COMPUTATIONAL METHODOLOGY FOR ELECTRO-THERMAL
ICE PROTECTION SYSTEM ANALYSIS

A Thesis by
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ICE PROTECTION SYSTEM ANALYSIS

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Aerospace Engineering.

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Ikram Ahmed, Committee Member
DEDICATION

To my parents, my sister, and my dear friends
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And of course, thanks to my parents and sister for encouraging, supporting and sacrificing, for the best of my achievements.
The new trend in aviation industry is towards “all electric aircraft”. Thus, there’s a strong desire to replace bleed air systems with efficient electrical ice protection systems that would provide adequate ice protection.

In the current thesis study, a computational methodology was developed to support the design and assess the performance of electro-thermal ice protection systems (ETIPS) for de-icing fixed wing aircraft. The methodology developed was tested using a range of geometries and electrical heater configurations and was validated with experimental data obtained by researchers at Wichita State University (WSU) and other organizations.
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<td>ETIPS</td>
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<td>Hot Air Anti-icing Research Program</td>
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<td>KART</td>
<td>Kansas Aviation Research and Technology</td>
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<td>LWC</td>
<td>Liquid Water Content</td>
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<td>NACA</td>
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CHAPTER 1
INTRODUCTION

Ice accretion is one of the important and critical phenomena that can cause adverse effects on the flight safety, handling qualities and performance (aerodynamics and stability) of an aircraft. Various fatal-accidents have been reported by the aviation authorities in consequence of in-flight icing conditions. Therefore, in order to maintain acceptable aircraft aerodynamic performance and safety in flight during icing conditions, aviation authorities have laid out „ice certification” regulations for small general aviation aircraft, transport aircraft and helicopters which must be followed in all icing conditions.

Water droplets in the air can be supercooled to below freezing without turning into ice. However, when these supercooled droplets are disturbed by the aircraft surfaces, they immediately turn to ice. Critical parts of the aircraft affected by icing includes the wings, the horizontal tail, the vertical tail, engine inlets and other components, helicopter rotors and propellers.

Icing cloud properties include liquid water content (LWC) which is amount of water contained in a volume of cloud, droplet size and distribution on temperature. These properties affect the ice deposit. As mentioned earlier, the supercooled water droplets turn into ice on impacting solid surfaces. The latent heat of fusion is released from the water which freezes and this tends to warm the accreted ice and the underlying surface towards 0°C. This tendency of warming is counteracted by convective heat transfer to the ambient air. Thus the temperature in the impact region is mainly the result of a balance between the rate of latent heat release and the convective heat transfer to the ambient air.
A condition in which LWC is low and the freezing fraction is unity is known as rime icing conditions. The ice deposit occurs due to droplets impact and adheres on the surface. They have an opaque appearance and their surface is somewhat rough.

When LWC is high and the freezing fraction is less than unity, glaze icing conditions are said to prevail. This icing condition causes unfrozen water present in the impingement zone to run back and freeze downstream. Because there are relatively less air inclusions, glaze ice deposits are normally clear.

Icing conditions degrade aircraft performance. From aerodynamics point of view, there is drastic loss in lift, stall angle, and increase in drag due to the consequence of ice accretion and surface roughness. Also from the stability and controls perspective, there will be impact on stick force (handling qualities) which will require a quick response from the pilot. Ice on wing and or tail surfaces throughout flight conditions may cause serious problems resulting in pitch up or down, reduced climbing capability, roll off, and stall. The initial ice formation on unprotected leading edge surfaces generates roughness elements of height sizes in the range of 0.57mm to 0.62mm depending on icing parameters and accretion time. The measured heights of these elements have been investigated during several icing tunnel tests conducted by Shin [1, 5]. Aerodynamic degradation due to leading edge roughness was investigated and the test results showed a decrease in the maximum lift coefficient in the range of 20% to 33% for the smallest to highest roughness heights, respectively [2, 3].

To overcome these adverse effects ice protection systems are typically used on critical aerodynamic surfaces. Ice protection systems can be classified as either anti-icing or de-icing. Anti-icing systems involve the prevention of formation of ice growth by use of chemical or thermal means. In contrast, de-icing systems involve removal of the accreted ice by mechanical
or thermal means. Various anti-icing and de-icing methods have been developed for ice removal and prevention which will be briefly described in the following section.

1.1 Ice Protection Systems

Ice Protection systems (IPS) are classified into chemical IPS, mechanical IPS, bleed air IPS (Hot air), and electrical IPS.

Chemical IPS includes fluid IPS. Fluid IPS operate on the principle that the surface to be protected is coated with a fluid that acts as a freezing point depressant (FPD). Fluid freezing point depressant can provide anti-icing and deicing protection by pumping glycol fluids under pressure through porous skin panels. Glycol based fluids when mixed with water, lower the water’s freezing point. Advantages of a fluid ice protection system include low hardware weight, cost, low maintenance requirements and small impact on aerodynamic performance. The disadvantages of these systems include a finite period of protection, dependent on fluid supply and reduced aircraft payload. [4]

Mechanical IPs includes pneumatic boot de-icing systems and electro-expulsive de-icing systems. Pneumatic boot deicing systems have been the standard ice protection method for small general aviation and commuter aircraft. The boot surfaces remove ice accumulations mechanically by alternatively inflating and deflating tubes within a boot that covers the surface to be protected. Tube inflation breaks the accreted ice into particles and destroys the ice bonded to the surface. Aerodynamics forces, then remove the ice. The pneumatic boots are usually oriented spanwise but may be oriented chordwise if dictated by a particular design [4]. Although repair, maintenance, inspection, and replacement are well understood, some aerodynamic drag penalty is expected on an airfoil when the boots are inflated and also a certain degree of pilot skill is required for safe and effective boot operation.
Electro-expulsive deicing systems (EEDS) are classed as mechanical ice protection systems because accreted ice is expelled from blanket-protected structures by a strong and rapid movement of the blanket outer weathering surface, which overlies parallel electro-expulsive conductors and a non-conducting elastomeric matrix. An electric current pushed in opposite directions through closely-spaced parallel conductors within the blanket causes the impulse movement. An electromagnetic force is thus created that acts to move the conductors.

Advantages of the EEDS are low power requirements and ease of installation to existing aircraft surfaces. Limitations of the EEDS include residual ice accumulations after cycling, noise associated with pulsing the system, composite blanket surfaces not as durable as metal surfaces, and fatigue of the deicer surface and conductors [4].

Most jet aircraft use hot air anti-icing systems where the thermal energy is provided by bleed air from the low or high pressure compressor of the jet engine. Bleed air from the jet engine is directed to the protected surfaces using ducted tube installed inside the leading edge of the wing, tail, or engine inlet. The sources of hot air supply can be extracted from engine compressor air (bleed air), exhaust manifolds or heating of ram air using a fuel-burning combustion heater.

The advantage of hot air IPS is the availability of thermal energy in the form of bleed air from the engine compressors. A disadvantage of hot air IPS would be designing and fabricating the leading edge heat exchangers which results in increased installation costs and system weight.

Electrical IPS includes electro-thermal systems and hybrid systems. Electro-thermal Ice Protection Systems (ETIPS) operate on the principle where heat is applied to an area embracing the water impingement region to evaporate the impinging water or prevent the impinging water from freezing. The source of the required electrical energy is the airplane’s electrical system or a
separate onboard generator with its own source of power. To ensure safe system operation provisions for redundant electrical energy sources are generally used.

Electro-thermal systems use electrical resistance heaters (film, foil, mesh, resistance wire) imbedded in metal, fiberglass, plastic, or rubber to heat the surface. The ETIPS can operate as electro-thermal anti icing systems, electro-thermal deicing systems or both depending on power availability [4].

*Electro-thermal Anti-Icing Systems*

Electrical heaters are used to maintain the temperature of the surface to be protected above freezing throughout an icing encounter. Electro-thermal anti-icing systems are further classified as „evaporative” or „running-wet.” Evaporative systems, as the name implies, supply sufficient heat to evaporate all water droplets impinging upon the heated surface. Running wet systems provide only enough heat to prevent freezing on the heated surface. The water can refreeze beyond the heated surface of a running wet system, resulting in runback ice.

