Deicing of Solids Using Radiant Heating

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This paper considers removing ice adhering to a solid substrate by irradiating the free surface of the ice layer. An acrylic and a metal are used as solids, and an array of quartz halogen dichroic lamps having a large fraction of their spectral energy in the visible and near-infrared spectrum are employed as the radiation source. The effects of ice layer thickness, radiation properties of the substrate surface, and the magnitude of the incident radiation flux are studied. A transient one-dimensional heat-conduction/radiation analysis is used to compare the model predictions with measurements. The results show that, for otherwise identical conditions, ice is more readily removed from an opaque metal than from a semitransparent acrylic substrate.

Nomenclature

c = specific heat
F = local radiation flux
F_1^o = radiation flux incident on ice surface
Fo = Fourier number, $(k_1/\rho_1 c_1)t/\delta_1^2$
g = mass-transfer coefficient
h = heat-transfer coefficient
Δh_{fg} = latent heat of fusion of ice
k = thermal conductivity
s = thickness of ice layer melted
T = temperature
t = time
x, = coordinate; see Figs. 2 and 3
α = absorptivity of surface for a substance considered to be opaque
β = extinction coefficient
δ_i = instantaneous ice layer thickness
δ_1 = initial thickness of ice layer
δ_2 = thickness of substrate plate
ϵ = emissivity
κ = absorption coefficient
λ = wavelength
λ_c = cutoff wavelength beyond which ice and Lucite are opaque to radiation from the source
ρ = density or reflectivity
σ = Stefan-Boltzmann constant
τ = transmissivity of an interface
ω = mass fraction of water vapor

Subscripts

i = ice
s = substrate
sur = air ambient surroundings
1 = ice or free surface
2 = substrate-ice interface or substrate
3 = insulation-substrate interface
∞ = ambient air

Superscripts

$+$ = forward direction
$-$ = backward direction
o = external radiation

Introduction

THE transparency of domestic, automobile, and aircraft windows is affected by condensation of water vapor, water droplets, and ice layers that may form and adhere to the glass. The inner window surfaces are also susceptible to condensation in the form of fog or frost during most of normal aircraft operation, particularly when the aircraft is descending from high-altitude flight, unless fog and frost protection system is provided.[1] In cold regions or during winter months, ice adhering to aircraft, ships, runways, streets, and all kinds of solid surfaces presents a problem of removing adhering ice layers which does not appear to have been solved satisfactorily. A description of various types of ice, fog, frost, and rain protection systems is available in the literature.[1] For years several methods have been used to control ice creation on ships, offshore units, aircraft, and other structures. These methods may be divided into three main groups: thermal, chemical, and mechanical.[2] Thermal methods may be used either to prevent icing or to remove ice already formed on some surface. For example, melting of ice layers adhering to solid surfaces using thermal[3-5] and radiant[6-10] energy sources has been suggested. It has also been recognized that the temperature of the radiation heat source plays a key role not only in the melting of ice[9,10] but also of other[11] materials. The purpose of these studies[6-10] was to melt ice and not to deice solids using radiant heating.

The purpose of this paper is to report on an experimental study of removing a thin ice layer adhering to solids using an external radiation source. Specifically, a source that contains a large fraction of its radiant energy in the visible and near-infrared part of the spectrum is suggested. In this part of the spectrum ice is translucent to radiation, and a significant fraction of the radiant energy incident on the free (ice-air) surface would reach the substrate-ice interface. The intent is not to melt the ice but to raise the interface temperature and to melt a microlayer of ice that weakens the adhesive strength between the solid and ice, since it is known that the adhesive strength increases with decreasing temperature of the ice-substrate interface.

In this paper, a consideration is given to removing a thin ice layer adhering to a vertical solid substrate using a radiation source that simulates the solar spectrum. The effects of the ice

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layer thickness, magnitude of the incident radiation flux, and different substrate materials are investigated. Deicing by direct irradiation of the back side of the semitransparent substrate to which an ice layer adheres (on the front side) and defogging of the substrate are also examined.

Experiments

Test Apparatus

A schematic of the test apparatus used for studying deicing by irradiation from an external source is shown in Fig. 1. A 80×80 mm^2 wafer of ice that adheres to a substrate was suspended from a sample holder. The radiation source used in the study was an array of quartz halogen dichroic mirror lamps (Philips, model 13117). The lamps are designed to simulate the spectral distribution of solar radiation and approximate the solar spectrum quite well. According to measurements, virtually all (>99%) of the radiant energy is located in the spectral range of 0.3–2.4 μm.[12] The lamp system provided uniform irradiation over the specimen to within 10%.[12]

Water was frozen in a square container made of Lucite (polymethylmethacrylate) that measured $80 \times 80 \times 15$ mm. The container was designed in such a way that the lateral walls could be removed after ice had formed and remained adhering to the substrate.

