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A CONSIDERATION OF FORCES AND THE MECHANISM OF ICE REMOVAL IN AIRCRAFT DE-ICING SYSTEMS

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INTRODUCTION

The hazards of aircraft icing in flight have had the attention of aircraft engineers and scientists for many years. Many different methods mechanical, chemical, and thermal, have been suggested to prevent, cure, or alleviate this condition. Mechanical systems, wherein ice is actually physically broken off the aircraft surfaces (e.g., by pneumatically inflatable shoes), have today little practical significance. Chemical methods, using coatings, paints, etc. on critical surfaces, have not been effective. The thermal methods of aircraft protection against icing conditions have many distinct advantages, which have warranted their recent increased development.

Thermal systems are usually divided into:

(1) anti-icing, where sufficient continuous heating is generated to prevent the formation of ice on critical components of the aircraft; and

(2) de-icing, where ice is allowed to form on the surface for a relatively short time; heat is then applied intermittently to break the high bonding forces of the ice to solid surfaces, and available external forces remove the ice.

Anti-icing systems have had and still have wide application, particularly for slower aircraft. Air heating of components (e.g., leading edges of wings) has been adopted in many aircraft. As flight speeds increase, however, the rate of water interception increases and higher and higher heat fluxes are necessary to evaporate all the water. If there is insufficient evaporation, the water will run back and freeze on the cold aft portions of the wing.

Thus the high flight speeds of current and future aircraft have placed the emphasis on cyclic or intermittent de-icing systems. Some of their advantages are:

(1) reduction of heat energy requirements,

(2) lower component weight, and

(3) minimization of the runback problem.

In those analytical and experimental studies of the de-icing phenomena that have been undertaken, heretofore, the emphasis has been on experimental research and development of various practical schemes for de-icing. The analytical studies have been quite limited because of the complex nature of the problem.

E. Brun, in an article in 1937, proposed an electrically heated intermittently operated de-icing system, apparently one of the first literature references in the field of intermittent heating. His static tests on samples of de-icer heating elements gave values of energy required to de-ice as a function of surface temperature below 32°F. By extrapolation he concluded that a finite energy input is required at 32°F, and therefore a finite amount of ice had been melted (approximately 1/20 mm). Other investigators have shown that ice removal takes place at a surface temperature of 32°F, while some show agreement with Brun (by extrapolation). The actual thermodynamic conditions have not yet been determined. These seemingly conflicting results have, at least in part, provided the incentive for the program described in this report.

The problem of the de-icing phenomenon can be subdivided into two separate groups for the sake of easier analysis:

(1) dynamic system of forces, and

(2) thermodynamic system of transient heat flow.

These effects are actually inseparable, but they can follow separate lines of basic thought. Future studies, integrating all these effects, will establish performance criteria of de-icing systems, with which the removal of ice can be predicted in terms of heat transfer and force parameters.

This report, a review and analysis of the dynamic forces occurring in de-icing systems, has been prepared in connection with the planning and interpretation of the experimental phase of the investigation. The research on the de-icing phenomena at the University of Michigan is concerned with all aspects of the problem. Other reports now in preparation deal with the heat transfer and other problems.

I. CLASSIFICATION OF FORCES

A study of the mechanism of ice shedding from aircraft surfaces, and the design of proper de-icing equipment necessitates a knowledge of the basic forces involved. The forces may be divided into two categories:

(1) Forces of adhesion are internal forces which make the ice adhere to the surface, and which have to be overcome in order to remove the ice. The adhesive forces occurring in the process of de-icing an iced aircraft surface may be classified in order of their occurrence as:

   (a) forces of solid adhesion and

   (b) forces with liquid interface, such as

      (i) surface tension and

      (ii) hydrodynamic forces.

(2) External forces available for removal, which depend on the particular physical application of a de-icing system.

II. FORCES OF SOLID ADHESION

In considering the chemical and physical phenomena of the adhesion of two solids, the most significant factor is the molecular attraction between the solids. Evidence in many pertinent fields indicates that molecular attractive forces are primarily responsible for the bond between any two surfaces and that the nature of the bond is a chemical one rather than a physical one. Considerable work has been done in this field, including some on the phenomena of ice-solid bonding. Current theroies on the adhesion of ice to solids indicate that the bonding force is due to the hydrogen bond between hydrogen and oxygen, or hydrogen and nitrogen.

Actual experimental values of the bonding forces are quite varied, since factors influence the ice and surface characteristics. Reported average values of adhesive strength of ice to metals (at 32°F) are:

Shear	77 lb/in.^{2}
Tension	90 lb/in.^{2}

In many cases the strength of the bond may be higher than the mechanical strength of the ice. The mechanical properties of ice are therefore pertinent to this topic. Many experiments have been performed on the mechanical properties of ice. However, as in bond forces, wide variations in reported values exist because of the difficulty of controlling the many important parameters. Exact quantitative interpretation is therefore rather difficult in most cases.

Ice, as a crystalline plastic solid, has adhesion and strength properties which are influenced by such parameters as:

(1) crystal orientation,

(2) impurities of ice and surface,

(3) ice age,

(4) ice structure (density),

(5) rate of loading, and

(6) temperature.

Average values of mechanical properties of ice (these are representative values: severe departures in reported data often occur) are given below.