*Electro-thermal Deicing Systems*

In a deicing system, ice is allowed to accrete on the surfaces to be protected and is then removed periodically. The watt density is sufficiently high enough to remove accumulated ice. Power consumption in totally evaporative systems is highly dependent on the water loading of the model (i.e., the product of the free stream velocity, the cloud liquid water content, and the droplet collection efficiency) of the protected surface. Due to the high value of the water latent heat of vaporization, the power requirement of evaporative systems tends to be very high. Power consumption in running-wet systems depends mostly on the ambient temperature. The power requirements increase with increase in temperature differential between the surface and the ambient [6].
CHAPTER 2
LITERATURE REVIEW

Current Technology

The new trend in aviation industry is towards “all electric aircraft.” Thus, there is a strong desire to replace bleed air anti-icing systems with efficient electrical ice protection systems that would provide adequate ice protection within the FAR Part 25 Appendix C icing envelope [4]. These systems would be applicable to jet powered general aviation aircraft as well as large commercial aircrafts and will eliminate the use of engine bleed air which has an adverse effect on engine performance. Figure 1 shows the remote electrical distribution system on Boeing 787 that saves weight and reduces maintenance costs.

![Figure 1. The 787’s electrical system [7]](image1)

![Figure 2. Heater mats for the B 787 [8]](image2)

The ice protection system for the BOEING 787 Dreamliner is the first all electro-thermal anti-ice/de-ice system to qualify for use on a civil airliner. The 787 utilizes several heater blankets...
bonded to the interior of the wing as shown in Figure 2. The power usage for ice protection is approximately half that of pneumatic systems [7, 8].

Development, testing and certification of ice protection systems require the use of icing tunnels, airborne icing tankers and aircraft flight in natural icing conditions. These testing and certification methods are very expensive and time consuming. Recent advances in simulation tools offer the possibility of reducing the time effort and costs associated with the development of ice protection systems. This chapter provides a description of electro-thermal ice protection systems (ETIPS), which are the subject of this thesis, and a brief review of experimental and numerical techniques used in their development and testing.

2.1 Testing of Electro-Thermal IPS

Electro-thermal systems require substantial energy input for ice protection while mechanical systems require considerable less power. From experimental studies, Werner [9] reported that the electro-thermal de-icing systems (ETDS) have been commonly used in rotary wing and fixed wing aircraft. Stallabrass [10] has found that electro-thermal de-icing offer many advantages regarding ice removal on different material; however, they are also subject to reliability and maintainability issues.

Lewis, J., and Bowden, T., [11] conducted an investigation to determine the characteristics and requirements of cyclic deicing of an airfoil equipped with an external electric heater as shown in Figure 3. A high power density and a 15 second heater ON time resulted in optimum ice removal, minimum runback ice, and minimum energy use.
Al-Khalil [6] conducted tests on a hybrid ice protection system consisting of an electro-thermal heater followed by a low power deicing system as shown in Figure 4. Power densities: 10.8 W/in$^2$ and 17 W/in$^2$ for the stagnation heater and 5.4 W/in$^2$ and 6.6 W/in$^2$ for the downstream heater respectively were selected during the tests. The combined action of electro-thermal heaters and deicing system eventually resulted in complete elimination of ice roughness on the leading edge of a horizontal stabilizer.

Botura, G., Sweet, D., [12] discuss the development of a low power electro-thermal deicing system (LPED) installed on a technology demonstrator airplane. LPED utilizes pulsing
anti-ice and de-ice heaters. The cross section of LPED heater is shown in Figure 5. The anti-icer is energized by turning the heater element on for a few seconds. Depending on the outside air temperature the energy provided to the heater was varied. The experiment showed that reducing heater ON time required higher heater watt density. Their analysis also showed that the thickness of the leading edge impacted the final leading edge skin temperature; i.e., the temperature was higher for thinner skins, for the same amount of energy supplied to the heater.

![LPED Heater Cross Section](image)

Figure 5. LPED Heater Cross Section [12]

### 2.2 Simulation Methods for Electro-Thermal IPS

Shinkafi and Lawson [13] simulated a model for conceptual sizing of aircraft electro-thermal deicing system. The model was used to optimize system power and energy consumption based on a combination of cyclic and pulsing de-icing techniques factoring radiation along with conduction and convection losses. A heater mat arrangement was designed to calculate energy balance on the surface of an airfoil. The values of heater power density varied along the chordwise locations starting with 11 kW/m² at or near the stagnation region and decreased along the chord. Ambient temperature of -30 °C and LWC of 0.2 g/m³ was taken as the critical design
point with an objective to evaporate entire surface water. De-icing cyclic process satisfied the performance requirements of electrical power of 40 kW and energy cost of 6 kJ.

Pourbagian and Habashi [14] show investigation of de-icing system performance through optimized cycling times and power densities of the heaters. The CFD simulation solver used several different modules (FENSAP, ICE3D, C3D, and DROP3D) to compute droplet impingement, ice shapes and conduction. A derivative free approach, called the mesh adaptive direct search method, was used to carry out the optimization process. To assess the performance of the simulation, a NACA 0012 model was employed with seven independently controlled electric pads placed inside a four layer composite panel and tested at certain conditions. The parting strip at the stagnation region with a power density of 15000 W/m$^2$ was continuously ON while other heater heaters with power densities in the range of 5000 to 10000 W/m$^2$, followed a 10-second ON/110-second OFF cycling time. The simulation results compared well to the experimental results of NASA.

Wright, W., and Masiulaniec, K., [15] incorporated an electro-thermal deicer module into LEWICE code. LEWICE is a computer program that analytically predicts the droplet impingement and ice accumulation characteristics of a 2D geometry. A subroutine called UTICE was added in the code which performs energy balance, as well as handles all the time-temperature transients below the ice surface for all the layers of a composite blade and ice layer itself. The modified LEWICE code was validated with other numerical codes and experimental data with an objective to predict ice shedding, ice accretion, and heat transfer on an electro-thermal pad.

The icing branch at the NASA Glenn Research Center has developed and validated two thermal ice protection codes, LEWICE/Thermal (electro-thermal deicing and anti-icing), and
ANTICE (hot gas and electro-thermal anti-icing). Validation of these codes was accomplished via comparison with experimental data obtained from icing tunnel tests with a NACA 0012 airfoil, conducted using a range of total temperatures, airspeeds, cloud liquid water contents and median volumetric diameters. Seven independently controllable heater zones were defined along the composite leading edge of the NACA 0012 airfoil. The computer code was based on two-dimensional analytical thermodynamic model developed by Al-Khalil to calculate the temperature distributions in the runback water and the solid wall. The authors remarked that LEWICE code predictions for the heat transfer coefficients under dry conditions were in good agreement with the experimental measurements. In addition, the running wet anti-icing conditions predicted by ANTICE code were very close to the experimental values [16, 17, 18].

Another numerical methodology was presented by Elangovan, R., and Olsen, R., [19, 20] wherein the transient heat conduction equation was solved using the alternating direction implicit method to analyze layered composite skin electro-thermal anti-icing system. References 19 and 20 also discuss performance of low power electric de-icing heater on engine inlet lip. The analysis was performed using a NACA 0012 airfoil geometry with seven heater zones divided into three on the upper surface and three on the lower surface of the airfoil separated by a parting strip surrounding the stagnation region. Constant power of 5.5W/in$^2$ was applied to the parting strip zone throughout a cycle time of 20 seconds while selected power settings of 6.5 and 7W/in$^2$ were applied to the other heater zones that followed the parting strip downstream of the chord. The heater zones were de-iced at 5 second intervals. Results showed that by periodically energizing the segmented deiced shed zones with short pulses of power, the ice interface can be melted.
2.3 Other Analysis Methods for Electro-thermal IPS

Khalil [21] illustrates the effect of mixed icing conditions on the power requirements for evaporative and running-wet modes of an anti-ice IPS. Two cases, evaporative and running-wet systems, were considered to represent the effect of ice and water content on the heat required. Plots illustrated power density versus total ice/water content (TWC) to anti-ice the surface in a warm (23°F) and in a cold (4 °F) icing condition. The results illustrated that evaporative anti-icing systems were affected by the total water content and not by the ambient air temperature or ice content in the cloud. On the other hand, power required in running-wet systems was largely dependent on the ambient temperature and ice content of the cloud.