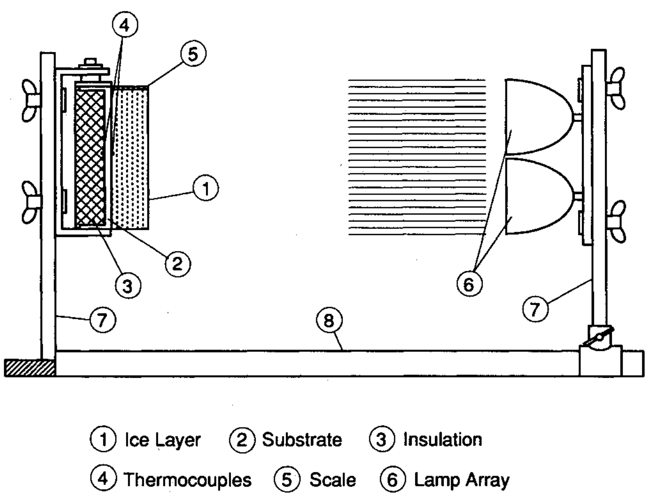
The radiation flux incident on the surface of the ice was measured with a thermopile (Eppley, model 4967) that was calibrated by the manufacturer. The sensing element of the thermopile is not spectrally selective; however, the quartz window placed in front of the detector to reduce the convection is selective. Quartz is transparent in the spectral range of 0.3–2.3 μm, and this effectively includes the entire spectrum of the solar simulation lamps used in the experiments.

Copper-constantan thermocouples that attached to the substrate-ice interface and to the back side of the substrate were used to measure temperatures. The thermocouple outputs were read with a programmable automatic scanning multichannel data logger with a printer (Esterline Angus model PD 2064). The voltage output of the radiometer was measured with a digital multimeter (Keithley model 160).

Experimental Procedure

Each experiment began with a preparation of the ice specimen. A rubber O-ring was used to seal the substrate and the container. The vertical walls of the container were coated with a high-vacuum grease (Dow Corning) to prevent the ice from adhering to the Lucite walls. After this preparation, the container was filled to about two-thirds of the desired depth with water. It was then placed in a compartment of a refrigerator. After the water was frozen, the remaining fraction of about one-third of water was added to be frozen in order to obtain a smooth ice surface. It took about 6 h to freeze the water and reach equilibrium conditions.

Before each test run, the radiant lamps were activated, and the data acquisition system was placed in operation. The test cell covered with insulation was removed from the refrigerator. The substrate with the ice adhering to it was detached from the container and was immediately mounted to the sample holder. The thermocouple leads were connected to the data logger. After this preparation, which took less than 1 min, the power to the radiant lamps was turned on and kept at the desired level, and the deicing process was started. The thermocouple readings continued to be recorded at the desired frequency, and the experiment was terminated when the ice fell off the substrate.



① Ice Layer ② Substrate ③ Insulation
④ Thermocouples ⑤ Scale ⑥ Lamp Array
⑦ Holder ⑧ Optical Rail

Fig. 1 Schematic of test apparatus.

Analysis

Physical Model and Governing Equations

To support the experimental work, a simple mathematical model of the physical system is constructed. The ice layer is uniform in thickness, and heat transfer in the layer of ice and in the substrate is assumed to be one-dimensional, i.e., in the direction perpendicular to the face only (Figs. 2 and 3). The radiation flux incident on the exposed ice surface was assumed to be uniform. The dependence of the thermophysical properties of ice and substrate materials on temperature is neglected. Water, if formed on the free ice surface upon melting of ice, is assumed to run off immediately and to bare the surface. In the analysis, volumetric emission of radiation is neglected in comparison to the absorption of external radiation. To simplify the analysis further, we assume that the ice falls off as soon as the temperature at the ice-substrate interface has reached the melting point of ice (0°C). A problem of combined conduction/radiation heat transfer in a layer of ice adhering to an opaque substrate was treated by Seki et al.[6,10] The analysis presented in this paper extends previous work by accounting for inter-reflections of radiation between the ice-air and the ice-substrate interfaces and by considering a substrate that is also semitransparent to radiation from the external source.