Ultimate tensile strength	140 psi
Ultimate compression	475 psi
Ultimate bending	222 psi
Ultimate shear	114 psi
Young's modulus	13,300 psi
Poisson ratio	0.365

Mechanical and solid bond properties of ice are of importance in mechanical de-icing systems. In thermal de-icing systems, it is apparent that the high forces involved in solid adhesion make it mandatory that they be decreased by creating a liquid layer between the ice and the solid, since no inherent external forces of sufficiently high magnitude are available to remove ice in the case of solid adhesion.

III. BONDING FORCES OF ICE-SOLID WITH A LIQUID INTERFACE

The dominant factor in the removal of ice from metal surfaces is the creation of a water layer in the interface between the ice and the metal. Thus, the very high forces of the solid bond are substantially reduced, and the force requirements for ice removal are decreased. The creation of a water interface demands the heating of the ice to the melting point. Thermal de-icing may be accomplished in various ways, however, the phenomenon of creating a water interface is common to all and not necessarily a function of the heating system used. Thus, the basic phenomenon involving the nature of adhesion and the mechanism of adhesive action is entirely a physical one.

To facilitate the practical problem of ice removal in an ice-water-metal system, the study of the internal adhesion forces in this system is necessary. For ease of analysis, the force system may be divided into:

(1) forces normal to the interface, and

(2) forces parallel to the interface.

A knowledge of these forces will give part of the information necessary to set up criteria for ice removal, and a comparison with the available external physical forces will indicate its feasibility.

The study of the physical force system in thermal de-icing with a water interlayer is concerned primarily with (a) the forces of surface tension, (b) separation forces (hydrodynamic), and (c) viscosity. These will be discussed in terms of the various parameters which influence their values.

This discussion will be concerned largely with a static system, using constant parameters, although a thermal de-icing system will by its very nature be a dynamic one where conditions are practically transient throughout. It is impossible to isolate a static condition where an ice-water-solid system will retain constant values. It is apparent that experimental work is quite difficult if it is to involve the entire phenomenon, and certain practical simplifications must therefore be made.

The forces in an ice-water-solid system are functions of many variables;

A. Type of Ice

1. Density
2. Structure
3. Thickness
4. Shape
5. Impurities
6. Age
7. Temperature

B. Type of Surface

1. Geometry
2. Surface finish

C. Water Layer

1. Thickness
2. Viscosity

The prime physical variables in any de-icing system which influence the forces and the ice removal will be the thickness of the water layer and the geometry of the surface. The water interlayer thickness is a transient variable, a function of time, rate of heating, and the thermal properties of the system. Further discussions will of necessity assume constant values of these variables.

Thermal heating of the interface will melt the ice when the temperature reaches 32°F. It is practically impossible to maintain an equilibrium condition where the thickness of the water remains constant. Values for the water thickness have hitherto been deduced from the energy input into the system and estimated at any instant with a relatively high probability of error. The water thickness will gradually increase and the forces will change accordingly. The further behavior of the system will depend on other parameters, such as geometry, acting external forces, etc.

A. Effects of the Water Interlayer Thickness

In the following discussion, the surfaces are assumed to be flat.

1. Adhesion with Liquid Interface - Normal Force. The normal force between two solids with a liquid interface is due to the low static pressure developed in the liquid layer. These are well predicted by the theory of surface tension, which yields the relationship

$$\Delta P = F/A = \gamma(1/R_1 + 1/R_2)$$

where

ΔP = pressure differential,

F = force,

A = area of liquid layer,

γ = surface tension, and

R_1, R_2 = principal radii of curvature of liquid layer.

This basic formula simplifies to:

(1) Flat parallel surfaces

$$\Delta P = \gamma/R_1 \ (R_2 = \infty) \ ,$$

where ΔP = decrease in pressure.

(2) Hollow spherical bubble

$$\Delta P = 4\gamma/r \ ,$$

where ΔP = increased pressure and

r = radius of bubble.

For the case of water, typical values of γ as a function of temperature are

$$\gamma = 72.75 \text{ dynes/cm} = 415.4 \times 10^{-6} \text{ lb/in. } (68°\text{F})$$

$$\gamma = 75.64 \text{ dynes/cm} = 431.9 \times 10^{-6} \text{ lb/in. } (32°\text{F}) \ .$$

No liquid can sustain a force exceeding that given by the above formulas, unless the principal radii of curvature are so small that the concept of an invariable surface tension is not valid.

This concept is valid for extremely thin water interfaces, or the order of 10^{-6} cm in thickness, and the forces involved are very large. The formula predicts tension far in excess of what is known as the tensile rupture of water. This value of rupture actually sets an upper limit to the adhension force, which has been measured up to values of 60 atms and more. With incomplete films of liquid in the interface the very high tension forces may be sufficient to cause buckling of thick plates of solids (glass). Dissolved air may cause the film to rupture much more readily. It is evident that in such a system this mechanism would serve to break up solids (ice) under certain favorable conditions. However, it is doubtful that such destruction will occur in an actual de-icing system, because

(1) one of the solids (ice) creates the water film, usually of uniform layer throughout, and

(2) the small thicknesses are of a transient nature and may exist only for a very short period of time.

