average kinetic temperature of a fully wetted blade are in satisfactory agreement with temperatures observed on propellers in conditions of icing.

3. Protection against ice by kinetic heating decreases as altitude increases, to a considerable extent.

LIST OF SYMBOLS

C_p	Specific heat of air at constant pressure, CHU/lb/deg C
e	Vapour pressure, mm mercury
g	Gravitational constant, ft^2/sec
H_1	Rate of transfer of heat by convection, CHU/sec/ft^2
H_2	Rate of transfer of heat by evaporation, CHU/sec/ft^2
J	Mechanical equivalent of heat, 1440 ft lb/CHU
k_h	Coefficient of transfer of heat by convection, no dimensions
k_w	Coefficient of evaporation of water, no dimensions
L_s	Latent heat of evaporation of water, CHU/lb
M	Mach number
n	Rotational speed of propeller, revs/sec
P	Barometric pressure, mm of mercury
Pr	Prandtl's number
R	Gas constant
r_t	Radius of tip, ft
r_n	Radius at neutral point, ft
T	Absolute temperature, deg K
t'	Temperature in clear air, deg C
t''	Temperature in cloud with blade wet, deg C
V_0	Resultant velocity of blade, ft/sec
V_a	Forward velocity of aircraft, ft/sec
γ	Ratio of specific heats of air
ρ'	Weight density of air, lb/cu ft

Subscripts

$_0$	Conditions in undisturbed stream
$_1$	Conditions locally at edge of boundary layer
$_s$	Conditions at surface of non-conducting blade

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5	L. A. Rodert	The Effect of Aerodynamic Heating on Ice Formation. N.A.C.A. T.N. 799. 1940.
6	J. Reeman	The Turbine for the Simple Jet Propulsion Engine. *Proc. Inst. Mech. Eng.* War Emergency Issue, No. 12. 1945.

APPENDIX

The Transfer of Heat Radially along a Blade.—There will be a transfer of heat along a blade from the outer parts, where the kinetic heating is greatest, to the inner parts. The heat is received from the air by convection because the temperature of the outer parts of the blade is below the kinetic temperature and is dissipated by the reverse process. The position along the blade where the direction of convective transfer is reversed will be termed the neutral point. An element of the blade at the neutral point loses as much heat to the inner parts as it receives from the outer. Its temperature, therefore, is unaffected by conduction, and is the kinetic temperature appropriate. The object of the analysis which follows is to calculate the position of the neutral point. The blade will be taken as having a constant width from the axis of rotation outward, and as having infinite thermal conductance.

The rate of transfer of heat by convection to a section of width dr can be expressed as

$$H = \text{const.}\ V_0^{0\cdot7}(t'_{s\,\mathrm{av}} - t'_b)\, dr \quad \ldots \quad (1)$$

the perimeter of the section being taken as of unit length.

The value of $t'_{s\,\mathrm{av}}$ is the average for the section as a whole. In clear air this is given by the equation

$$t'_{s\,\mathrm{av}} = t_0 + \frac{x\, V_0^2}{2gJC_p} \quad \ldots \quad (2)$$

x being the ratio of the average kinetic temperature to stagnation temperature; x' will be written for $x/2gJC_p$.

In a condition of equilibrium there is no gain or loss of heat from the blade as a whole, so that from (1)

$$\int_0^R V_0^{0\cdot7}(t_0 - t'_b + x'V_0^2)\, dr = 0\,. \quad \ldots \quad (3)$$

At the neutral point, radius r_n, blade temperature and kinetic temperature are equal, so that

$$t'_b = t_0 + x'(V_a^2 + 4\pi^2 n^2 r_n^2) \quad \ldots \quad (4)$$

with V_a the forward speed of the aircraft. It will be assumed that the speed of rotation at the tip, radius r_t, is twice the speed of the aircraft, so that

$$V_a = \pi n r_t$$

and

$$V_0 = \sqrt{(\pi^2 n^2 r_t + 4\pi^2 n^2 r^2)}\,.$$

Equation (3) thus reduces to

$$4x'(\pi n)^{2\cdot7} \int_0^R (r_t^2 + 4r^2)^{0.35}\,(r^2 - r_n^2)\, dr = 0\,. \quad \ldots \quad (5)$$