The transient energy equation in a plane, one-dimensional layer of ice is

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = k_1 \frac{\partial^2 T_1}{\partial x^2} - \frac{\partial (F_1^+ - F_1^-)}{\partial x} \tag{1}$$

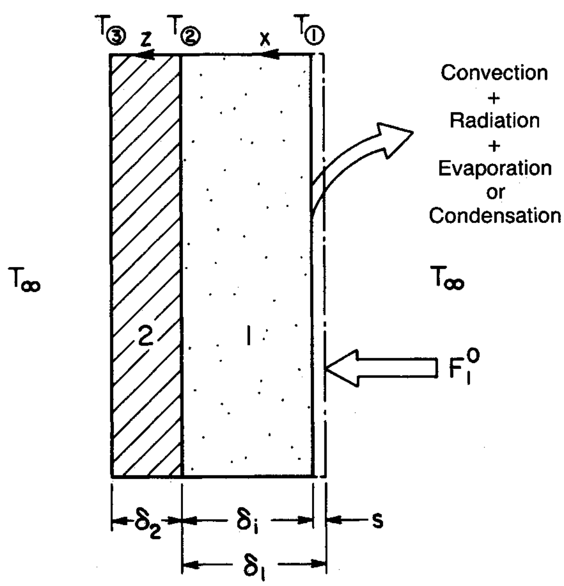


Fig. 2 Physical model and coordinate system for conduction/radiation heat transfer in the substrate-ice system.

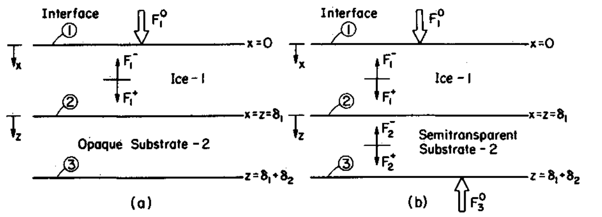


Fig. 3 Schematic of the radiation model: a) opaque substrate plate; b) semitransparent substrate plate.

and in the substrate it is

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = k_2 \frac{\partial^2 T_2}{\partial z^2} - \frac{\partial (F_2^+ - F_2^-)}{\partial z} \tag{2}$$

where F^+ and F^- are the radiative fluxes in the forward and backward directions, respectively, and will be defined later. Note that the origin of the coordinate is $z = \delta_1$ (Figs. 2 and 3). This was done to simplify the notation for the radiative transfer.

The boundary conditions on temperature at the free (ice-air) surface were obtained from an energy balance that accounted for heat conduction in the ice, convection, evaporation, or condensation and radiation heat exchange in the part of the spectrum ($\lambda > \lambda_{c,i}$) where ice is considered to be effectively opaque (i.e., radiation is considered to be a surface phenomenon) to radiation. The energy balance at the free surface ($x = 0$) can be expressed as

$$k_1 \frac{\partial T_1}{\partial x} = h[T_1(0) - T_\infty] + g\Delta h_{fg}\rho(\omega - \omega_\infty)$$

$$+ \epsilon\sigma T_1^4(0) - \alpha\epsilon\sigma T_{\rm sur}^4 - \int_{\lambda_{c,i}}^{\infty} \alpha_\lambda F_{1,\lambda}^o \lambda \, d\lambda \tag{3}$$

The first term on the right-hand side of Eq. (3) accounts for convection and the second for evaporation or condensation heat transfer. The third term accounts for emission of radiation, and the fourth and the fifth represent absorption of external long-wave radiation ($\lambda_{c,i} < \lambda < \infty$), which originates outside of the layer (i.e., the ambient surroundings and the external source). In writing Eq. (3) the energy required to melt ice was neglected.

At the ice-substrate interface 2 ($x = z = \delta_1$; see Figs. 2 and 3), the energy balance yields

$$k_1 \frac{\partial T_1}{\partial x} - k_2 \frac{\partial T_2}{\partial z} = \int_0^{\lambda_{c,i}} \alpha_{2,\lambda} F_{1,\lambda}^+(\delta_1) \, d\lambda \tag{4}$$

The term on the right-hand side of this equation accounts for absorption of the external radiation by an opaque substrate. The external radiation in the semitransparent part of the spectrum ($0 \le \lambda < \lambda_{c,i}$) incident on the air-ice interface 1 is partially transmitted across the layer of ice and is in part absorbed by the substrate. If the substrate is semitransparent for $\lambda_{c,s} < \lambda_{c,i}$ and opaque for $\lambda > \lambda_{c,s}$, the boundary condition at interface 2 becomes

$$k_1 \frac{\partial T_1}{\partial x} - k_2 \frac{\partial T_2}{\partial z} = 0 \tag{5a}$$