Developing an analytical model taking account of all the physics involved, system parameters and conditions is very difficult. However, Krammer, P., and Scholz, D., [22] demonstrated calculations of power requirements of electro-thermal de-icing systems using approximate values and formulas suggested in Aerospace Information Report, AIR 1168/4. The design point for sizing the parting strip for electro-thermal cyclic deicing was set to -18°C in accordance with the flight envelope by airworthiness authorities. Calculations deduced from thermodynamic formula resulted in specific parting strip power requirement of 21.9 kW/m² (13.55 W/in²) compared to suggested value of 18.6 kW/m² (12 W/in²) in the Aerospace information report. While the calculated results of cyclic power requirements produced values much lower than suggested values of AIR 1168/4. The methodology developed can be used to estimate total system power loads.

To develop an analytical model in predicting the performance of an electro-thermal de-icer pad and determining the time-temperature history throughout the pad is virtually impossible. A numerical model is a little more realistic, but even this is somewhat impractical, unless
simplification is made to the geometry and thermodynamics. The first to attempt a numerical solution of an electro-thermal de-icing problem constituting several layers metal and insulation materials appears to be Stallabrass [10, 15]. He used a one-dimensional model in which the temperature at a given location was assumed constant throughout the plane. Also an explicit finite difference method was used in his numerical scheme.

The same problem was modeled by Baliga [23, 15], by using high heat capacity formulations for handling the phase change heat transfer on the temperature transients within the composite blade. Also Gent and Consdale [24, 15] modeled the same problem for no phase change (conduction only).

The results of the literature review performed indicate that although a number of numerical methodologies have been applied to design and assess the performance of ETIPS, a well defined approach for the design and analysis of these ice protection systems is still lacking particularly in the public domain. In addition, validation of numerical methodologies is needed to support the design, development and certification of electro-thermal ice protection systems. In the current study, a cost effective numerical approach is presented for electro-thermal IPS analysis and performance assessment. The methodology developed was tested using a range of geometries and electrical heater configurations and was validated with experimental data obtained by Wichita State University (WSU) and other researchers. The numerical methodology is based on commercial software so that it can be readily used by the local and national aviation industry for the design, development and certification of electro-thermal IPS.
CHAPTER 3

OBJECTIVE AND RESEARCH TASKS

The objective of this thesis is to develop and validate a numerical methodology to support the design and performance evaluation of electro-thermal ice protection systems for the deicing of fixed wing aircraft. The computational methodology developed makes use of COMSOL Multiphysics software.

The tasks performed during the course of this thesis are outlined below.

1. Methodology development using COMSOL Multiphysics and preliminary computations using an electric heater installed on an aluminum rectangular plate.

2. Parametric studies with electric heaters attached to an aluminum rectangular plate to assess the effect of grid resolution and other numerical parameters on the computational results and to validate the numerical results with experimental data obtained at WSU.

3. Performance assessment of an electric heater on a composite rectangular plate made of graphite fiber and epoxy. The purpose of this study was to assess the performance of the computational methodology on non-metallic materials.

4. Use of the numerical methodology to design an electro-thermal ice protection system for a business jet wing to match the performance of a bleed air system tested in an icing tunnel facility.

5. Analysis of an electro-thermal ice protection system installed on a full scale engine inlet and validation with experimental data obtained from icing tunnel tests.
CHAPTER 4

COMSOL MULTIPHYSICS

COMSOL Multiphysics is multipurpose software used to model and solve scientific and engineering problems. The software provides access to all functionality such as built-in physics interfaces, database of material properties, ability to extend one type of physics into multiphysics models that can solve coupled physics phenomena simultaneously.

4.1 Governing Equations and solver physics

The goal of the simulation conducted during this thesis study was to calculate time-temperature histories from electrical heating applied to the geometry surface. To capture this physics phenomenon, Joule heating interface was selected which further adds an Electric Current interface and a Heat Transfer in Solids interface.

The Joule heating effect is described by conservation laws for electric current and energy. Once solved for, the two conservation laws give the temperature and electric fields respectively. Heat transfer can be defined as the movement of energy due to a difference in temperature [25].

The electric current interface computes electric field and current in conducting media. Heat conduction occurs as a consequence of different mechanisms in different media. In metals, it takes place mainly by electrons carrying heat. Typically for heat conduction the heat flux is proportional to the temperature gradient. Convection (including convection cooling and convection heating) refers to the heat dissipation from a solid surface to a fluid, generally described by a heat transfer coefficient.

4.2 The Mathematics interface

The physics interface in COMSOL Multiphysics uses partial differential equations, PDEs, as a mathematical model of physical reality [25] as outlined below:
- Coefficient form PDE in which coefficients can be specified for the derivative of
different orders in both space and time.

- General form of conservation laws and PDEs resulting from nonlinear material models.

- „Weak form” of PDE suitable for discretization and numerical solution.

Internally, equations written on general or coefficient form are converted to weak form, which is therefore the most fundamental one. In particular, the weak form is closely linked to the theory behind the finite element method, FEM.

Consider a general form of PDE with a single dependent variable u, in \( \Omega \) on \( \partial \Omega \)

\[
\begin{align*}
\begin{cases}
 e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \cdot \Gamma &= f & \text{in } \Omega \\
 -n \cdot \Gamma &= g - qu + h^T \mu & \text{on } \partial \Omega \\
u &= r & \text{on } \partial \Omega_d
\end{cases}
\end{align*}
\] (1)

where

- \( \Omega \) is the computational domain

- \( \partial \Omega \) is the domain boundary

- \( n \) is the outward unit normal vector on \( \partial \Omega \)

The first line in equation (1) is the PDE, which must be satisfied in whole computational domain, \( \Omega \). The second and third lines in equation (1) are the boundary conditions, which must be applied on the surface (defined as boundary in COMSOL) of the model in the computational domain, \( \partial \Omega \). The equation in second line corresponds to a Neumann boundary condition. Dirichlet boundary condition on the third line is an essential boundary condition in finite element theory. The terms \( f, g, q \) and \( r \), are scalar, whereas \( \Gamma \) is the flux vector. These are user defined coefficients such as spatial coordinates, the space derivative of dependent variable.
4.3 Solving Time–Dependent problems

When solving a Time-Dependent problem, the mass coefficient, $e_a$, becomes important. The name mass coefficient, or mass matrix in case of a system of equations, stems from the fact that in many physics applications, $e_a$ contains the mass density. The $d_a$ coefficient in such equations usually represents damping of wave-like phenomena. However, if $e_a = 0$, then $d_a$ is often called the mass coefficient instead. The default settings are $e_a = 0$ and $d_a = 1$, representing a parabolic time-dependent PDE such as the heat equation.

**Boundary conditions for the general form PDE**

Neumann condition on line 2 in equation (1) specifies the value of the heat flux at the boundary. The Dirichlet condition on line 3 of the same equation is a special case that directly specifies the value of the dependent variable at the boundary, $u=r$. In the current study, the dependent variable is temperature.

The fundamental law governing all heat transfer is the first law of thermodynamics, commonly referred to as the principle of conservation of energy. The basic law is usually rewritten in terms of the temperature, $T$. For a fluid, the resulting heat equation is:

$$\rho C_p \left( \frac{\partial T}{\partial t} + (u \cdot \nabla)T \right) = - (\nabla \cdot q) + \tau : \mathbf{S} - \frac{T}{\rho} \frac{\partial p}{\partial t} \left| p \left( \frac{\partial p}{\partial t} + (u \cdot \nabla)p \right) + Q \right.$$

Where

- $\rho$ is the density (SI unit: kg/m$^3$)
- $C_p$ is the specific heat capacity at constant pressure (SI unit: J/ (kg·K))
- $T$ is the absolute temperature (SI unit: K)
- $u$ is the velocity vector (SI unit: m/s)
- $q$ is the heat flux by conduction (SI unit: W/m$^2$)
- $p$ is the pressure (SI unit: Pa)
\begin{itemize}
  \item $\tau$ is the viscous stress tensor (SI unit: Pa)
  \item $S$ is the strain-rate tensor (SI unit: 1/s)
  \item $Q$ contains heat sources other than viscous heating (SI unit: W/m$^3$)
\end{itemize}

The above heat equation assumes that mass is always conserved, which means that the density and the velocity must be related through:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

The heat transfer interface uses Fourier’s law of heat conduction, which states that the conductive heat flux, $q$, is proportional to the temperature gradient:

$$q_i = -k \frac{\partial T}{\partial x} \quad (3)$$

Where $k$ is the thermal conductivity (SI unit: W/ (m.K)). In a solid, the thermal conductivity can be anisotropic. Then $k$ becomes a tensor.

