# NUMERICAL SIMULATION OF DE-ICING AND ICE SHEDDING ON MULTILAYERED STRUCTURES

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***Abstract:*** Electro-thermal de-icing problems occurring in multilayered structures covered with ice was numerically modeled. The enthalpy method was applied to solve transient heat transfer equations with the phase change between ice and water. Assumed phase state for each node was used to linearize the equations such that a direct solution is possible. Numerical results are presented to compare the present code simulations to some data provided by other de-ice prediction codes and to show the capabilities of the present numerical tool. Ice shedding model based on bonding strength was developed. The ice shedding time and temperature distribution after shedding were simulated and analyzed.

## 1. INTRODUCTION

The formation of ice on structures can severely affect our lives. De-icing systems remove ice after, or during ice buildup. It is an effective method to eliminate ice hazards.

The objective of this study is to develop and validate a two-dimensional numerical method to simulate removal of ice buildup on structure surfaces. Numerical results are compared to NASA prediction data to show the capabilities of the present method.

## 2. RESULTS AND DISCUSSION

De-icing test case on two-dimensional multilayered structure has been simulated. Fig. 1 and Fig. 2 plot the ice-titanium interface temperature distribution and ice melted height at the end of 50s and 60s respectively. Results show that excellent agreement with the NASA prediction data is obtained.

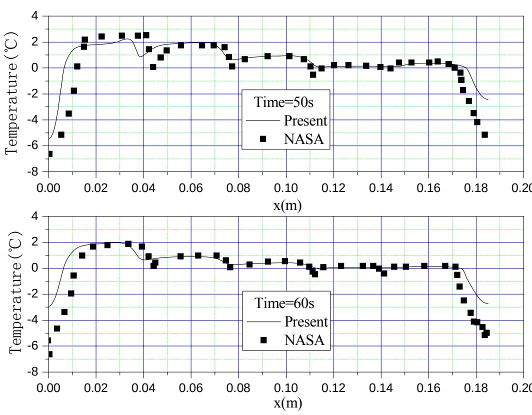


**Figure 1:** Temperature distribution at the end of 50s and 60s

Fig. 3 plots the temperature history with ice shedding considered. Ice shedding can be observed from the figure by a change in slope of the temperature curve. So ice shedding occurred approximately 47 sec. after the heaters turned on.

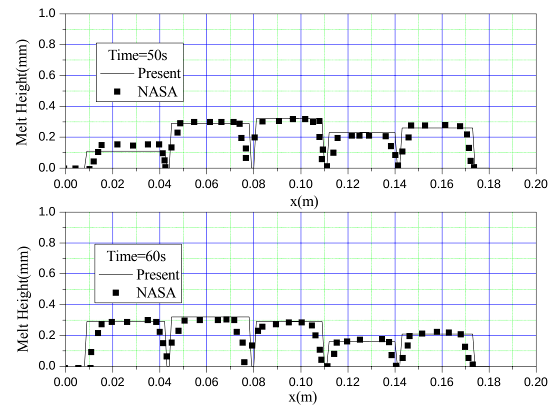


**Figure 2:** Ice melted height at the end of 50s and 60s

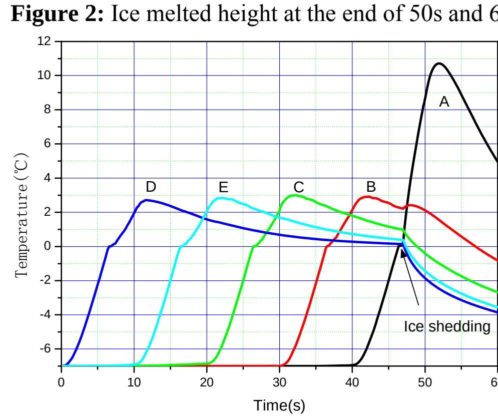


**Figure 3:** History of temperature with ice shedding

## 3. CONCLUSION

De-icing and ice shedding on multilayered structure surfaces are simulated in this study. Temperature distribution and melted ice height at ice-structure interface have been compared with the numerical results from NASA to show that the enthalpy method is effective method to model the phase change in the ice layer and to predict the time of ice shedding.

## 4. REFERENCES

[1] Stallabrass, J. R., "Thermal Aspects of Deicer Design," 1st Int. Helicopter Icing Conference, National Research Council of Canada, Ottawa, Canada,23-26 May 1972.

[2] Wright, W. B., Keith, T. G., Jr., Dewitt, K. J., "Transient two-dimensional heat transfer through a composite body with application to deicing of aircraft components," AIAA-88-0358, January 1988.