If the substrate is semitransparent for $\lambda_{c,s} > \lambda_{c,i}$ and is opaque for $\lambda > \lambda_{c,s}$, the boundary condition at interface 2 must be modified to

$$k_1 \frac{\partial T_1}{\partial x} - k_2 \frac{\partial T_2}{\partial z} = \int_{\lambda_{c,s}}^{\lambda_{c,i}} \alpha_{2,\lambda} F_{1,\lambda}^+(\delta_1) \, d\lambda \tag{5b}$$

The right-hand side of this equation represents the net radiative flux absorbed by the substrate in the part of the spectrum where it is opaque to radiation. For $\lambda_{c,s} \le \lambda_{c,i}$ the integral vanishes since there is no absorption of radiation, because the substrate is semitransparent, and, according to the accepted definition, $\alpha_{2,\lambda} = 0$ in this part of the spectrum. The integral would also vanish if both the ice and the substrate were considered to be semitransparent media over the entire spectrum (i.e., $\lambda_{c,i} = \lambda_{c,s} = \infty$). The continuity of temperature at the interface can be expressed as

$$T_1 = T_2 \quad \text{at} \quad x = z = \delta_1 \tag{6}$$

At the back face of the substrate, $z = \delta_2 + \delta_1$, the boundary conditions on temperature are either

$$k_2 \frac{\partial T_2}{\partial z} = 0 \tag{7}$$

if the substrate is insulated, or

$$-k_2 \frac{\partial T_2}{\partial z} = h[T_2(z = \delta_1 + \delta_2) - T_\infty] \tag{8}$$

if it is exposed to the ambient environment and is heated by convection.

Radiative Transfer Model

Both clear and cloudy ice are semitransparent to radiation.[10] Clear ice is transparent in the visible and infrared part of the spectrum, and scattering is negligible in comparison to absorption. Cloudy ice that contains entrapped gas bubbles is translucent up to $\lambda = 1.2$ μm, and scattering of radiation predominates over absorption.[10]

It is assumed in the analysis that ice-air and ice-Lucite interfaces are smooth and the radiation characteristics are known or can be predicted from Fresnel equations. The entire radiation spectrum is divided into two parts: 1) the band between $0 \le \lambda < \lambda_c$, for which ice and/or the substrate are semitransparent to radiation; and 2) the band $\lambda_c \le \lambda \le \infty$, for which the ice and the substrate are very strongly absorbing (i.e., $\beta_\lambda \to \infty$ cm^{-1}). In the latter band $\lambda_c \le \lambda \le \infty$, radiation is considered to be surface phenomenon. In the experiments the lamps produce a somewhat divergent radiation flux; however, in the analysis it is assumed that the radiation flux incident on the free ice surface is in the form of a beam. If emission of radiation from ice is neglected in comparison to absorption and the forward-scattering approximation[13] (i.e., radiation is scattered in the forward direction only) is used, the local radiative fluxes in ice for the opaque aluminum substrate and the semitransparent Lucite substrate are different and are discussed separately.

For the metallic (opaque) substrate shown schematically in Fig. 3a, the radiative fluxes in the forward and backward directions can be expressed, respectively, as

$$F_1^+(x) = \int_0^{\lambda_c} F_{1\lambda}^+(x) \, d\lambda = \int_0^{\lambda_c} \tau_{1\lambda}^o F_{1\lambda}^o \, e^{-\beta_\lambda x} \gamma_{1\lambda} \, d\lambda \tag{9}$$

and

$$F_1^-(x) = \int_0^{\lambda_c} F_{1\lambda}^-(x) \, d\lambda = \int_0^{\lambda_c} \tau_{1\lambda}^o F_{1\lambda}^o \rho_{2\lambda} \, e^{[-\beta_\lambda(2\delta_1 - x)]} \gamma_{1\lambda} \, d\lambda \tag{10}$$

In these equations

$$\gamma_{1\lambda} = [1 - \rho_{1\lambda}\rho_{2\lambda} \exp(-2\beta_\lambda \delta_1)]^{-1} \tag{11}$$

is a parameter that accounts for inter-reflection of radiation between interfaces 1 and 2 (across the ice layer). In the analysis of Seki et al.,[6,10] the inter-reflection of radiation between the interfaces has been neglected.