And the conductive heat flux is given by

$$q_i = - \sum_j k_{ij} \frac{\partial T}{\partial x}$$

The second term on the right hand side of equation (2) represents viscous heating in the fluid. The third term represents pressure work and is the result of heating under adiabatic compression as well as some thermo acoustic effects.

Inserting equation (3) into equation (2), reordering the terms, and ignoring viscous heating and pressure work, the heat equation is written as:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (4)$$
The *Heat Transfer in Solids* interface solves equation (4) for the temperature, T. If the velocity is set to zero, the equation governing purely conductive heat transfer is obtained and is shown in first line of equation (5).

Rewriting equation in general PDE form,

\[
\begin{align*}
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) &= Q \quad \text{in } \Omega \\
\mathbf{n} \cdot (k \nabla T) &= q_0 \quad \text{on } \partial \Omega \\
T &= r \quad \text{on } \partial \Omega_d
\end{align*}
\]

Where, \( r \) is the value of the temperature on the domain boundary.

**Boundary conditions for the Heat Transfer Interface**

The heat equation accepts two basic types of boundary conditions: specified temperature and specified heat flux. Relating to subsection 4.3, the value of power density of the electric heater (heat flux) is specified as the Neumann boundary condition in the second line of equation (5) and initial temperature value is specified as Dirichlet boundary condition in the third line. The values of density, specific heat and thermal conductivity in line 1 of equation (5) are substituted from the material properties respectively. The temperature on a boundary is defined as

\[ T = T_0 \quad \text{on } \partial \]

While the heat flux is defined as

\[-\mathbf{n} \cdot \mathbf{q} = q_0 \quad \text{on } \partial \]

Where

- \( \mathbf{q} \) is the conductive heat flux vector (SI unit: W/m\(^2\)), \( \mathbf{q} = -k \nabla T \)
- \( \mathbf{n} \) is the normal vector on the boundary.
- \( q_0 \) is the inward heat flux (SI unit: W/m\(^2\)), normal to the boundary.
**Importing CAD model**

In COMSOL Multiphysics, the user can apply solid modeling with Boolean operations or boundary modeling with common modeling shapes to create objects in 1 Dimension, 2 Dimensions, and 3 Dimensions. In addition the software includes a CAD Import module feature, which provides an interface for the import of CAD files. There are multiple import file format options for example, STL, STEP, PARASOLID, IGES, and many more. In the current study, STEP file format was used for importing complex 3D geometries as it preserved all faces and curves without any issues.

**Material selection**

The software features predefined built-in material database to simulate models. Each material describes a number of physical properties and corresponding values. These values can be edited or modified depending on custom requirements. Each physics module adopts specific material properties to solve. In the current study for Joule heating physics, four material properties namely, density, specific heat, electrical conductivity and thermal conductivity of the material had to be specified.

**Grid generation methods**

The software adopts free meshing which automatically creates an unstructured mesh regardless of geometry shape. Two mesh type options are available: Physics-controlled and User-controlled mesh. The physics-controlled mesh adapts to the joule heating physics (selected for the current study) while the latter allows building and editing mesh manually. The mesh generator discretizes the boundary into triangular or quadrilateral mesh elements for 2 Dimensional geometries and tetrahedral, hexahedral, prism or pyramid mesh elements for 3 Dimensional geometries.
In the present study both unstructured and structured mesh types were utilized. The user-controlled mesh option was used to control the maximum element size and growth rate for the geometries analyzed.

4.4 Temporal Discretization

In the current study, a time-dependent interface in the software was opted for the heat transfer model to find the solution to unsteady problem using the implicit time-stepping method. By default, the software defines backward differentiation formula (BDF) time-stepping method for its numerical stability. The numerical stability deals with the behavior of the solution with change in time-step values. The BDF solver uses backward differentiation formulas with order of accuracy varying from first to fifth order (that is, backward Euler).

For implicit time-stepping schemes, a nonlinear solver updates the variables at each time step. The nonlinear solver is controlled/manually selected in the segregated solver interface. The segregated solver interface provides options to control nonlinear tolerance, damping factor, how often the Jacobian is updated such that the algorithm solves the nonlinear system more efficiently.

4.5 Spatial Discretization

The solution was obtained via a Finite element method (FEM) for the spatial discretization, a damped version of Newton’s method for the linearization. Both segregated solver and fully coupled solver options are available in COMSOL and apply Newton-Raphson iterations to solve the system of equations. The software selects either of the solvers based on the physics.

The segregated approach solves each physics sequentially until convergence of the solution. Each segregated step or iteration is used to solve the linear system of equations by
using a damped version of Newton’s method. Fully coupled approach solves all governing equations simultaneously and applies Newton method iterations until solution converges. This approach also uses damped version of Newton’s method to handle parameters for a fully coupled solution approach. Simulations were run separately with the segregated and fully coupled solvers in the current study without any convergence issues. However the fully coupled solver took more memory and computer time per iteration than the segregated solver. No difference in the solution was observed between segregated and fully coupled solver.

**Damped Newton Method**

COMSOL detects a given problem that is being solved into linear or nonlinear problem based on physics interface. The Newton solver algorithm analyses variables (like temperature in the current study) to detect linearity and nonlinearity through boundary conditions assigned. The solver breaks down linear or nonlinear problem into several linear systems of equations.

The nonlinear solver uses an invariant form of the damped Newton method. To start with an initial guess $U_0$ for the discrete form of the equations as $f(U) = 0$, where $f(U)$ is the residual vector and $U$ is the solution vector. The software forms the linearized model using $U_0$ as the linearization point and solves the discretized form of the linearized model $f(U_0) \delta U = -f(U_0)$ for the Newton step $\delta U$ using the selected linear system solver ($f(U_0)$ is the Jacobian matrix). It then computes the new iteration $U_1 = U_0 + \lambda \delta U$, where $\lambda$ is the damping factor.

**4.6 Iterative Solvers**

The iterative solvers applied in COMSOL are Conjugate gradients, BiCGStab, GMRES, and then FGRMES. In the current study, conjugate gradients iterative solver that requires less memory and computational time per iteration was employed. Conjugate gradients iterative solver
is an iterative method for linear systems of the form $Ax=b$ where the matrix $A$ is positive definite and symmetric.

A snapshot of COMSOL graphic user interface (GUI) is shown in Figure 6.

![Figure 6. Snapshot of COMSOL GUI](image)
CHAPTER 5

PERFORMANCE ASSESSMENT OF ELECTRIC HEATERS

The current chapter describes performance assessment of electric heaters installed on an aluminum rectangular plate. Section 5.1 discusses experimental test setup and procedure conducted by Wichita State University (WSU). A brief description of data acquisition system used to collect data during testing is provided. The tests were conducted for silicone and Kapton electric heaters respectively. This section is followed by section 5.2 which briefly describes computational setup in COMSOL to simulate the configurations tested at WSU. Section 5.3 compares the computational results with experimental results for both the respective heaters.

In section 5.4, parametric study of Kapton electric heater is carried out using COMSOL. The studies simulated are:

1. Time-step study
2. Grid refinement study
3. Power density study

The numerical results obtained from the parametric studies are compared with experimental results from section 5.1.

5.1 Experimental setup

A series of laboratory experiments were conducted by WSU to assess heater element properties such as time for heater element to reach operational temperature, power usage, and determine the uniformity of temperature distribution.

The heaters selected for evaluation were Silicone-rubber encapsulated and Kapton encapsulated heater elements 3-inch wide by 4-inch long were purchased for performance tests at
WSU. The silicone heaters had a thickness of 0.03-inch, input voltage of 115 VAC, average output power density of 10.6 W/in$^2$, average resistance density of 9.2 $\Omega$/in$^2$, a PSA adhesive backing, and a maximum operational temperature of 250°F (121°C). The Kapton heater’s operational conditions were 120 VAC, 120 W, 10 W/in$^2$, and 9.9 $\Omega$/in$^2$ (at room temperature) with thickness of 0.01-inch.