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***Abstract*—Electro-thermal de-icing problems occurring in multilayered structures covered with ice was numerically modeled. The enthalpy method was applied to solve transient heat transfer equations with the phase change between ice and water. Assumed phase state for each node was used to linearize the equations such that a direct solution is possible. Numerical results are presented to compare the present code simulations to some data provided by other de-ice prediction codes and to show the capabilities of the present numerical tool. Ice shedding model based on bonding strength was developed. The ice shedding time and temperature distribution after shedding were simulated and analyzed.**

***Keywords-de-icing; ice shedding; numerical simulation***

## I. INTRODUCTION

The formation of ice on structures can severely affect our lives. The ice on transmission line may cause conductor breaking, pole leaning or collapse, and insulator flashover etc. The ice on the exterior surfaces of aircraft increases drag and decreases lift. As a result, there is a need to develop effective systems which can either keep ice from forming(anti-icing) or remove the ice once it has formed(de-icing).

Anti-icing systems prevent ice from forming by maintaining the surface temperature above the melting point. However, the energy requirement is quite high and is impractical for most structures. De-icing systems remove ice after, or during ice buildup. It is an effective method to eliminate ice hazards. Electro-thermal deicer pad is widely used by thermal de-icing system, as shown Fig. 1. When the icing takes place the heater pads installed beneath the skin of structures are activated to destroy the adhesion forces at the ice-surface interface. Then external forces remove the accreted ice from the surface.

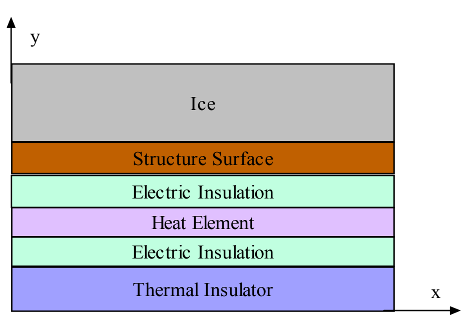



Figure 1. Typical deicer pad.

Much work has been done about the electro-thermal deicer pad simulation and experiment. Stallabrass[1] may be the first to attempt a numerical solution of an electro-thermal de-icing problem using a one-dimensional computer model. Wright[2] modeled two-dimensional heat transfer through a composite body to simulate de-icing on aircraft components. The review[3] contains references to about hundred papers and reports devoted to de-icing method and model.

The objective of this study is to develop and validate a two-dimensional numerical method to simulate removal of ice buildup on structure surfaces. Numerical results are compared to NASA prediction data to show the capabilities of the present method.

## II. NUMERICAL MODELING

### *A. Governing Equations*

The following assumptions are made to model thermal transient heat conduction system in multilayered structures:

*1)* The thermal physical properties of the material composing each layer of the structures do not depend on temperature;

*2)* Thermal resistence between layers is neglected;

*3)* The heat transfer coefficient and ambient temperature are constant;

*4)* The density change due to melting is negligible;

*5)* The phase change is assumed to occur over a small temperature interval near the melting point rather than at the melting point itself.

*6)* The ice sheds as a whole.

With the above assumptions, the mathematical formulation for the problem of unsteady heat conduction in multilayered structures can be represented as:

$$(\rho C_p)_k \frac{\partial T_k}{\partial t} = k_k \frac{\partial^2 T_k}{\partial x^2} + k_k \frac{\partial^2 T_k}{\partial y^2} + q_k^{''} \qquad (1)$$

Where subscript $k$ stands for the layer, and

$\rho_k$ = Density of the $k^{th}$ layer;

$C_{p,k}$ = Heat capacity of the $k^{th}$ layer;

$T_k$ = Temperature of the $k^{th}$ layer;

$k_k$ = Thermal conductivity of the $k^{th}$ layer;

$q_k^{"}$ = Heat generation rate per unit volume of the $k^{th}$ layer;

For the ice layer, the governing equation is written in terms of the enthalpy:

$$\frac{\partial H}{\partial t} = k_{ice}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (2)$$

The standard relationships between enthalpy and temperature are:

When $T < T_m$ :

$$H = (\rho C_p)_s T \quad (3)$$

When $T = T_m$ :

$$(\rho C_p)_s T_m < H < \rho_l C_{ps} T_m + \rho_l L_f \quad (4)$$

When $T > T_m$ :

$$H = (\rho C_p)_s T_m + \rho_l L_f + (\rho C_p)_l (T - T_m) \quad (5)$$

Where subscript $s$ and $l$ stand for solid phase (ice) and liquid phase (water) respectively, and:

$T_m$ = Melting temperature;

$L_f$ = Latent heat of ice melting per unit mass.