Graphical integration gives the radius of the neutral point as

$$r_n = 0\cdot62 r_t\,. \quad \ldots \quad (6)$$

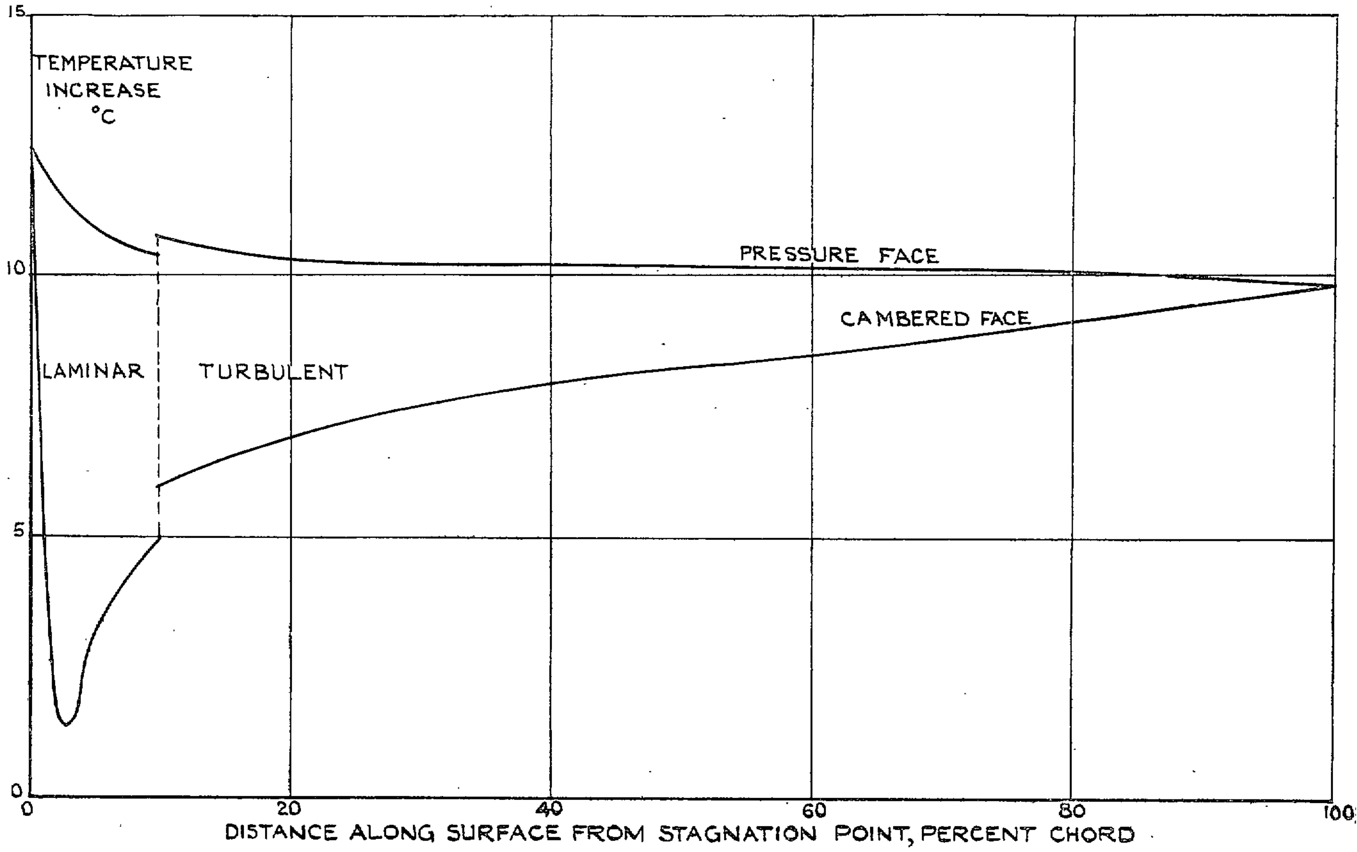

FIG. 1. Non-conducting blade. Increase in temperature from kinetic heating in wet air. $C_L = 0 \cdot 8$, velocity 640 ft/sec, air temperature —15 deg C, altitude 20,000 ft.