The test article is shown in Figure 7 and consisted of a flat aluminum plate (0.0625 inch thick) which was attached to a rectangular aluminum box (9 x 6 x 2.75 inches) for increased thermal mass. The heater to be investigated was installed on the interior surface of the flat aluminum plate as shown in Figure 8. Temperature measuring instrumentation consisted of 26 T-type thermocouples embedded within the thickness of the plate lid as shown in Figure 7. The 12 yellow circles in Figure 7 represent thermocouples embedded in the actively heated region of the plate. Tests were conducted under ambient (room temperature) and cold conditions (inside a freezer).
Figure 9 shows the experimental setup during the laboratory tests with the Silicone 3-inch x 4-inch heater at ambient conditions. The test setup for cold conditions was similar except that the box was placed inside a chest freezer.
A voltage input was applied to the heater, until the desired average or maximum temperature measured using the 12 thermocouples embedded within the thickness of the aluminum box lid over the heated area was achieved. Upon reaching this temperature, the heater was deactivated. Heater activation and deactivation was controlled manually using the power strip switch shown in Figure 9. The data acquisition system and LabView software developed were used to monitor and display temperature readings from the thermocouples in real time.

For ambient temperature tests (≈70°F or 21°C), the heater was deactivated when the maximum temperature reading reached a 150°F (66°C), which corresponded to an increment of approximately 80°F (44°C) above the ambient temperature. For cold temperature tests, the heater was deactivated when the minimum temperature recorded by the 12 thermocouples was at least 45°F (7°C). Note that the time to reach maximum plate temperature was not the same as the time interval from heater activation to deactivation. This was due to a continued buildup of residual heat in the aluminum box lid for 1 to 2 seconds following heater deactivation.

DATA ACQUISITION SYSTEM-

A PC-based, high-speed data acquisition system was used for monitoring and recording ETS performance. The data acquisition system used commercial off-the-shelf equipment. The DAS was designed with sufficient measuring capacity to collect data from 32 T-type thermocouples simultaneously at a rate of 64K samples/second/channel. Based on experiments conducted at WSU the maximum error in temperature measurements was ±1.5°F. Thermocouple measuring capability was included to address future needs with hybrid ice protection system tests. National Instrument LabView software was used to develop a program allowing various data collection options, and user-specified number of data samples per channel to be captured during testing. A screenshot of LabView DAS is shown in Figure 10.
The experimental setup for heater tests conducted at cold temperatures using an infrared (IR) camera is shown in Figure 11.

![Figure 11. Experimental setup with an Infrared camera](image1.png)

5.2 **Computation setup**

A brief description of the computation setup in COMSOL is provided in this section. To simulate heat conduction due to an electric heater, time-dependent Joule heating physics module was opted as explained in section 4.1. A 3D rectangular box with 3 inch x 4 inch electrical heater was simulated in COMSOL with the dimensions identical to the model tested at WSU. The plate/lid thickness was 0.0625 inches and the heater thickness was 0.03-inch (silicone heater). Figure 12 shows a 3 Dimensional isometric view of the rectangular box with heater placed at the centre on the bottom surface of the lid.

![Figure 12. 3 Dimensional isometric view of the rectangular box](image2.png)
In material selection interface, aluminum was selected for the rectangular box and silicone material for the heater. Four material properties, namely, density, specific heat, electrical conductivity and thermal conductivity of the material, are required to solve the governing equations. These material properties are summarized in Table 1. The value of the heater watt density was prescribed in the heat flux interface tab which solves inward time-dependent heat flux equation. Electric Potential interface tab was also chosen to provide voltage of 120 V. The heater surfaces (defined as boundary in COMSOL) selected was same for electric potential and heat flux interface.

**TABLE 1**

GEOMETRY AND HEATER MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg/m$^3$)</th>
<th>Specific Heat (J/Kg*K)</th>
<th>Electrical Conductivity (S/m)</th>
<th>Thermal Conductivity (W/m*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2780</td>
<td>875</td>
<td>1.7187e7</td>
<td>121</td>
</tr>
<tr>
<td>Silicone</td>
<td>2329</td>
<td>700</td>
<td>1e-12</td>
<td>130</td>
</tr>
<tr>
<td>Kapton</td>
<td>1530</td>
<td>1.1</td>
<td>6.67e-16</td>
<td>0.12</td>
</tr>
</tbody>
</table>
After setting up the physics model, the geometry was meshed. A free unstructured mesh was generated when physics controlled meshing option was selected. The meshed model is shown in the Figure 13. In order to mimic the heater ON and OFF time respectively, a time-step function was set up. The time-step function required specification of heater ON and OFF times in seconds. The test conditions are shown in Table 2. After the simulation was complete, temperature measurements were probed at locations on the lid surface where the thermocouples were embedded in the experimental setup.

![Figure 13. Unstructured Mesh](image)

<table>
<thead>
<tr>
<th>Run #</th>
<th>Test Condition</th>
<th>Heater Type (3inx4in)</th>
<th>Heater Thickness (inches)</th>
<th>Lid/Plate Thickness (inches)</th>
<th>Initial Temperature (°F)</th>
<th>Time step (sec)</th>
<th>No. of Mesh Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Warm</td>
<td>Silicone</td>
<td>0.03</td>
<td>0.0625</td>
<td>70</td>
<td>0.05</td>
<td>52863</td>
</tr>
<tr>
<td>2</td>
<td>Cold</td>
<td>Silicone</td>
<td>0.03</td>
<td>0.0625</td>
<td>-10</td>
<td>0.05</td>
<td>52863</td>
</tr>
<tr>
<td>3</td>
<td>Warm</td>
<td>Kapton</td>
<td>0.01</td>
<td>0.0625</td>
<td>70</td>
<td>0.05</td>
<td>52863</td>
</tr>
<tr>
<td>4</td>
<td>Cold</td>
<td>Kapton</td>
<td>0.01</td>
<td>0.0625</td>
<td>-6</td>
<td>0.05</td>
<td>52863</td>
</tr>
</tbody>
</table>
A temperature contour profile of the aluminum plate is shown in Figure 14 with red and blue contours denoting warm and cold region respectively. It is important to mention again that the aim of the computational study was to understand and evaluate the numerical methodology using experimental data.

![Temperature Profile](image)

Figure 14. Temperature profile on the lid-top view

5.3 Comparison of Experimental and Computational Results

5.3.1 Silicone 3-inch x 4-inch Heater

Selected test results demonstrating the performance characteristics of the 3-inch x 4-inch silicone heater such as heater response time, temperature uniformity are presented in this section.

*Ambient temperature test*

Ambient test performance was first assessed for the silicone 3-inch x 4-inch heater, using the experimental setup shown in Figure 9 and the test procedure described in section 5.1. From the temperature profiles shown in Figure 16-a, it is evident that the difference between the maximum and minimum skin temperatures recorded above the heater region, as indicated by the max and min lines respectively in Figure 16-a, was approximately 35°F (19°C). The maximum
and minimum values correspond to temperature readings obtained from the thermocouples located at the center and periphery of the heater region, (Figure 15). The computational results followed almost the same line trend as the experimental results with 2°F difference in the temperature values. From Figure 16-a, it can also be observed that it took less than 18 seconds for the heater to raise the temperature at the center of the aluminum box lid by about 80°F (45°C) from an initial temperature of approximately 70°F (21°C).

Figure 17-a. shows maximum surface heat distribution contours comparing infrared camera readings and simulation readings. A DAS channel reading is also shown in Figure 17-b representing temperature distribution inside and outside of heater periphery.

Cold Temperature Test

Heater performance in a cold environment was evaluated with the aluminum box placed inside a standard chest freezer. The difference between the maximum and minimum skin temperatures recorded above the heater region was approximately 35°F (19°C), which was the same as that observed in the ambient test results. The computed temperature slope was similar to that of the experimental results. A difference of 2°F during initial heating period of 10 seconds and 5°F at in maximum temperature was observed between experimental and computational
values. The main reason for the difference in maximum temperature was due to the silicone material properties used in the computation. Since heater properties were not available, the default silicone properties available in COMSOL database were selected. As seen in Figure 16-b, it took less than 16 seconds for the heater to raise the temperature at the center of the aluminum box lid by about 80°F (44°C) from an initial temperature of approximately -10°F (-23°C).

Figure 18 shows the uniformity of the box lid’s surface temperature distribution during a cold temperature test. The instant shown corresponds to the maximum plate temperature recorded by the thermocouples during laboratory tests. As evident in the contour plots in Figure 18, the heater’s center was approximately 19°F to 41°F (11°C to 23°C) hotter than its adjacent heated zones, and 61°F to 75°F (34°C to 42°C) hotter than the rest of the aluminum lid region surrounding the heater.

![Graph 16-a. Ambient Temperature Test](image1)

![Graph 16-b. Cold Temperature Test](image2)

Figure 16. Comparison of experimental and computational results
Fig. 17-a Ambient temperature test; Initial test temperature ≈ 70°F; Comparison of Infrared camera reading (left) and simulation reading (right).