*B. Melting Assumption*

The relationship between enthalpy and temperature is non-linear because the melting temperature keeps constant at $0^\circ$C during melting, as shown Fig. 2(a). The non-linear characteristic requires using an iterative solution procedure to find the appropriate temperature at each node.

In this paper, the relationship between enthalpy and temperature is modified to be used. A one-to-one relationship is adopted by assuming that the ice melts over a small range of temperatures $T_r$ rather than at a single temperature, as shown in Fig. 2(b). This range of temperature must be reasonably small to give good accuracy of the solutions. The relationship (4) and (5) are changed into:

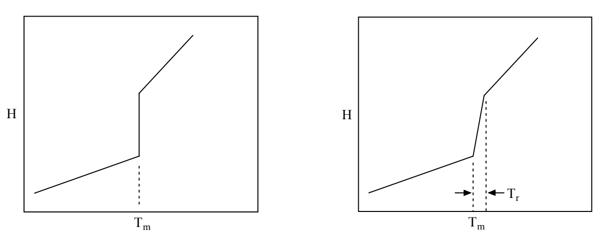
When $T_m \le T \le T_m + T_r$ :

$$H = \rho_s C_{ps} T_m + [(\rho_l - \rho_s) C_{ps} T_m + \rho_l L_f](T - T_m)/T_r \quad (6)$$

When $T > T_m + T_r$ :

$$H = \rho_l C_{ps} T_m + \rho_l L_f + (\rho C_p)_l (T - T_m - T_r) \quad (7)$$

The modified enthalpy-temperature relationships can linearize the equation by assuming phase state for each node and eliminate the enthalpy in favor of temperature and permits non-iterative methods to be used.



(a) Standard (b) Assumed

Figure 2. Relationship between enthalpy and temperature.

*C. Boundary Conditions*

The boundary condition and initial conditions are as follows:

At interior interfaces, heat fluxes are continuous, i.e.

$$(-k\frac{\partial T}{\partial y})_{layer1} = (-k\frac{\partial T}{\partial y})_{layer2} \quad (8)$$

At the upper surface of the ice, convective heat exchange condition is applied:

$$(-k\frac{\partial T}{\partial y})_{upper} = h(T_s - T_\infty) \quad (9)$$

Where $h$ is the convective heat transfer coefficient, $T_s$ is the surface temperature, $T_\infty$ is the ambient temperature.

At the left, right and lower boundary, adiabatic condition is used.

*D. Ice shedding model*

Ice shedding model in the present paper assumes that the ice will shed when the net average external forces exceed the net average force holding the ice to the surface. External forces included aerodynamic force, centrifugal force or gravity.

The aerodynamic force[4] is computed by the formula (10), where $\rho_\infty$, $V_\infty$, $A$ are air density, velocity and area respectively.

$$F_{aero} = \frac{1}{2}\rho_\infty V_\infty^2 A \quad (10)$$

The centrifugal force is computed by multiplying the mass by the arm length and the angular velocity squared:

$$F_c = m_{ice} D \Omega^2 \quad (11)$$

The relationship between bonding strength of the ice and temperature is obtained by curve-fitting Scavuzzo's experimental data[5].

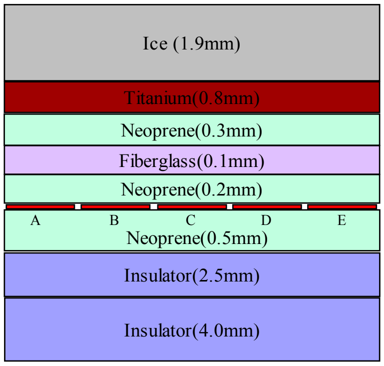
## III. TEST CASE

De-icing test case on two-dimensional multilayered structure has been simulated and compared with data obtained from NASA.

*A. Geometry*

The geometry of multilayered structure[6][7] and material properties are shown on Fig. 3.

The five heaters have the power of $32\,kw/m^2$ and are activated in the sequence DECBA. Each heater lasts for 10 seconds. At time 60s all heaters are switched off. Ambient air temperature is $-7^\circ C$. Heat transfer coefficient at outer surface of ice layer keeps constant of $450\,W/(m^2\cdot{}^\circ C)$.