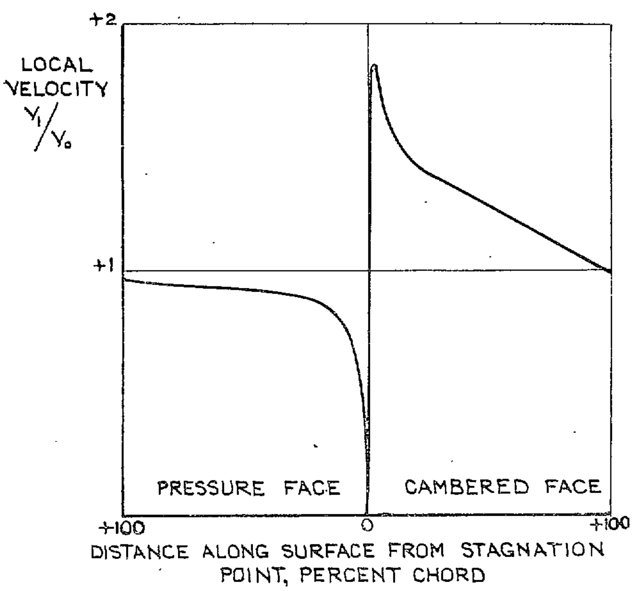

FIG. 2. Local velocity round section NACA 2409 at $C_L = 0 \cdot 8$.

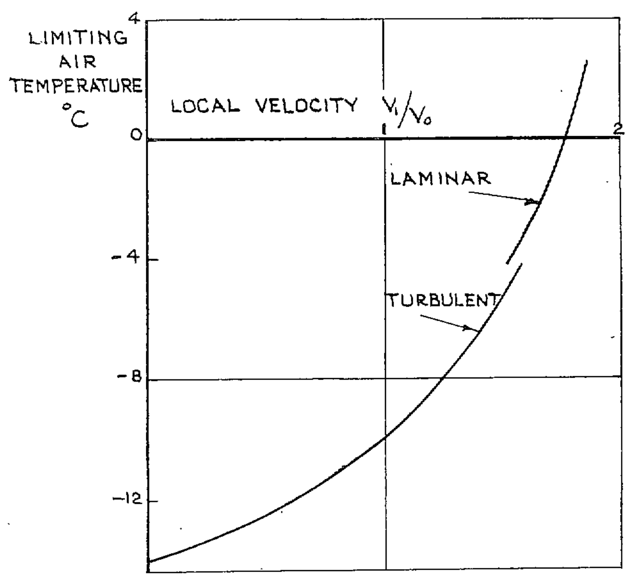

FIG. 3. Non-conducting blade. Variation of limiting air temperature for protection with velocity locally round section.
Blade velocity 640 ft/sec, altitude 8,000 ft.

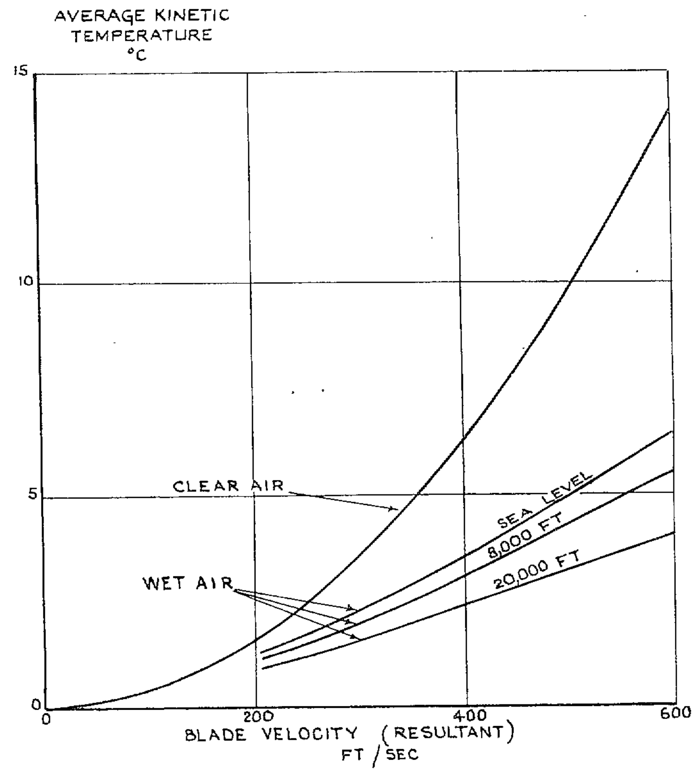

Fig. 4. Conducting blade. Variation of average kinetic temperature with velocity and altitude. $C_L = 0 \cdot 8$, air temperature 0 deg C.