For the semitransparent substrate shown schematically in Fig. 3b, the radiative fluxes in the forward and backward directions are found to be

$$F_1^+(x) = \int_0^{\lambda_c} F_{1\lambda}^+(x)\, d\lambda = \int_0^{\lambda_c} [\tau_{1\lambda}^o F_{1\lambda}^o + \tau_{2\lambda}\rho_{1\lambda} \exp(-\beta_\lambda \delta_1) \times F_{2\lambda}^-(z=\delta_1)] \exp(-\beta_\lambda x)\gamma_{1\lambda}\, d\lambda \tag{12}$$

and

$$F_1^-(x) = \int_0^{\lambda_c} F_{1\lambda}(x)\, d\lambda = \int_0^{\lambda_c} [\tau_{1\lambda}^o \rho_{2\lambda} \exp(-\beta_\lambda \delta_1) F_{1\lambda}^o + \tau_{2\lambda} F_{2\lambda}^-(z=\delta_1) \exp[-\beta_\lambda(\delta_1 - x)]\gamma_{1\lambda}\, d\lambda \tag{13}$$

In these equations $F_{2\lambda}^-(z=\delta_1)$ represents the radiation flux in the substrate incident on interface 2 (substrate-ice); thus, the analysis shows that the radiative fluxes in the ice and the substrate are coupled and must be determined simultaneously. The forward- and backward-directed radiative fluxes in the semitransparent substrate are found to be

$$F_2^+(z) = \int_0^{\lambda_c} F_{2\lambda}^+(z)\, d\lambda = \int_0^{\lambda_c} [\tau_{2\lambda} F_{1\lambda}^+(\delta_1) + \tau_{3\lambda}^o \rho_{2\lambda} \exp(-\kappa_\lambda \delta_2) \times F_{3\lambda}^o] \exp[-\kappa_\lambda(z - \delta_1)]\gamma_{2\lambda}\, d\lambda \tag{14}$$

and

$$F_2^-(z) = \int_0^{\lambda_c} F_{2\lambda}^-(z)\, d\lambda = \int_0^{\lambda_c} [\tau_{2\lambda}\rho_{3\lambda} \exp(-\kappa_\lambda \delta_2) F_{1\lambda}^+(\delta_1) + \tau_{3\lambda}^o F_{3\lambda}^o] \exp[-\kappa_\lambda(\delta_2 + \delta_1 - z)]\gamma_{2\lambda}\, d\lambda \tag{15}$$

where

$$\gamma_{2\lambda} = [1 - \rho_{2\lambda}\rho_{3\lambda} \exp(-2\kappa_\lambda \delta_2)]^{-1} \tag{16}$$

and $F_{3\lambda}^o$ represents an external radiation flux incident on interface 3 (semitransparent substrate-air), if any. Comparison of Eqs. (12) and (13) with Eqs. (14) and (15) reveals that the radiative fluxes in ice are coupled with those in the substrate and must be determined simultaneously.

Method of Solution

The model equations were solved numerically using an implicit finite-difference method.[14] A uniform grid size was used, and to ensure stability[15] a time step of 0.1 s was selected. The boundary and interface conditions were implemented by making energy balances at the boundaries and interfaces and using the control volume approach.[16]

The total radiation fluxes were evaluated numerically using a spectral-band model. A total of only 21 spectral bands was used, because a more detailed spectral distribution of incident radiation flux was not available.[12] Ice and Lucite are selective absorbers of radiation, and their volumetric radiation properties were taken from Seki et al.[6,10] and Touloukian and DeWitt,[17] respectively. The cutoff wavelengths for ice ($\lambda_{c,i}$) were assumed to be 2.5 μm, and for the substrate ($\lambda_{c,s}$) it was taken to be 2.6 μm. The radiation surface properties of aluminum and Lucite were taken from available literature sources.[17,18] It should be stressed here that the radiation surface properties use in the analysis are those for the solid-air (or vacuum) and not for the solid-ice interface.

Results and Discussion

Experimental Observations

Before the comparison between model predictions and experimental data is presented, it is desirable to discuss some of the experimental observations for several different tests. It should be mentioned that during the experiments there was little melting of the ice surface exposed directly to the incident flux. In some experiments of shorter duration only several drops of water were melted and were collected below the test sample, and in some experiments of longer duration as much as 0.5 mm of ice melted (see Figs. 2 and 3 for coordinate and schematic systems, respectively).