2. Adhesion with Liquid Interface - Tangential Force. The tangential force is associated with friction of solids, i.e., the resistance experienced in the process of sliding one surface over another. In general, friction phenomena are of a complex nature, and different mechanisms are postulated for the various forms. For ice-solid friction the coefficient of friction is quite low. The theories explaining this condition vary considerably; their one common factor is that all attribute the low friction to the lubricating effect of a water layer between the sliding material and ice. They differ in the reasons for this liquid layer. There are two current postulates which explain ice-solid friction at least qualitatively: the friction-melting theory and the vapor-film theory of lubrication. However, the actual mechanism of sliding friction is yet to be determined.

In the case of de-icing, the actual mechanism of sliding friction is not of immediate importance, and the friction between two solids does not occur in its basic form, i.e., the lowering of friction as an effect of sliding. In de-icing, the melting of ice to form a water interlayer is accomplished by means of external heating. The tangential surface forces are thus changed from the high values of a solid chemical bond to the low values of water layer lubrication. Many experiments indicate the very rapid change of the force magnitude. It appears that, almost without regard to the intensity of heating of the solid surface, the force changes almost instantaneously. One conclusion which may be qualitatively drawn from these limited descriptive experiments is that the presence of even a minute layer of water (monomolecular) will abruptly and considerably change the adhesive force. An increase in the water-layer thickness by further heating and melting of ice does not to any visible extent change the magnitude of this force.

It would seem that the molecular nature of boundary lubrication may be equal in effectiveness to that of complete or film lubrication, where a relatively thick layer of water exists between the surfaces. However, the molecular nature of the friction force in the case of boundary lubrication should be reconciled with the hydrodynamic nature in complete lubrication with layers of appreciable thickness, where the resistance is due entirely to the viscosity of the interface layer. Although considerable detailed work has been done on the effect of films on static friction for mechanical lubrication with oils, no data exist for water as a lubricant, and no data exist for the case of ice-water-solid friction. The effect of water-layer thickness on friction forces is not known. However, one qualitative conclusions may be surmised: that even the smallest layer of water will cause a substantial reduction of the adhesive force, and the friction force will be very small in the case of subsequent tendency to relative motion. The melting point of ice is clearly defined, and the attainment of 32°F at the ice-solid bond surface will cause a sharp breakdown of the tangential force necessary to move the ice along the surface. The phase relationship of ice to water may also have an influence on the nature and magnitude of the force, an effect which is not known.

As in the case of normal forces, the tangential forces are affected by the transient nature of the ice melting phenomenon in thermal de-icing. Static experiments involving ice are extremely difficult, and are further complicated by the molecular, and therefore extremely thin layers of water, the direct measurement of which is almost impossible.

The normal and tangential forces at the bond between ice and a solid change abruptly when a water layer is created by melting the ice by heating. The tangential force changes to a very low value at even small thicknesses of the layer, while the normal force, governed by surface tension, will remain appreciable until a relatively large thickness of water is created. The relative change of these two forces probably plays a dominant role in removing ice from a flat surface. Experiments directed toward the study of the interrelationship of these forces as a transient function of heating would be very revealing. A qualitative graph of this relationship for flat surfaces is shown in Fig. 1.

The graph of removal force for ice from flat surfaces as a function of heating time at constant heat flux (Fig. 1) indicates the changes in force magnitude and the character of the force. Up to the melting temperature the forces retain their maximum values for solid adhesion; then the normal component diminishes gradually with an increase in water layer thickness, governed by the physics of surface tension at very small thicknesses and by hydrodynamic effects at larger thicknesses. The tangential component drops rather abruptly as soon as the melting of ice starts and is of a viscous nature.

Because of the complex nature of the ice surface phenomena, especially near 32°F, the available data on the viscosity of ice are unsatisfactory. The various parameters affecting the viscosity of ice include

(1) temperature (especially near 32°F),

(2) stress magnitude and rate,

(3) structure and nature of the ice,

(4) impurities in the ice, and

(5) experimental procedure.