Ice: K=2.2 W/mK; $\rho c=1.93*10^6 J/m^3K$

Titanium: K=17.03W/mK; $\rho c=2.35*10^6 J/m^3K$

Neoprene: K=0.293W/mK; $\rho c=5.15*10^6 J/m^3K$

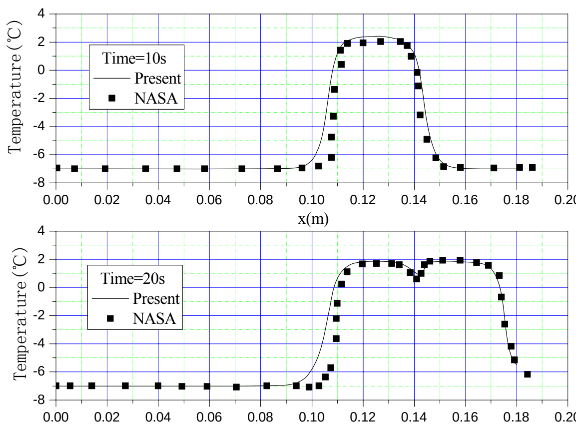
Fiberglass: K=0.313W/mK; $\rho c=3.88*10^6 J/m^3K$

Insulator: K=0.25W/mK; $\rho c=1.717*10^6 J/m^3K$

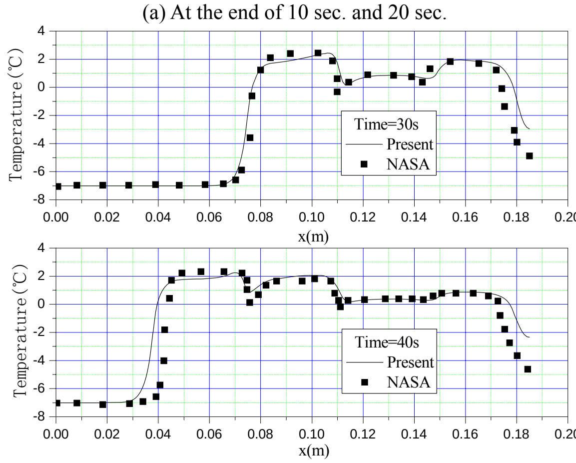
Figure 3. Multilayered structure geometry and material properties.

### B. *Temperature distribution*

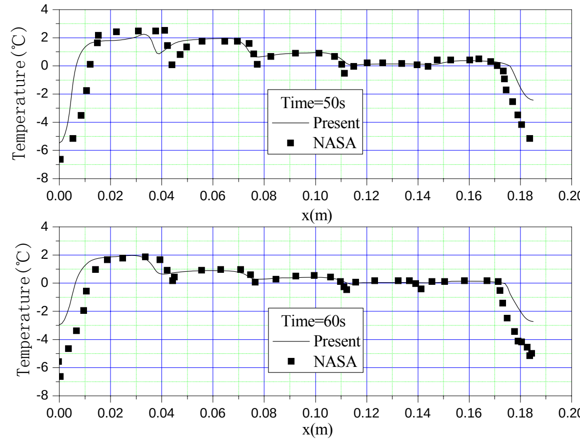
Fig. 4 shows the ice-titanium interface temperature distribution at the end of each time interval. As can be seen from the figure, excellent agreement with the NASA prediction data is obtained except a small difference over the gap between heaters.




(a) At the end of 10 sec. and 20 sec.




(b) At the end of 30 sec. and 40 sec.

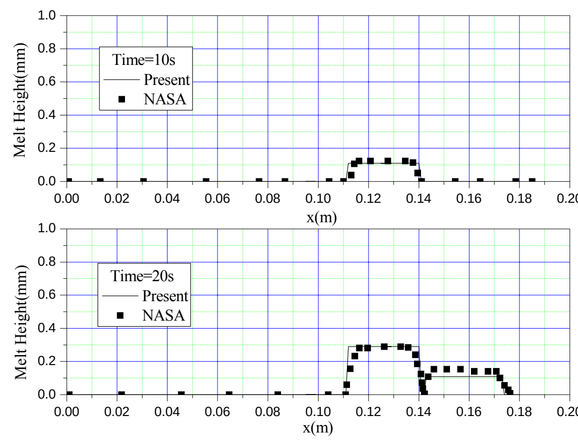



(c) At the end of 50 sec. and 60 sec.

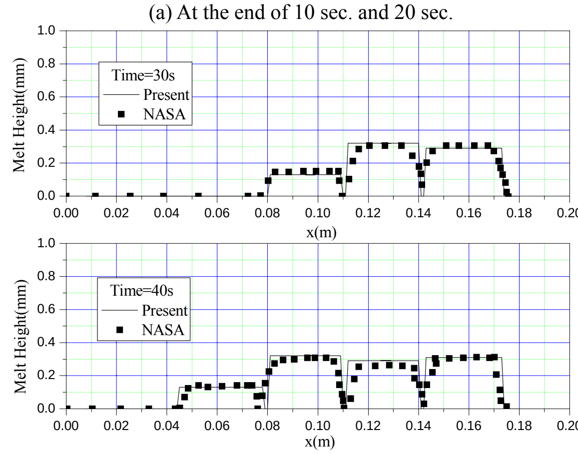
Figure 4. Temperature distribution at the end of each time interval.