Fig. 17-b DAS max channel reading

Figure 17. Maximum surface heat distribution contours with silicone 3-inch x 4-inch heater
5.3.2 Kapton 3-inch x 4-inch Heater

The computation setup for Kapton heater was exactly the same as explained in section 5.2, except the kapton heater had a thickness of 0.01-inch. This section discusses results from heater performance tests conducted with a 3-inch x 4-inch kapton encapsulated heater attached to the inside of the lid of the aluminum box as shown in Figure 19. Heater performance tests were conducted at room temperature as well as inside a freezer following the same procedure as for the silicone heater performance tests.
Figure 19. Kapton 3-inch x 4-inch

**Ambient Temperature Test**

The Kapton 3-inch x 4-inch heater’s operational conditions were 120 VAC, 120 W, 10 W/in², and 9.9 Ω/in² (at room temperature). Similar to the silicone heater, the Kapton heaters had a non-uniform heat distribution over the region directly under the heater as shown in Figure 21. Among the twelve thermocouples embedded in the aluminum lid portion over the heater, the difference between the maximum and minimum temperatures was approximately 32°F (maximum temperature ≈ 150°F; minimum temperature ≈ 120°F) while the fourteen thermocouples located around the heater registered a minimum temperature of about 86°F and hence a drop of 64°F with respect to the maximum temperature of 150°F. The computational results were in good agreement with the experimental results shown in Figure 20-a.

**Cold Temperature Test**

Heater performance in cold conditions was evaluated with the aluminum box placed inside a standard chest freezer. The difference between the maximum and minimum skin temperatures recorded above the heater region was approximately 37°F, which was about 5°F
higher than that observed in the ambient temperature test curve. Again the computational and experimental results are in close agreement as shown in Figure 20-b.

Comparison of experimental and computational results

Fig. 20-a Warm Temperature Test

Fig. 20-b Cold Temperature Test

Figure 20. Comparison of results

Figure 21. Temperature distributions at the instance of reaching maximum plate temperature of approximately 150°F. DAS [left] vs. COMSOL [right] Note: heater location is identified by black dashed line.
5.4 Parametric Studies

To investigate the capabilities of COMSOL Multiphysics software, a number of preliminary studies were performed the course of this research. For these studies a Kapton heater installed on an aluminum rectangular plate was used. Parameters explored during this part of the investigation included time-step size and grid resolution.

5.4.1 Time-Step Study

Table 3 presents the test conditions used in the time-step study. The computational results were evaluated with experimental test results discussed in section 5.1.

TABLE 3

<table>
<thead>
<tr>
<th>Run #</th>
<th>Test Condition</th>
<th>Initial Temperature (°F)</th>
<th>Time step (sec)</th>
<th>No. of Mesh Elements</th>
<th>Heater Type (3inx4in)</th>
<th>Heater Thickness (inches)</th>
<th>Lid/Plate Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Warm</td>
<td>70</td>
<td>0.025</td>
<td>52863</td>
<td>Kapton [10 W/in²]</td>
<td>0.01</td>
<td>0.0625</td>
</tr>
<tr>
<td>6</td>
<td>Cold</td>
<td>-6</td>
<td>0.025</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Warm</td>
<td>70</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Cold</td>
<td>-6</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Warm</td>
<td>70</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Cold</td>
<td>-6</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time-step studies were conducted for both ambient and cold temperature cases to assess the numerical stability of the computational scheme and numerical accuracy as the time-step was increased. Time-steps of 0.025 second, 0.05 second and 0.1 second were used.

5.4.1.1 Comparison of experimental and computational results

In Figure 22, the probe locations for the maximum and minimum temperature values were same as shown in Figure 15. For both warm and cold temperature tests, it was observed that
changing the time-steps did not affect the solution. It was noted that as the time-step was reduced, the simulation time increased.
5.4.2 Mesh Refinement Study-

Test details of the mesh study are presented in Table 4.

TABLE 4

MESH STUDY TEST DETAILS

<table>
<thead>
<tr>
<th>Run #</th>
<th>Test Condition</th>
<th>Initial Temperature (°F)</th>
<th>Mesh Elements</th>
<th>Heater Type (3inx4in)</th>
<th>Heater Thickness (inches)</th>
<th>Lid/Plate Thickness (inches)</th>
<th>Time step (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Warm</td>
<td>70</td>
<td>32817</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Cold</td>
<td>-6</td>
<td>32817</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Warm</td>
<td>70</td>
<td>43096</td>
<td>Kapton [10 W/in²]</td>
<td>0.01</td>
<td>0.0625</td>
<td>0.05</td>
</tr>
<tr>
<td>14</td>
<td>Cold</td>
<td>-6</td>
<td>43096</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Warm</td>
<td>70</td>
<td>52863</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Cold</td>
<td>-6</td>
<td>52863</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 22-b. (continued) Cold Temperature Test
COMSOL primarily uses a finite element method (FEM) for multiphysics simulations. In FEM, the accuracy of the solution is linked to the number of mesh elements. The more elements, the more accurate is the solution. However, there is a cost associated with computational resources, both in terms of time and hardware. A mesh study was performed for a Kapton heater for both ambient and cold temperature cases. The study involved three unstructured meshes with 32817, 43096, 52863 elements as shown in Figure 23.

23.a. 32817 mesh elements

23. b. 43096 mesh elements

23. c. 52863 mesh elements

Figure 23. Unstructured Mesh elements on the Aluminum Box
5.4.2.1 Comparison of experimental and computational results

Figure 24 indicates that for the computational meshes used, the accuracy of the computational results was significantly affected by grid resolution. Computational times for the three meshes (32817, 43096, and 52863 elements) investigated were approximately 25 minutes, 55 minutes and 80 minutes respectively.

Figure 24. Comparison of Results; Warm Temperature Test
5.4.3 Power Density Study-

Samples of heater elements of different power densities were purchased from heater manufacturer for evaluation. A pressure sensitive adhesive (PSA) was used to attach the heaters to metal surface. Generally, these Kapton encapsulated etched-foil heaters had operating temperatures up to 392°F (without PSA) or 250°F (with PSA).

A model of a 3D rectangular box with a 3 inch x 4 inch heater bonded to the box’s plate lid was simulated in COMSOL. The dimensions of the aluminum box used in the simulation were identical to the ones of the box used in the laboratory tests. The plate/lid thickness was 0.1 inches and the heater thickness was set to 0.01-inch. Aluminum and Kapton material were defined for box and heater respectively (Table 1). Table 5 shows test and heater parameters. Heater power densities of 5W/in² and 20W/in² were investigated. The computational procedure followed was same as mentioned previously in section 5.1 describing the heater performance.
tests and analysis. Probe locations for reading maximum and minimum temperature values are shown in Figure 25.

**TABLE 5**

HEATER WATT DENSITY STUDY TEST DETAILS

<table>
<thead>
<tr>
<th>Run #</th>
<th>Test Condition</th>
<th>Initial Temperature (°F)</th>
<th>Heater Watt Density (W/in²)</th>
<th>Heater Type (3inx4in)</th>
<th>Heaters Thickness (inches)</th>
<th>Lid/Plate Thickness (inches)</th>
<th>Time step (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Warm</td>
<td>74</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Cold</td>
<td>0</td>
<td>20</td>
<td>Kapton</td>
<td>0.01</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>19</td>
<td>Warm</td>
<td>74</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Cold</td>
<td>0</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 25. Maximum (MAX) and minimum (MIN) temperature probe locations

5.4.3.1 Comparison of experimental and computational results

*Heater Watt Density of 5W/in²*

A heater element with watt density of 5 W/in² was evaluated to assess the heating performance on an aluminum plate of thickness 0.1 inch. The line trend of maximum temperature readings for warm and cold tests increased gradually as shown in Figure 26. In warm (ambient) test, the heater took about 123 seconds to reach a maximum temperature of 150°F, whereas in the old test the heater element took about 104 seconds to reach 80°F. A large drop in temperature was seen after the deactivation of heater.
The surface skin temperature contours of warm and cold tests are shown in Figure 27.