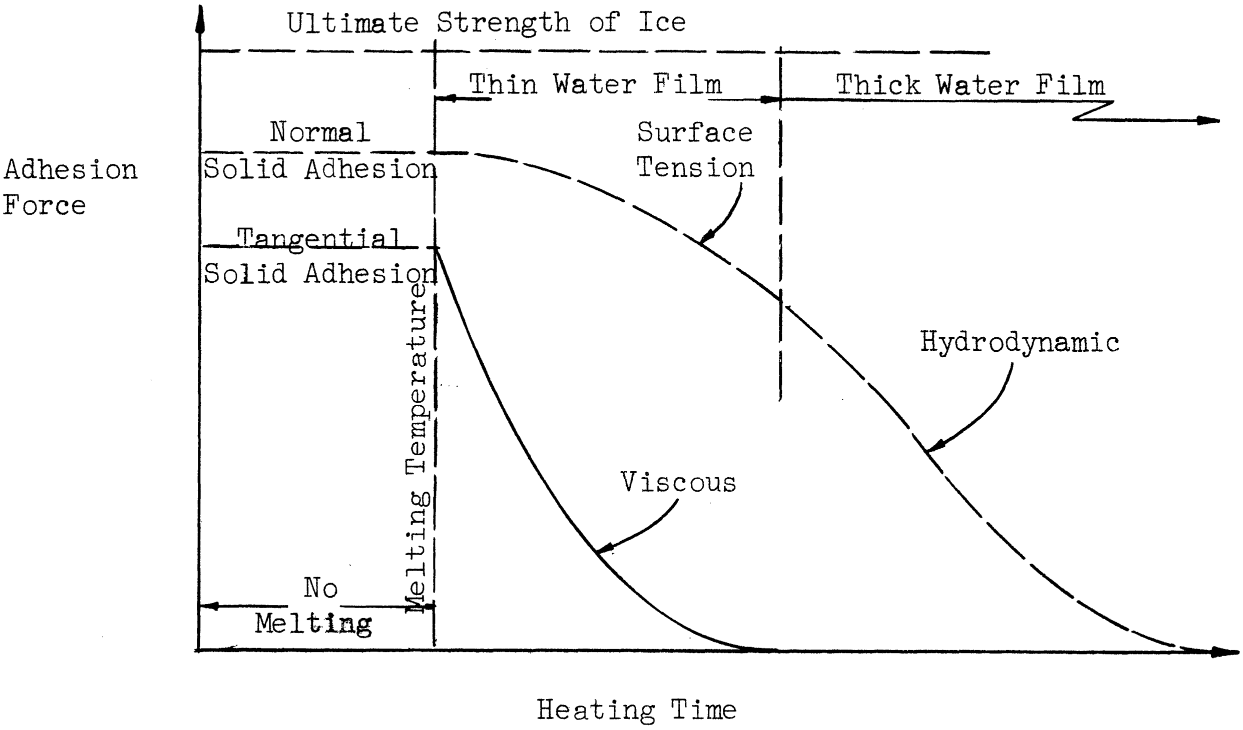

Fig. 1. Typical Diagram of Probable Variation of Adhesion Force with Heating Time.

Although some of the observations are very interesting, they have been made under such experimental circumstances that absolutely reliable values do not exist. The influencing parameters are so varied in the existing data that any satisfactory correlation is impossible. It may be stated that the effective viscosity is of the order of 10^{10} to 10^{12} poises.

The friction phenomenon of ice on solids is probably influenced by parameters:

(1) load,

(2) structure and nature of the ice,

(3) structure and nature of the solid,

(4) water lubricant thickness,

(5) temperature, and

(6) experimental procedure.

General agreement is reported in that the static coefficient of friction is larger than the dynamic coefficient. Of particular significance is the extremely low value with water lubrication, wherein the ice may slide on the solid surface at the smallest inclination. Data on this point are meager and inconclusive.

3. Separation Forces. In the case of solid flat surfaces having a thick liquid interface between them and completely surrounded by the liquid, the surface tension and friction forces are practically zero. They may be separated by the smallest normal force; however, the separation must be carried out very slowly. The viscosity of the liquid becomes an important factor here; if separation is fast large forces may be induced especially if the viscosity of the liquid is appreciable. As the surfaces are being pulled apart, the liquid must flow into the region between them. Hydrodynamic considerations lead to the Stefan equation, verified experimentally

$$\frac{F}{A} = \frac{3}{4} \frac{\mu R_e^2}{t} \left(\frac{1}{h_1^2} - \frac{1}{h_2^2}\right) ,$$

where R_e = equivalent diameter of surface area,

μ = viscosity of liquid,

t = time to separate liquid from solid,

F = separation force,

A = area of surface, and

$h_1 - h_2$ = separation distance.

Assuming complete separation for water ($1/h_2 \cong 0$),

$$\left(\frac{F}{A}\right) t = \frac{0.01794 \times 3}{4} \frac{R_e^2}{h_1^2} .$$

Assuming $A = 1\ \text{cm}^2$ $\mu = 0.01794$ gr/cm-sec at 32°F

$R_e = 0.564$ $R_e^2 = 0.318$

$$\left(\frac{F}{A}\right)t = \frac{0.004425}{h_1^2} \text{ dynes/cm}$$

$$\text{or} \quad \left(\frac{F}{A}\right)t = \frac{0.00451 \times 10^{-6}}{h_1^2} \text{ Kg/cm}^2 .$$

The graph in Fig. 2 indicates the separation time necessary at the value of surface tension between two surfaces as a function of the distance between the surfaces. The surface tension force for water is

$$F_2 = \frac{154}{h_1} 10^{-6} \text{ Kg/cm}^2 .$$

The time for separation of the two surfaces at the above values F_2 is

$$t = \frac{.00451}{\left(\frac{F_2}{A}\right) h_1^2} 10^{-6} \text{ Kg/cm}^2 .$$

The constants in the above equations for water are

μ = 0.01794 poise,

γ = 75.6 dynes/cm, and

A = 1 cm^2 .

The validity of this treatment is not known, as complete experimental data do not exist, especially at small values of h_1. At these small values the assumption that the separation force is the force necessary to impart to the liquid layer the speed determined by the speed of separation may not be wholly valid, as molecular forces of attraction may exist between the solid surfaces.

Thus the mechanism and the theory of the separation of two surfaces have been developed. A comparison with available external forces will indicate the possibility of ice removal in the case of flat surfaces.

B. Effects of Geometry on the Forces in De-Icing Systems

So far the ice-water-solid system has been discussed for flat surfaces. When a surface such as a cylinder or sphere (constant radius of curvature) is heated, the tangential force drops rapidly, while the normal surface tension may remain high. This permits the ice layer to move freely along the surface, but still be quite well attached to it. This often happens in the case of de-icing of cylindrical surfaces. The ice layer is difficult to remove, as any aerodynamic force will simply change its position and the gravity force is usually too small to have any appreciable effect. Increasing the thickness of water layer, and thereby decreasing the surface-tension effects, will permit easier removal.