Figure 4 shows the effects of the ice layer thickness and of the incident radiation flux on the timewise variation of the interface temperature $[T_2(z = \delta_1)]$. In this and all remaining figures where data are given, the last experimental data point shows the time at which ice lost contact with the substrate and fell down (i.e., deicing occurs). For these experiments an acrylic (Lucite) was used as the substrate. The material is transparent in the visible part of the spectrum, has thermophysical properties that are similar to glass, is readily machinable, and was therefore used as a substrate on which ice was formed. The results show that, as the ice layer thickness is increased, the time required to deice the substrate increases. This is understandable, because the attenuation of incident radiation flux increases nonlinearly with the ice layer thickness, and a smaller radiation flux reaches the substrate-ice interface. Note that the solid is deiced not when the interface reaches 0°C, but when temperatures in the range of about 2–4°C are attained. There is a significant time delay before deicing occurs. Since the time required to deice the solid increases with the ice layer thickness, it is suspected that a certain temperature overshoot is required to overcome the adhesive force between the substrate and the ice before the ice loses contact and falls down. It is believed that this adhesive force depends not only on the temperature but also on the substrate material and the type of its finish. As expected, an increase in the magnitude of the incident radiation flux decreases the time that it takes to deice the solid. Since acrylics are hygroscopic, Leidenfrost[19] has suggested that the deicing of the Lucite plate is delayed until all of the ice in the subsurface layer has been melted.

The effects of the substrate and of the ice layer thickness on the deicing are shown in Fig. 5. The left-hand ordinate and the lower abscissa is for 2-mm-thick ice, and the right-hand ordinate and the top abscissa is for 11-mm-thick ice. This was necessary to put the data for the two ice layers thicknesses on a single figure. Unfortunately, the two scales have made the results more difficult to interpret. The experimental temperature data for Lucite and aluminum substrates show different trends. After reaching and exceeding slightly (by a few tenths of degrees Celsius) the melting temperature of ice, the aluminum substrate-ice interface temperature remained practically constant some time before the ice fell off, whereas the Lucite-ice interface temperature increased gradually before the ice fell off. The trends are the same for different ice layer thicknesses ($\delta_1 = 2$ and 11 mm). The scales used in Fig. 5 are appropriate for pure conduction[20] and not for combined conduction/radiation heat transfer in ice; therefore, it is not surprising that the data do not scale properly. Attempts to scale the experimental data using other dimensionless variables were unsuccessful because the data could not be collapsed onto a single curve. The results indicate that the adhesive force between the substrate and ice depends on the material of the substrate and possibly its surface finish.

Additional experimental results on deicing of solids irradiated on the back side of the substrate and of the effect of a black coating on the substrate have been reported elsewhere[21] and are not included here. Some results on defogging of a surface by radiant heating have also been presented.[21]

Comparison of Model Predictions with Experimental Data

A comparison between the predicted and measured interface temperatures with time for a Lucite substrate to which ice adheres is shown in Fig. 6. The calculations were terminated when the interface reached 0°C, because the adhesive force between the substrate and ice and the viscous force between the substrate and the microlayer of water are not modeled. Good agreement is obtained between the predicted and measured temperatures for thin ($\delta_1 = 2$ mm) ice layer thickness, but for

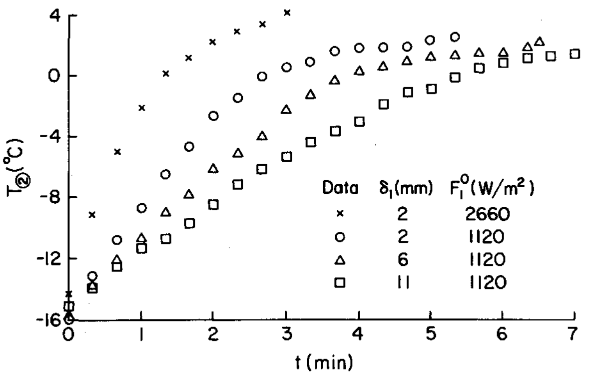


Fig. 4 Effects of ice layer thickness and incident flux on the variation with time of the substrate-ice interface 2 temperature during deicing of a Lucite plate, $T_\infty = 23°C$.

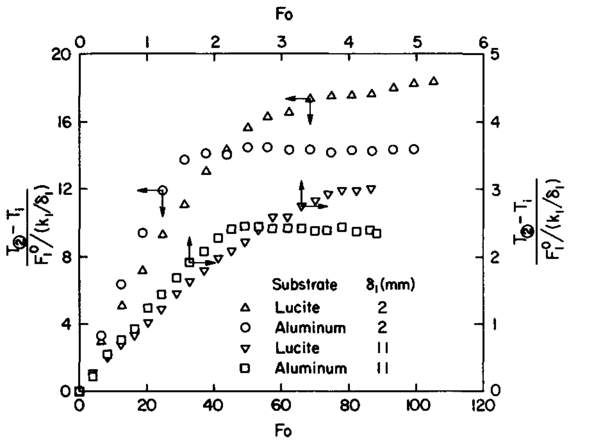


Fig. 5 Effects of substrate and ice thickness on deicing of ice adhering to an aluminum and Lucite plates; $F_I^o = 1120$ W/m², $T_\infty = 23°C$.