**Heater Watt Density of 20W/in²**

For ambient temperature test (≈70°F or 21°C), the heater was deactivated when the maximum temperature reading reached a 150°F (66°C), which corresponded to an increment of approximately 80°F (44°C) above the ambient temperature shown in Figure 28-a. For cold temperature tests, the heater was deactivated when the maximum temperature reading reached 80°F as shown in Figure 28-b. The results indicate that the heater reached the maximum
temperature in both warm and cold tests, in approximately 11 seconds which is about 5 second faster compared to 10W/in$^2$ Kapton heater. A difference of 5°F and 10°F is observed in maximum temperature between experiment and computation value for the warm and cold cases respectively. Though the minimum value probed was outside of heater region, the plate temperature was still warm due to transfer of heat. Computed surface temperature contours of the warm and cold cases are shown in Figure 29.

Figure 28. Comparison of experimental and computational results

Figure 29. Surface temperature contours; warm (left) and cold (right) tests
CHAPTER 6
COMPOSITE LID TEST

Composite materials have broad applications in aerospace due to their high strength to weight ratio, thermal and electrical insulating properties and can be tailored to industry requirements. Chapter 6 presents experimental and simulation results related to the performance assessment of an electric heater attached to a graphite-epoxy flat plate.

Simulation analysis data using other composite materials commonly used in aerospace applications are also presented in this chapter.

6.1 Experimental setup

An experiment was performed at WSU Icing lab to assess Kapton heater element properties such as temperature distribution and time to reach operational temperature on 9 inch x 6 inch plate made of composite material. The test article is shown in Figure 30-a and consisted of a flat graphite-epoxy plate (approximately 0.1 inch thick) which was attached to a rectangular aluminum box (9 x 6 x 2.75 inches) for increased thermal mass. A Kapton heater of power density 2.5 W/in² was used. The heater was installed on the interior surface of the composite plate with thermocouple ducted with aluminum tape on top of the lid shown in Figure 30-b, for temperature measurement. Similar experiment was performed on a rectangular aluminum plate Figure 30-c, to assess the heater performance on metal.

For ambient test (72°F), the heater was deactivated after 600 seconds. The maximum temperature was noted at this time.
TABLE 6

GRAPHITE PLATE MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg/m$^3$)</th>
<th>Specific Heat (J/Kg*K)</th>
<th>Electrical Conductivity (S/m)</th>
<th>Thermal Conductivity (W/m*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite-Epoxy</td>
<td>1900</td>
<td>711</td>
<td>66667</td>
<td>20</td>
</tr>
</tbody>
</table>

6.3 Comparison of experimental and computational results

In the experimental investigation, temperature distribution contours on the graphite plate surface were obtained using an infrared camera as shown in Figure 31.

The composite plate was not attached with screws to the aluminum box during the experimental testing. Due to which, residual heat loss occurred. This might be the reason for the lower experimental values compared to computation results shown in Figure 32. However the computational and experimental line trends were similar.

On the other hand, for aluminum flat plate, the computation and experimental results matched well. Due to low power density of the heater on the aluminum plate, the heater took 600
seconds to reach maximum surface temperature of 140°F. While the graphite fiber plate reached the same temperature value in just 50 seconds because of its low density material property.

![Figure 32. Surface temperature distribution](image)

6.4 Computation study on Composite Materials

With respect to previous simulation test on graphite plate, a computational study to determine heater performance on different types of composite materials was performed. The material types selected for the lid were:

a) Ceramic-Matrix type: Silicon Carbide SiC

b) Metal-Matrix type: Aluminum-silicon Carbide Al-SiC

c) Carbon fiber types: Carbon T-300 and Carbon AS-4

These materials were opted due to their wide usage in aerospace applications. A Kapton heater (0.01 inch thick) of watt density 10 W/in² was simulated on the interior surface of the lid. Flat plate/lid composite properties are provided in Table 7 [26, 27, 28]. The computations were carried out for both warm and cold temperature tests.
<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg/m³)</th>
<th>Specific Heat (J/Kg*K)</th>
<th>Electrical Conductivity (S/m)</th>
<th>Thermal Conductivity (W/m*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>2329</td>
<td>700</td>
<td>0.1</td>
<td>120</td>
</tr>
<tr>
<td>Carbon T-300</td>
<td>1760</td>
<td>795</td>
<td>58824</td>
<td>10.5</td>
</tr>
<tr>
<td>Carbon AS-4</td>
<td>1790</td>
<td>1171.5</td>
<td>58824</td>
<td>6.83</td>
</tr>
<tr>
<td>Al-SiC</td>
<td>2600</td>
<td>700</td>
<td>1.11e7</td>
<td>150</td>
</tr>
</tbody>
</table>

The geometry used in the simulation consisted of a flat composite plate (0.0625 inch thick) attached to a rectangular aluminum box (9 x 6 x 2.75 inches).

### 6.4.1 Comparison of experimental and computational results

The computational results for all the composite material types are shown in Figure 33. Experimental tests were not available for these cases. However, experimental results obtained with the aluminum flat plate are plotted in Figure 33 to compare with the composite materials used in the simulations.

In both warm and cold temperature cases, composite plates made of carbon fibers T300 and AS-4 reached high temperatures due to their low density property. While the Ceramic-matrix type, SiC and Metal-matrix type Al-SiC composite plates reached temperature values closer to those obtained for aluminum plate.
Figure 33-a Warm temperature test

Figure 33-b Cold temperature test

Figure 33. Comparison of results; Warm and Cold temperature tests respectively
CHAPTER 7

INSTALLATION OF ELECTRO-THERMAL SYSTEM ON WING GEOMETRY

The current chapter discusses a computational approach for implementing an electro-thermal system on aircraft wings. This study was done in COMSOL to get an understanding of boundary condition setup, grid generation on curvilinear geometry and also to analyze the ETS potential to support anti-icing and de-icing performances. In section 7.1, a NACA 0012 airfoil was used to conduct a preliminary study with electric heaters and to compute heater response time and wing skin temperatures. In section 7.2, the simulation methodology was applied to replace a business jet wing bleed air system with an electro-thermal system capable of generating the same ice protection performance as the bleed air system. The performance of the electro-thermal system was assessed using experimental data from icing tunnel tests conducted at NASA Glenn Research Center with a business jet wing model equipped with a bleed air system.

7.1  NACA 0012 Wing

The computational setup in COMSOL was initiated by importing the airfoil profile of NACA 0012. The airfoil thickness was offset to 0.0625 inches. The electric heater was designed on the inner surface of the airfoil as shown in Figure 34. The airfoil and heater sections were extruded along z-axis to form a 3D wing model as shown in Figure 35. On reviewing previous research methods of electro-thermal installation on wing models, the electric heater was installed covering approximately 10-15% of the leading edge of the wing. For a wing span of 72 inches and chord length of 36 inches, the heater measured 24 inches of the span and 24 inches of chord length.
As a general rule, the heater chordwise and spanwise extensions were wide enough to encompass the range of movements of the aerodynamic attachment (stagnation) line under all possible operating flight conditions and aircraft configuration (angle of attack) [6].

7.1.1 Wing model

Figure 34. Two-dimensional NACA 0012 airfoil with Electro-thermal Heater

Figure 35. Extruded 3D Wing Model
7.1.2 Grid generation

An unstructured mesh was constructed for the computational study. The mesh resolution was better near the heater and wing adjoining areas as shown in Figure 36 and 37. The total number of mesh elements was 587254 and consisted triangular elements and tetrahedral elements.

A structured mesh was also generated to evaluate grid dependency on the solution. A “Mapped” function was used to create quadrilateral cells along the 2-D chord section of the airfoil. Then, a “swept” function was adopted to sweep the quad cells in z-axis or along the wing span direction generating hexahedral elements. Table 8 lists the number of elements for unstructured and structure grids.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Grid type</th>
<th>Number of elements</th>
<th>Initial Temperature (°F)</th>
<th>Time step (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>Unstructured grid</td>
<td>587254</td>
<td>76</td>
<td>0.05</td>
</tr>
<tr>
<td>25</td>
<td>Structured grid</td>
<td>30032</td>
<td>76</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The generation of the unstructured grid consumed much computational time and memory while the structured grid was more efficient.
7.1.3 Materials and Physics setup

The wing model and heater were defined as aluminum and Kapton materials with the properties shown in Table 1. In Joule heating physics interface, all the inner surfaces of the heater were assigned as heat flux with power density of 10W/in$^2$. The heater was turned off 16 seconds after activation as for the previous box simulation cases described in section 5.
7.1.4 Computational Results-

Run# 24 (unstructured grid) and Run# 25 (structured grid) were used to simulate heater performance at ambient temperature (76°F). Three locations, at $z=37$-in, $z=48$-in, and $z=49$-in, along the span on the leading edge of the wing model were probed as shown in Figure 38, to document the time-temperature profile. From Figures 39 and 40 it can be resolved that the maximum skin temperature was obtained at midspan, that is, $z=37$ inch location. At 48 inch span location, a relatively high skin temperature was still maintained on the leading edge surface of the wing as the probe point was still within the heater region and heat continued to propagate across the surface. However, at 49 inch span location, gradual propagation of heat occurred at periphery of the heater region and hence temperature at this location was lower than previous probe locations which were inside heater region.