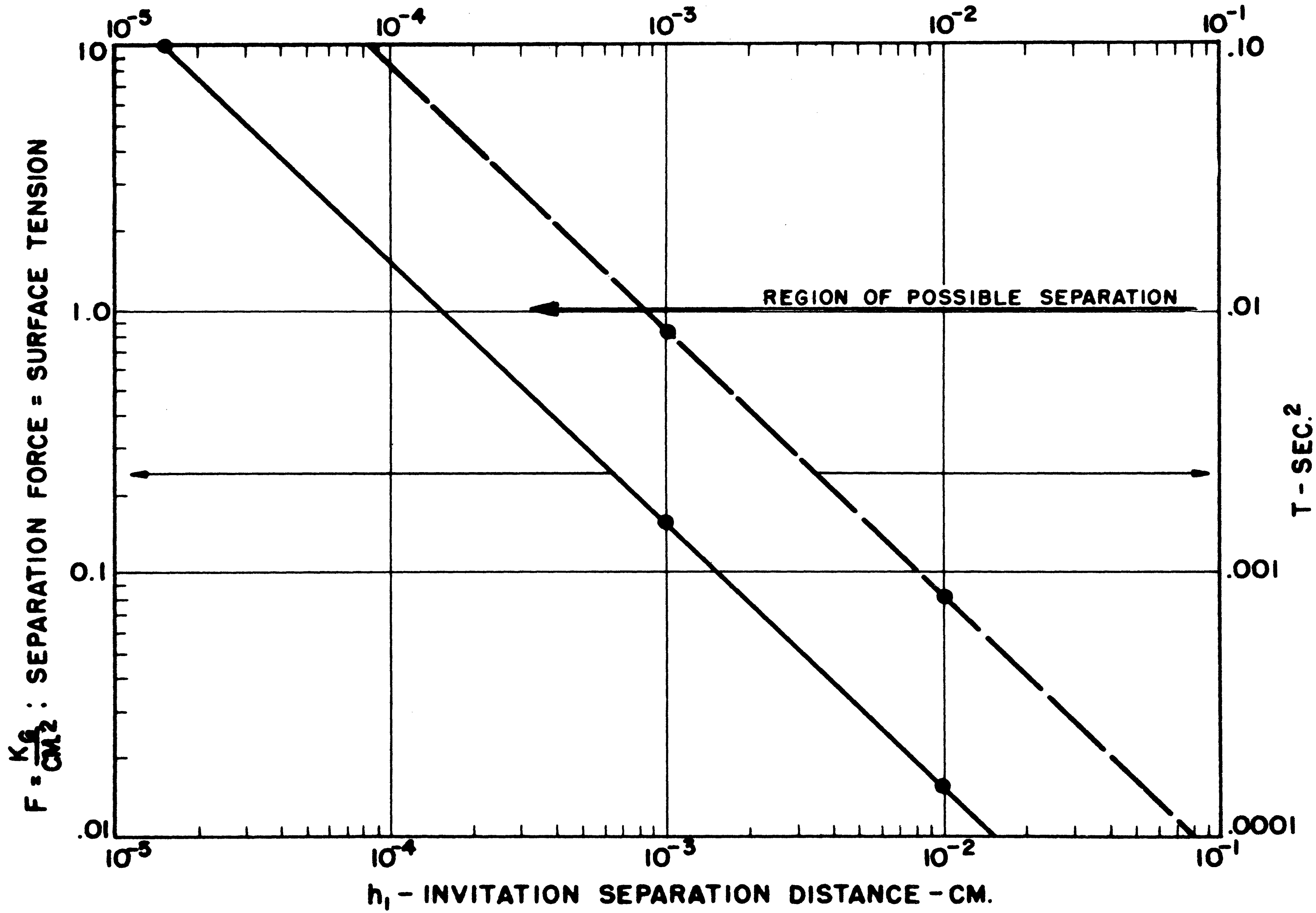

FIG. 2. FORCE BETWEEN TWO FLAT PLATES AS A FUNCTION OF SEPARATION DISTANCE.

Of more practical value and interest are surfaces with a variable radius of curvature. The parabola may be used to simulate closely the surface of a typical airfoil, and the conclusions derived may be directly applicable to wing surface de-icing. Figure 3 indicates the radius-of-curvature variation of a parabola fitted to an airfoil section near the leading edge.

A finite block of ice adhering to a parabolic surface has the same surface geometry over the covered portion. If the bond is now broken, the ice block will have only a small tangential restraining force, except for the geometrical mismatching between the two surfaces in any possible displacement relative to each other. If the ice surface is near the leading edge and the ice tends to move back, the surface mismatching will give rise to an increase in volume between the ice and the solid. In the case of flat or constant-radius-of-curvature surfaces the volume does not change, and no forces due to geometrical effects exist. Apparently this volume increase plays a dominant role in the mechanism of ice removal from wing surfaces.