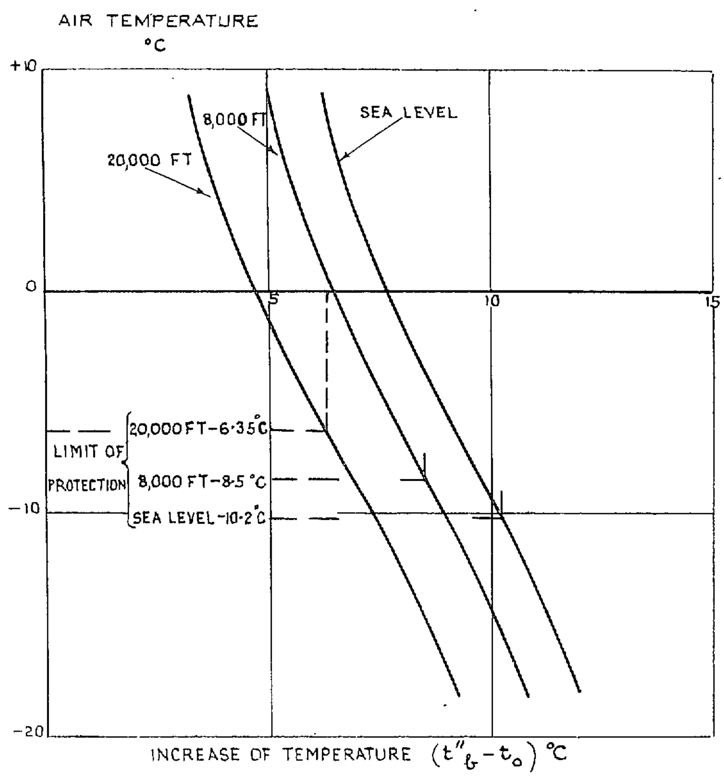

Fig. 5. Conducting blade. Increase in temperature from kinetic heating in wet air. $C_L = 0 \cdot 8$, velocity 640 ft/sec. Increase of temperature, clear air 16·1 deg C.