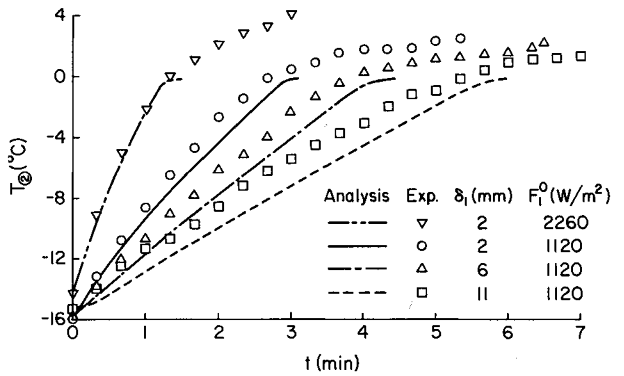


Fig. 6 Comparison of predicted and measured substrate-ice interface temperatures during irradiation of ice on a Lucite plate, $T_\infty = 23°C$.

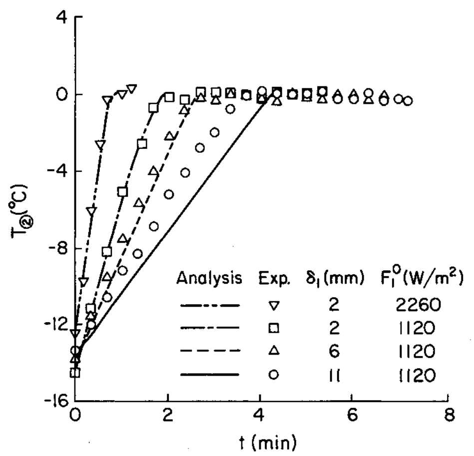


Fig. 7 Comparison of predicted and measured substrate-ice interface temperatures during irradiation of ice on an aluminum plate; $T_\infty = 23°C$.

a thicker ice layer ($\delta_I = 11$ mm), the time required for the interface to reach 0°C is overpredicted. The spectral absorption coefficients for a Lucite sheet were determined from spectral absorptance data reported in the literature.[17] The data were then used in the calculations of the total radiative flux and the flux divergence. A total of 21 spectral bands was used in the calculation of the flux. The effects of the ice layer thickness and of the incident radiation flux predicted by the model are consistent with experimental measurements. The model in general underpredicts the temperature. Incorrect modeling of the heat transfer from the free surface of the ice and the back face of the substrate can be dismissed as the reason for the discrepancy, because the heat losses account only for a small fraction of the radiation incident on the ice surface.

A comparison between measured and predicted interface temperatures for the aluminum-ice system is shown in Fig. 7. Note that additional time period (or temperature rise) after the interface has attained the melting temperature (+ 0°C) is required before the ice falls down. An anonymous reviewer has suggested that the additional increase in temperature (and time period) after 0°C may be explained by the surface tension. He reasoned that the ice falls down when the vertical force (to hold the ice and wall surface together) becomes smaller than the gravitational force. This could possibly explain the results for the opaque (aluminum) substrate but not for the semitransparent (Lucite) substrate (see Fig. 6). The agreement between the predictions and the data is better for thinner ice layers, and in general the discrepancy is smaller than for the Lucite-ice system shown in Fig. 6. A value of 0.45 was used for the absorptivity of aluminum (type 6061-T4)[18]; however, it should be noted that this value is for absorption of radiation at an aluminum-air (vacuum) interface and not at an aluminum-ice interface. Unfortunately, the aluminum was not optically smooth, and classical electromagnetic theory cannot be used to estimate the reflection (absorption) characteristics of the aluminum-ice interface even if the optical constants of aluminum and ice were available. The value taken from the literature may not be appropriate. If a somewhat larger value of absorptivity was used, the discrepancy between the measured and predicted temperatures could be made smaller. This suggests that the heat losses from the back side are insignificant compared to the radiant energy incident on the front surface of the ice.