The rate of volume change between two solid parabolic surfaces matched over a small portion, as one tends to move or moves over the other, may be readily calculated. For Fig. 4 this change was calculated for a parabola ($6y^2 = x$ and chord length of ice cap = 1/2 in.) at various positions of the ice in its initial motion to the rear. The significant aspect of this calculation is the high rate of volume change at and near the leading edge. As the block of ice starts from a position farther back, the volume rate change becomes smaller and smaller. If ideal conditions are now assumed for two solid surfaces with a finite, but quite small, water-layer thickness, any small external tangential force will tend to move the ice surface toward the direction of increasing volume between the two surfaces. Under these conditions a capillary is created with a variable cross section. For water with an acute contact angle the water layer will tend to flow toward the narrowest portions of the section, i.e., the front and rear ends of the ice surface. This flow in turn creates an air gap in the center portion of the ice cap. With small liquid thicknesses, and therefore small internal pressures, the relatively higher external pressure will give rise to a highly stressed ice cap. Under favorable conditions these forces may readily break the ice cap, which will subsequently be removed from the surface in small pieces. The actual phenomenon is a dynamic and transient one; i.e., heat is continuously being fed to the system and water is continuously being created. What will happen to the ice cap will be determined by two factors

(1) rate of water creation (ice melting), and

(2) rate of volume increase between ice cap and wing surface, i.e., relative motion between them.