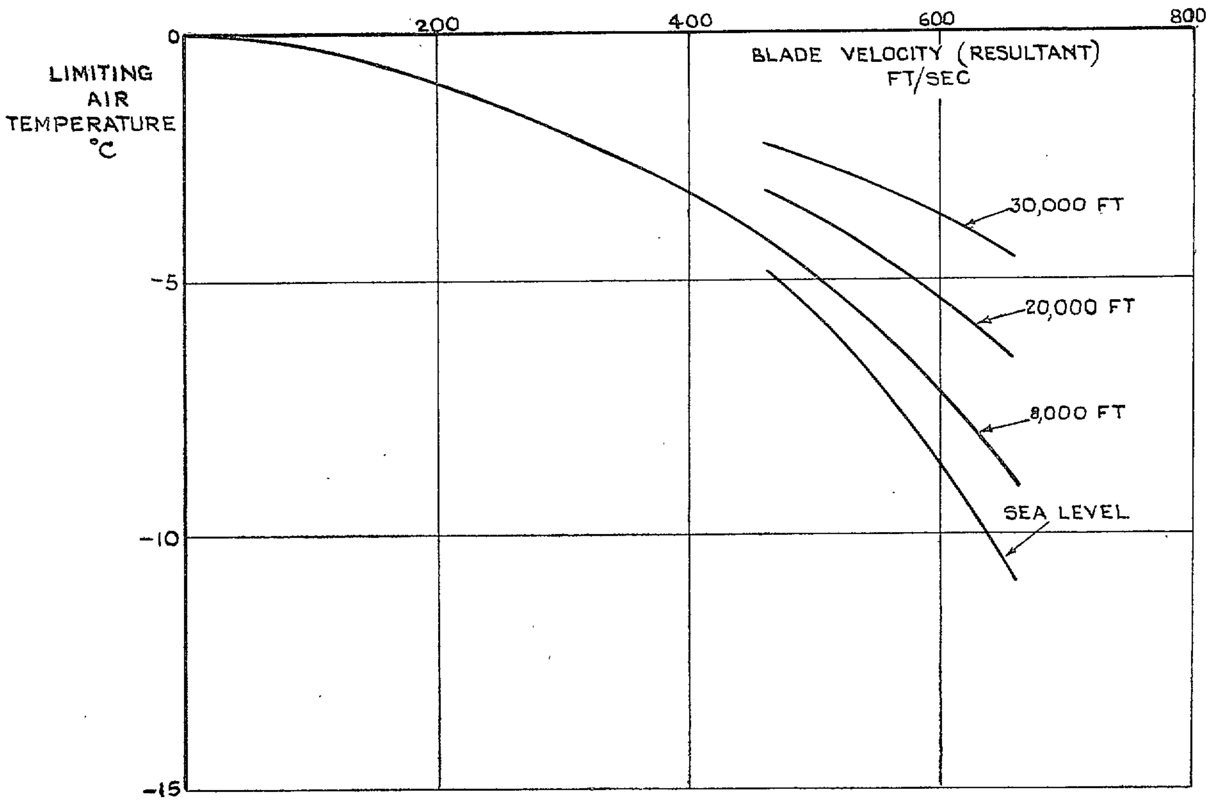

FIG. 6. Conducting blade. Variation of limiting air temperature for protection with velocity and altitude. $C_L = 0{\cdot}8$.