### C. *Height of melted ice*

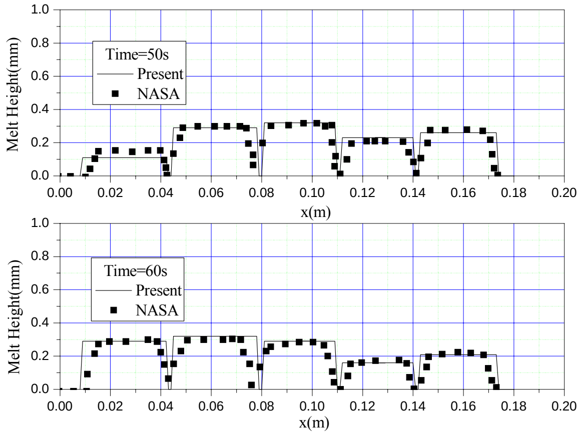
Fig. 5 shows the height of melted ice when the heaters are activated in turn. Melting process of the ice over each heater, heater D for example, includes three stages. Firstly, the interface temperature goes up and begins to melt when the heater activated. Then the temperature decreases because of the heater turned off while the ice melted height continues to increase. Finally the melted ice begins to refreeze due to convective cooling at the outer surface.




(a) At the end of 10 sec. and 20 sec.




(b) At the end of 30 sec. and 40 sec.




(c) At the end of 50 sec. and 60 sec.

Figure 5. Ice melted height at the end of each time interval.

### D. *Ice Shedding Results*

By assuming ice cannot shed Fig. 6 shows the temperature history at the ice–titanium interface over the center of each heater. Six temperature positions display the same trends. Temperature rises up when corresponding heater turned on and decreases when the heater turned off. It should be noticed that the temperature does not go down immediately when the heater is turned off, it keep going up for 2 or 3 seconds. This may be attributed to thermal inertia in the multilayered structure.

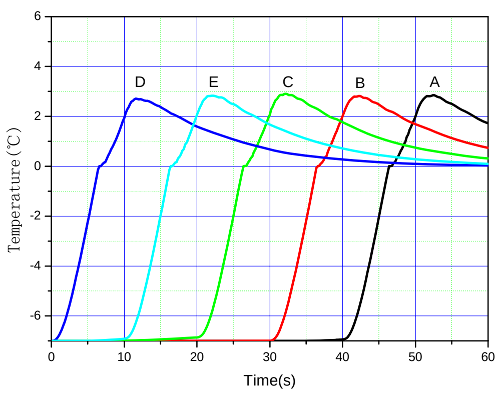



Figure 6. History of temperature without ice shedding

The multilayered structure above is a typical electro-thermal deicer pad on the surface of aircraft fixed wing. The aerodynamic force is the major force which acts on the ice. It can be calculated by (10). The bonding strength between ice and structure surface can be estimated by Scavuzzo's experimental data[5] according to the temperature of the interface. Here, the external force exceeds the bonding strength when the interface temperature reaches $-0.2^{\circ}C$. Then the ice layer plus any water which has formed is shed from the structure surface. Fig. 7 plots the temperature history with ice shedding considered. Ice shedding can be observed from the plot by a change in slope of the temperature curve. So ice shedding occurred approximately 47 sec. after the heaters turned on.

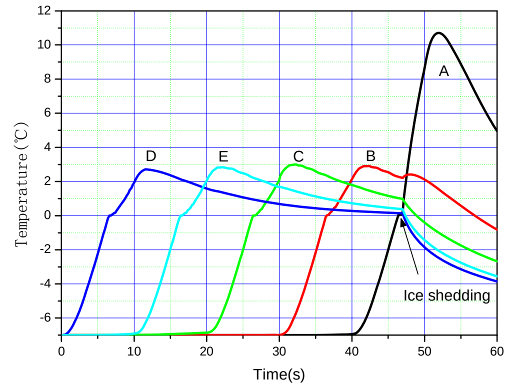



Figure 7. History of temperature with ice shedding

## IV. Conclusion

De-icing and ice shedding on multilayered structure surfaces are simulated in this study. Temperature distribution and melted ice height at ice-structure interface have been compared with the numerical results from NASA to show that the enthalpy method is effective method to model the phase change in the ice layer and to predict the time of ice shedding.

## References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