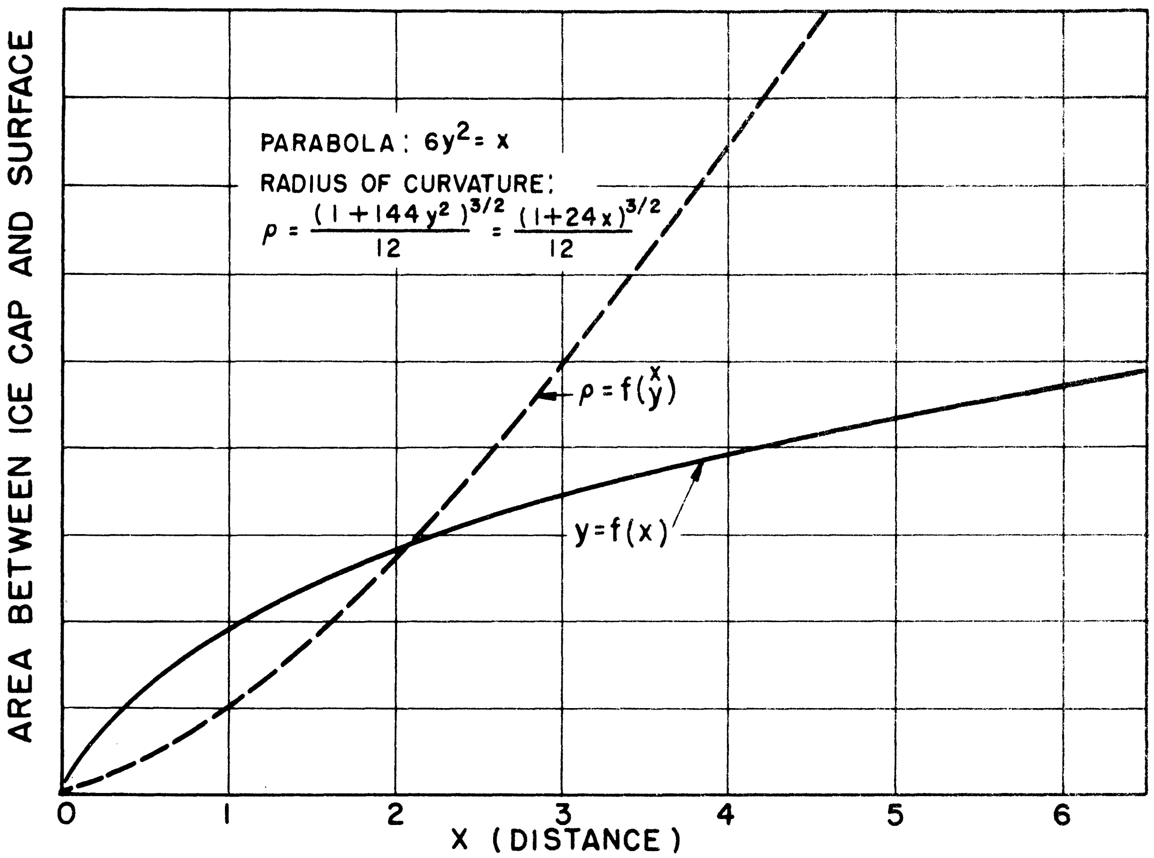

FIG. 3. TYPICAL CURVE FOR PARABOLA AND ITS RADIUS OF CURVATURE

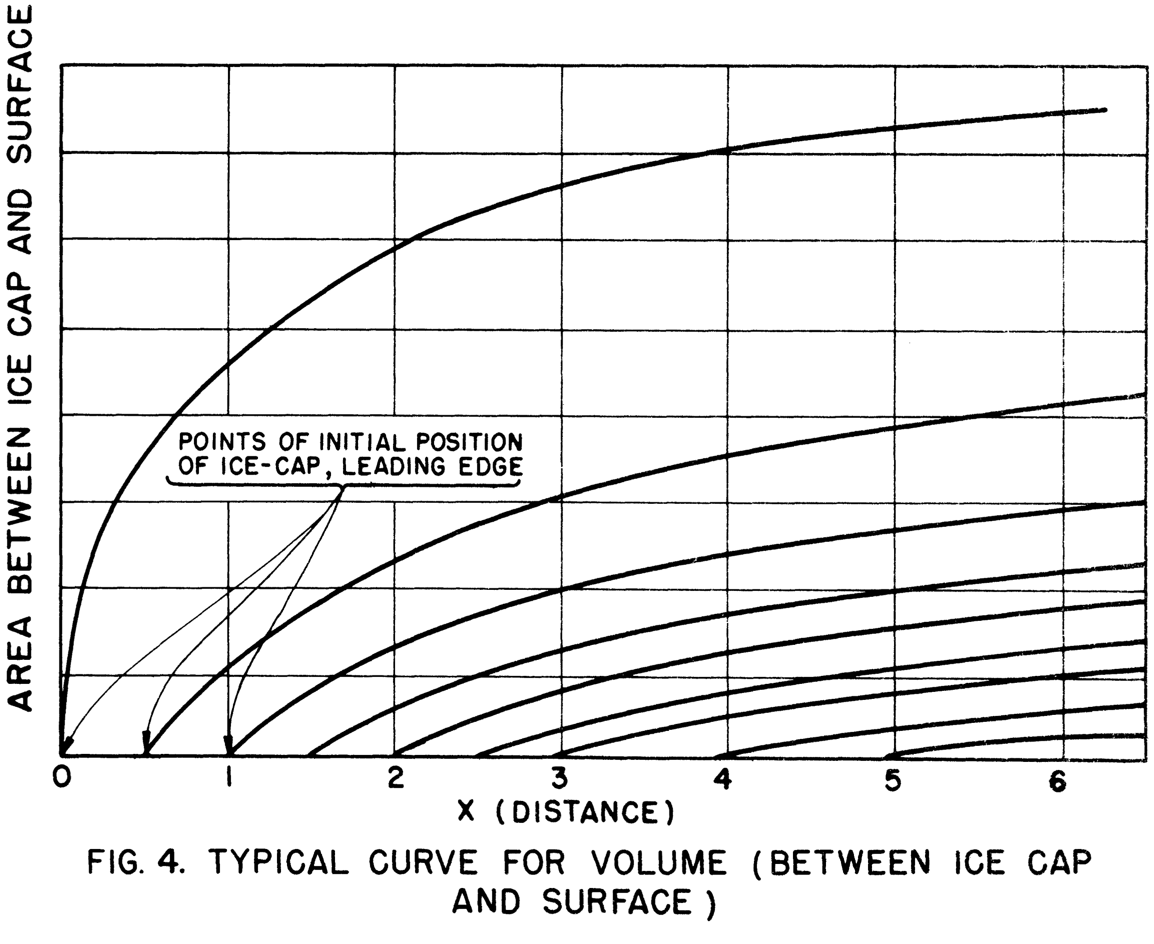

FIG. 4. TYPICAL CURVE FOR VOLUME (BETWEEN ICE CAP AND SURFACE)

If the rate of ice melting is greater than the rate of volume increase, then the water-layer thickness will continually grow, and the ice will be lifted bodily until the normal force becomes small, and the ice is removed in one piece. On the other hand, if the rate of ice melting is less than the rate of volume increase, the water will not fill the full volume, but will flow toward the edges and leave an air gap of lowered pressures in the center. Thus, the mechanism apparently exists for breaking the ice into small pieces and removing it by tangential aerodynamic forces. It is evident, then, that the mechanism of ice removal may be of dual nature, depending on the effect of geometry and the magnitude of heat flux (rate of melting).

If both rates are nearly equal, however, no mechanism for ready removal exists and the ice may persist on the surface for some time, until the water layer gets quite thick; it may even move back substantially, until a component of external force removes it.

The actual phenomena may be quite a bit more complex. Other factors which may modify this behavior include

(1) nature and density of the ice (porosity),

(2) impurities in the ice and the solid surface (air gaps),

(3) position of hot ice on the surface,

(4) extent of leading-edge parting strip, and

(5) nonuniform heating (cold spots on the surface).

Removal of ice from wing surfaces is further complicated by the fact that the ice does not exist in small isolated pieces but rather in long stretches of ice surface. Strip heating, wherein only a portion of the total surface ice is removed in a cyclic fashion, will impose end conditions on the ice with a water layer which will retard, if not prohibit, the removal of the ice. The practical solution would be to begin the strip heating on ice portions where at least three edges are free (in the case of rectangular formations), for example the tip or the root of a wing. Heated ice fences, running chordwise, would break the ice sheet into smaller portions which would be more readily removed. It therefore seems quite essential to have parting strips

(1) along the leading edge, and

(2) chordwise.

The necessity of a leading-edge parting strip is obvious. A complete envelope of ice around the leading edge provides a very stable equilibrium condition in terms of forces, and no mechanism or forces exist for removal. The parting strip may be very thin, just enough to break the continuity of the ice strip around the leading edge. The best leading-edge-strip location is determined by (1) the stagnation point at each angle of attack, and (2) the point of maximum impingement. However, if a finite parting strip is used, its exact location would not be critical. This strip should be heated (anti-iced) continuously, as the accumulation of ice is highest here, and much longer intermittent heating would be required for initial melting of the thick leading-edge portion. Chordwise parting strips, if flush with the surface, should also be heated continuously. However, if a protruding-type fence is used, intermittent heating may prove to be as efficient.

IV. EXTERNAL FORCES AVAILABLE FOR ICE REMOVAL

The external forces available for ice removal in the case of fixed aircraft components during flight may be classified as

(1) gravitational,

(2) vibrational,

(3) centrifugal, and

(4) aerodynamic.