The effect of absorptivity of the aluminum plate was examined by coating the plate with black paint (Kryolen flat-black paint) and performing experiments. Some typical results are shown in Fig. 8. It is seen that coating the aluminum surface with a black paint decreases the length of time required to deice the solid substrate. The decrease would have been more dramatic for a thinner ice layer, because more radiant energy would have penetrated through the ice layer and heated the aluminum surface. Note that coating the metal with a thin layer of a dielectric (black paint) material changes the interface condition sufficiently so that, after reaching 0°C interface, the temperature remains above 0°C until the ice loses the adhesive strength or the gravitational force exceeds surface tension force and falls down. This finding suggests that the adhesive strength of ice depends on the substrate material, and this is consistent with published results[22,23] that the adhesion force between aluminum and ice is greater than that between plastics and ice. The results also suggest that deicing occurs when the adhesive force becomes larger than the internal shear or cohesive force of the ice itself. It is believed that adhesion of ice to substrate is essentially due to the attraction of the ice molecules to the substrate molecules (Van der Waal forces) and because

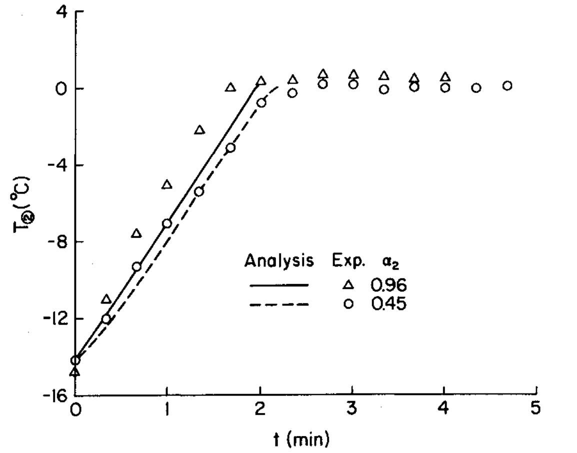


Fig. 8 Comparison of the substrate-ice interface temperatures for deicing of an uncoated and a black paint coated aluminum plate; $F_l^o = 2660$ W/m², $\delta_l = 11$ mm, and $T_\infty = 23$°C.

the minute ice crystals imbed themselves into the surface irregularities of the substrate. Therefore, the cohesive strength over the area of ice imbedded in the surface is overcome by melting a microlayer of ice in contact with the substrate.

The theoretical and experimental evidence suggests that there exists a liquid-like transition layer between a solid substrate and ice.[24,25] Adhesion measurements have established that the thickness of the layer at an ice-metal and ice-quartz interfaces is approximately between 1×10^{-5} and 1×10^{-6} cm, and its viscosity is several hundred poises at -40°C. It is not known if the layer is Newtonian or not, but it is believed that the transition layer influences greatly the adhesive force between ice and the solid substrate.[25] For systems with the same type of bonding between the ice and substrate, the ice detachment is believed to occur in accordance with the postulates of the mechanical deformation theory.[22] However, the analysis is only qualitative, since too little is known about the extrinsic factors that accept adhesion, such as test temperature, interfacial area, and the ice-substrate load.

The convective heat-transfer and mass-transfer coefficients at the free ice surface and the heat-transfer coefficient at the back face of the substrate were calculated using published correlations.[20] Unfortunately, the geometry of the test arrangement is more complicated than those for which correlations are available. In order to assess the importance of convective heat transfer and the uncertainty in the coefficients, the constants in the correlations were changed. The results showed that changing the coefficient by $\pm 100\%$ changed the time required to deice the substrate relatively little (only a few percent). This finding suggests that convective heat transfer is not a very important model parameter under the conditions considered in the tests. Insulation placed on the back face of the Lucite substrate that has been coated with a black paint was found to have a relatively small effect on the time required to deice the solid.

Conclusions

The feasibility of deicing metals and nonmetals using a radiation source has been investigated experimentally. Quartz halogen dichroic mirror lamps having a large fraction ($>99\%$) of the radiation in the short-wavelength part of the spectrum ($0.3\ \mu m < \lambda < 2.4\ \mu m$) were used as a radiation source in the study. Experiments were performed on a test specimen held in a vertical position, with the ice adhering to an opaque (aluminum) or a semitransparent (Lucite) substrate. To support the experiments a simple thermal (conduction-radiation heat transfer) model was also constructed. Based on the results obtained, the following conclusions can be drawn.

The type of ice (cloudy or clear), ice layer thickness, radiation properties of the solid substrate, and the force between ice and substrate influence the conditions at which a solid is deiced by radiant heating from an external radiation source. There is reasonably good agreement between the measured and predicted substrate-ice interface temperatures. The shortcoming of the analysis is that the adhesive force at the interface is not modeled.

The results of the investigation suggest that deicing of semitransparent and opaque solids using an external radiation source is feasible. For practical application of the scheme, the radiation characteristics of the source and the radiation properties of the ice and of the substrate must be properly matched and optimized to achieve an effective utilization of radiant energy. Fundamental understanding of the adhesive force between the substrate and ice and how this force is influenced by the internal cohesive or internal shear force in ice is lacking and must be obtained before this scheme of deicing can be optimized and implemented in practice.

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