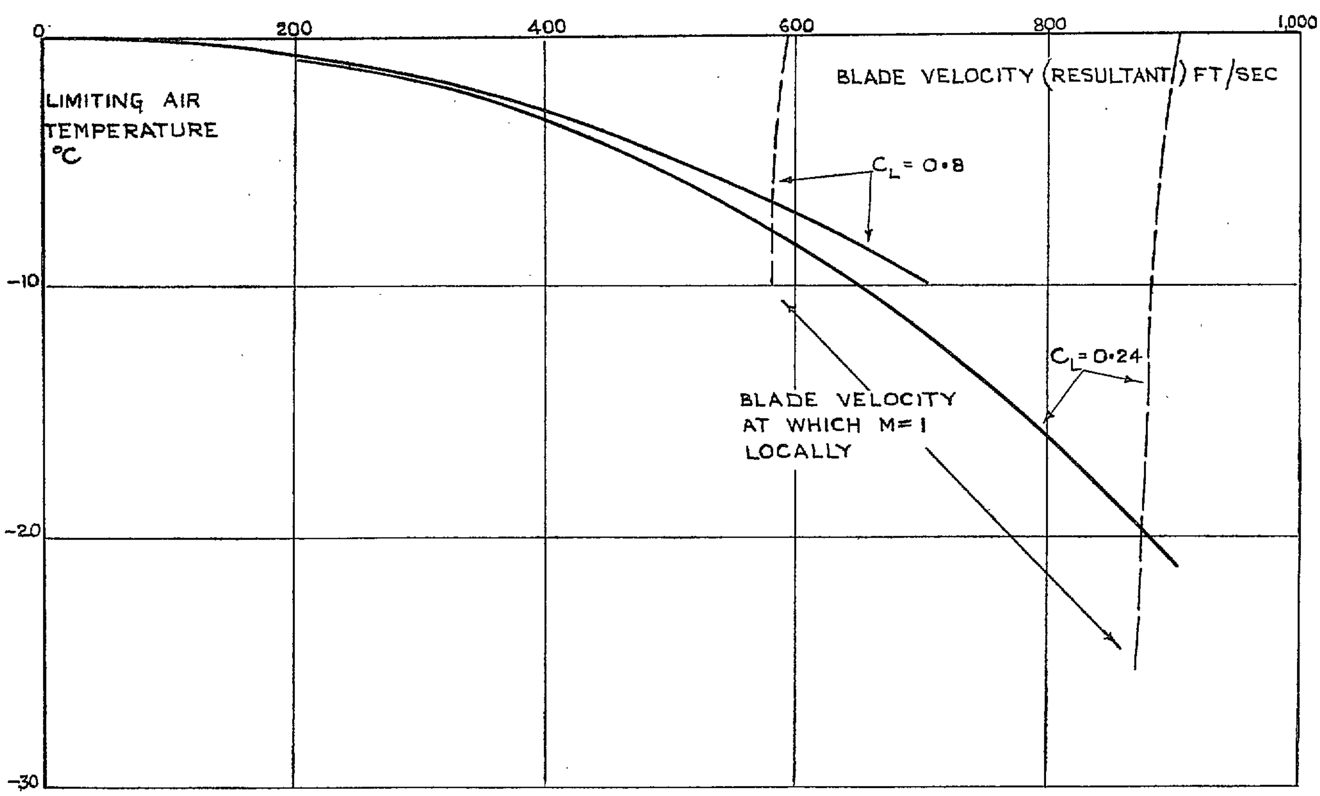

FIG. 7. Conducting blade. Effect of C_L on limiting air temperature for protection. 8,000 ft.

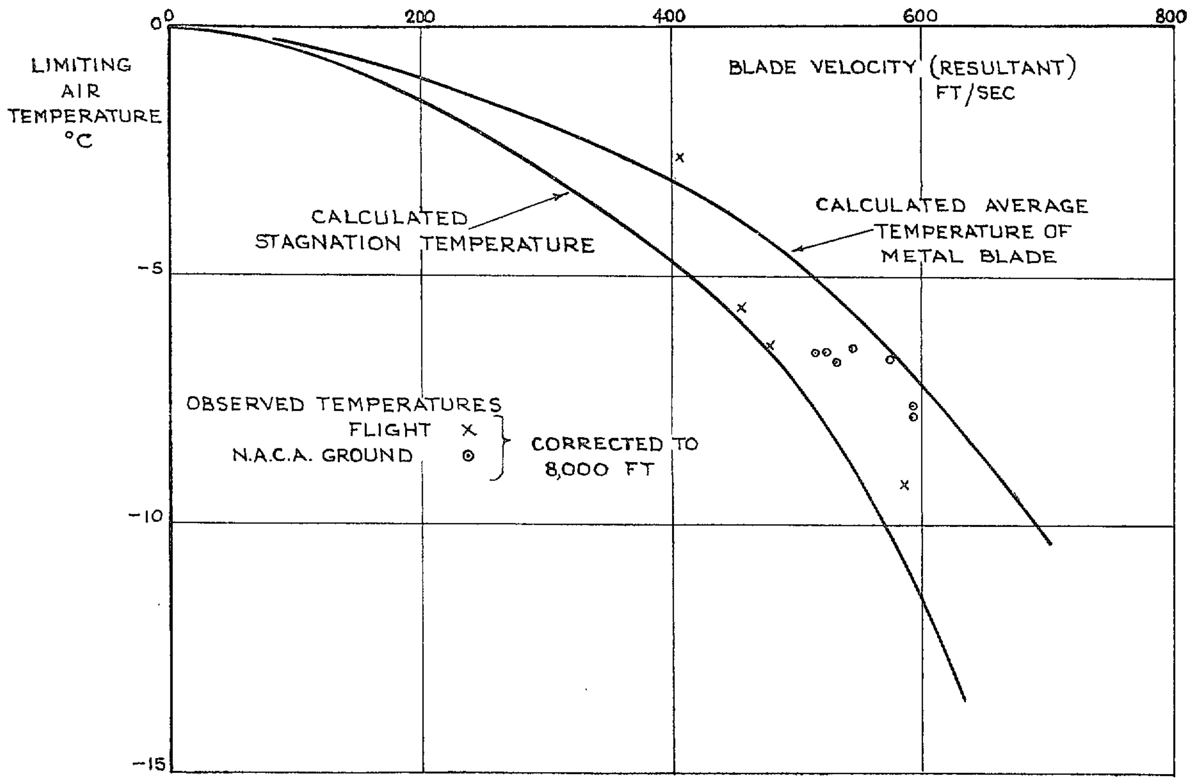

FIG. 8. Comparisons between temperatures of conducting blade as calculated and as observed on propellers. $C_L = 0 \cdot 8$. 8,000 ft.

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