A stationary wing surface may have the ice fall off by gravity action along, after a water layer is created to decrease the bonding forces appreciably. The ice removal process in this case may be a long one. Gravity effects, wherein ice slides off a surface suitable inclined to give a downward component, play an insignificant role in the mechanism of ice removal.

The vibrations of an aerodynamic surface may give rise to appreciable forces, especially in the case of large amplitudes. These forces may have sufficient magnitude to influence the equilibrium of an ice cap, particularly if the normal adhesion is low. It is doubtful that these vibrational forces have any significant practical influence in modern aircraft, where rigidity requirements are imposed by flutter prevention.

Centrifugal (inertia) forces may be generated by the motion of an ice cap over a curved surface. However, the motion of the ice is usually quite limited and these forces are never encountered in appreciable magnitude.

The aerodynamic force is the most influential external factor in the mechanism of ice removal. Pressure and viscous forces over the aircraft surfaces will give force components which have a direct effect on the removal of ice, but only after a water layer has been created with a radical lowering of the adhesion forces. In the case of a solid bond, the relatively low aerodynamic forces will have no influence on the very stable icing force system. Creating a small layer of water between the ice and the solid lowers the tangential component of internal resistance to such an extent that a relatively small drag component of the aerodynamic force will have an appreciable effect on the mechanism of ice removal. In fact, the breaking of the tangential bond is so rapid, with tangential internal force becoming practically zero almost instantaneously, that the time for removal of a relatively small cap of ice (small mass) is practically independent of the external force, providing it is above a certain minimum value sufficient to move the ice cap with some finite acceleration. This mechanism of operation assumes, of course, that the conditions of geometry and heating are compatible, as previously described. It may be stated, then, that the influence of velocity, which determines the magnitude of the aerodynamic force, is a secondary factor; and even substantial increases in velocity would not have a large effect on the time or mechanism of practical ice removal.

A possible external effect on the removal of ice arises in the case of nonuniform heating of a surface, which produces cold spots. In this case, the ice cap will be anchored by the high adhesion at any point where the temperature remains below freezing. If the water layer increases appreciable at the free end (above the boundary-layer extent) of the ice cap, the dynamic head built up underneath the ice may cause bonding fracture of the ice.

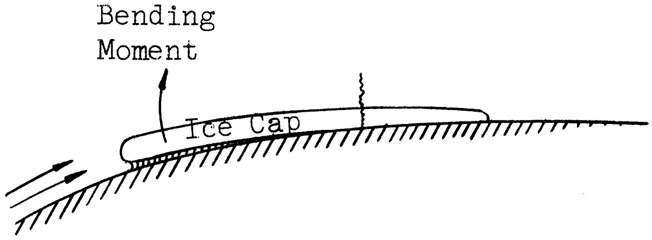

Fig. 5. Mechanism of Ice Fracture with Cold Spots.

Numerical values for representative velocities and thicknesses of ice of current aircraft indicate the correct order of magnitude of this effect.

V. CONCLUSIONS

The previous discussion indicates several conclusions which characterize the mechanics of ice removal in de-icing systems:

(1) The removal of ice from aircraft surfaces by a de-icing system is dependent on a water layer being created between the ice and the solid surface.

(2) Geometrical and heating effects must be compatible for fast removal of ice.

(3) Leading-edge and chordwise heating strips are necessary for efficient and fast removal.

(4) Heating requirements for melting of ice are minimal, as only a very thin layer of water is necessary to break the high adhesion of ice to solid.

(5) The effect of available external forces on the time for ice removal is secondary, providing the force is above a certain minimum.

It is apparent that considerable uncertainty exists as to the exact mechanical nature of ice removal from aircraft surfaces. This uncertainty is emphasized and complicated by the lack of understanding and lack of experimental evaluation of the basic operation of adhesion forces between solids with a water interface. The number of physical parameters affecting this process is quite large, and they have not been systematically evaluated.

Study of the following factors would assist a rational evaluation of de-icing systems:

(1) the change of normal and tangential forces as a function of heat input, and

(2) the rate of change of water-layer thickness as a function of heat input and the rate of melting, with emphasis on the rate at the moment of breaking the ice-solid bond.

APPENDIX

SOME PROPERTIES OF WATER AND ICE

		Water (32°F)	Ice (32°F)
Weight	$\frac{lb}{ft^3}$	62.41	57.50
	$\frac{gm}{cm^3}$	.97	.92
Specific Gravity		1.0	.922
Specific Heat	$\frac{Btu}{lb\,°F}$	1.00	(.504)
C	$\frac{cal}{gm\,°C}$	1.00	(.504)
Thermal Conductivity	$\frac{Btu}{hr\ ft\ °F}$	.348	1.294
K	$\frac{cal}{sec\ cm\,°C}$	1.44×10^{-3}	5.35×10^{-3}
Thermal Diffusivity	$\frac{ft^2}{hr}$	.0066	.0456
K	$\frac{cm^2}{sec}$	1.69×10^{-3}	11.8×10^{-3}
Latent Heat	$\frac{Btu}{lb}$	970.2 (heat of vaporization)	144 (heat of fusion)
Viscosity	(1 atm) poise	0.01793	

Conversion factors:

1 Btu = 252 cal = 1055 joules = 775 ft lb
1 Watt = .2389 cal/sec = 3.413 Btu/hr
1 lb = 453.6 gm

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