From Figure 40 it can be observed that for both unstructured and structured grids, the temperature results were similar and hence a structure grid approach would be more efficient to use in future simulations depending on the complexity of the geometry.

![Different probe locations (red dot) along wing span](image)

Figure 38. Different probe locations (red dot) along wing span

a. Span location, $Z=37$-in
Span location, Z=48-in

Span location, Z=49-in

Figure 38. (continued)

Figure 39. Wing skin temperature contour from unstructured (left) and structured grid (right) respectively
7.2 ETIPS for a Business Jet Wing

This section describes the simulation effort performed to replace a bleed air system with an electro-thermal system capable of matching the performance of the bleed air system. The chordwise distribution of electric heater power density was tailored to match the performance of the bleed air system. Following subsections discuss the experimental setup of testing the business jet wing at the NASA Glenn Icing Research Tunnel facility and the computational methodology for designing an equivalent electro-thermal system using COMSOL. Computed wing skin temperatures obtained with electro-thermal ice protection system and experimental wing skin temperatures obtained with the bleed air systems are compared to demonstrate the ability of ETIPS to match bleed-air system performance.
7.2.1 Experimental Setup of Bleed Air System

A highly instrumented wing model representative of business jet aircraft was designed and fabricated at WSU icing personnel. Extensive tests were performed at NASA Glenn Icing Research Tunnel (IRT) facility to develop an experimental database of bleed air system performance for a range of bleed air system mass flows and temperatures, and for icing conditions representative of Warm Hold and Cold Hold icing conditions. The wing had 72-in span, 60-in chord. The leading edge of the wing was equipped with a bleed air system extending to 10% chord on both upper and lower surfaces. The bleed air system consisted of a piccolo tube and an inner-liner skin as shown in Figure 41-a. Hot air entered the piccolo tube near the tunnel floor and was delivered to the leading edge of the wing through jets emanating from a series of small holes in the piccolo tube. The diameter of each piccolo hole was 0.052 inches and the spacing between adjacent holes was 2.44 inches and was arranged in a diamond (staggered) pattern shown in Figure 41-b [29]. Thermocouple locations and their corresponding surface distances at two stations A and B are shown in Figures 41-c and d.

![Image](image.png)

a. Bleed air system details  

b. Piccolo tube details

Figure 41. Hot air anti-icing system installed inside the leading edge of the wing model [29]
7.2.2 Computation Setup of Electro-Thermal System

Two dimensional airfoil profile of the wing model tested in the IRT was imported and extruded along the span (z-axis). A wing span of 72 inches was modeled as constructed for the experimental test. The wing chord was extended to 15% of the total chord length (60-in) since the main focus of the study was around the leading edge. Along with the airfoil geometry, a 2-D heater element extending to 10% of the chord was extruded along the span as shown in Figure 42. The heater was designed with span of 24-in and thickness of 0.01-in.
7.2.2.1 Materials

Aluminum material was selected for the wing skin which was used for the fabrication of the wing leading edge. Silicone material properties were defined for the heater element attached to the wing LE. As the thermal conductivity and specific heat of aluminum varies with flight altitude (temperature), a polynomial regression was calculated for thermal conductivity and specific heat in terms of temperature and defined in the form of an equation.

Thermal Conductivity $K$ change with temperature ($T$ in Kelvin):

$$K = (5 \times 10^{-9} \times T \left( \frac{1}{K} \right)^3 - 0.0009 \times T \left( \frac{1}{K} \right)^2 + 0.6529 \times T \left( \frac{1}{K} \right) + 33.088) [W/m/K]$$
Specific Heat capacity change in terms of temperature (T in Kelvin):

\[
(1 \times 10^{-7} \times \left( T \left[ \frac{1}{K} \right] \right)^3 - 0.0022 \times \left( T \left[ \frac{1}{K} \right] \right)^2 + 1.6108 \times \left( T \left[ \frac{1}{K} \right] \right) + 616.15) \text{ [J/kg/K]}
\]

7.2.2.2 Grid on Wing model

A structured grid was used for the computational study. Figure 43 shows quadrilateral and hexahedral elements created on the surface and thickness of the wing skin respectively. The steps involved selecting the chordside boundary and generating quadrilateral elements using "mapped" function under mesh category. Then, these elements were swept along the span or z-axis using "swept" function to produce hexahedral elements.

A finer mesh was constructed when the grid generated on the first attempt proved to be coarse for the curved wing geometry. As the LE radius of the airfoil was smaller than the NACA 0012, decrement in temperature results were observed at the leading edge when the coarse grid was used. The wing profile was remeshed by increasing the number of elements.

Figure 43. Number of mesh elements, 30182 (left) and 141302 (right) respectively
7.2.2.3 Initial and Boundary conditions

Warm hold and Cold hold conditions were used in the simulations. Warm hold icing conditions are characterized by high water catch rates, whereas Cold hold cases have large temperature differences between the wing leading edge skin and the external flow [29]. Convective cooling values for both cases were obtained using ANSYS’s FLUENT software. These values were used as boundary conditions in COMSOL simulation. The physics was implemented by defining „Boundary Heat Flux” with respective convective cooling values on the outer surface of the wing model. Table 9 provides grid and input parameters for the warm and cold hold cases.

Initially, several simulations were performed to match the maximum temperature on the leading edge skin of the wing model obtained during the experimental tests. The heater watt density required to obtain the maximum temperature was 27.4 W/in².

<table>
<thead>
<tr>
<th>TEST</th>
<th>Run #</th>
<th>Number of mesh elements</th>
<th>Initial Temperature (°F)</th>
<th>Convective cooling (W/in²)</th>
<th>Heater Watt Density (W/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm Hold</td>
<td>26</td>
<td>30182</td>
<td>23</td>
<td>4.29</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>36612</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>141302</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Hold</td>
<td>29</td>
<td>21926</td>
<td>-19</td>
<td>4.73</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>46956</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.2.2.4 Probe locations and Results

The probe locations for obtaining skin temperature distribution along the chord at two span locations 6-in and 18-in are shown in Figure 44. The two span locations 18-in and 6-in were
selected to relate thermocouple locations at station A and B respectively used in experimental setup.

In Figure 45-a, the chordwise temperature profile for run 26 shows a small drop in temperature near the leading edge of the wing. To investigate the cause of this effect, runs 27 and 28 were repeated using a refined grid. The computed chordwise wing skin temperature profile is compared with experimental results in Figure 45. The results presented in this figure indicate that the skin temperature predicted by COMSOL were significantly higher downstream of the LE. This was due to the uniform power density used for the electric heaters. In the experimental data, wing skin temperatures decrease downstream of the leading edge. The heat supplied by the bleed air system is typically maximum near the wing leading edge region and decrease downstream of the leading edge due to the cooling of the interior hot air flow.

![Figure 44. Probe locations along wing span](image-url)
7.2.2.5 Heater Element Design Modification

The heater element power density was modified by dividing the protected area into three regions as shown in Figure 46. Region 1 covered leading edge section and consisted of one segment; region 2 followed aft of the leading edge and consisted of two segments one along the upper and one along the lower surface and region 3 downstream of region 2 contained two heater segments on the upper and lower surfaces respectively shown in Figure 46.

While defining the heat flux density for the heater regions, region 1 was assigned a value of 27.4 W/in\(^2\), regions 2 and 3 were assigned power densities of 15 W/in\(^2\). Different values of watt density numbers starting with 10, 20, 25 and 30 W/in\(^2\) were simulated to match the temperature along the chordwise of the wing obtained in the experimental results. The results matched well with heater watt density 27.4 W/in\(^2\) for region 1 and 15 W/in\(^2\) for regions 2 and 3.
Figure 46. Airfoil with three heater regions

Figure 47. Heater regions on extruded wing model

Temperature contours of the wing LE skin obtained with segmented heater are presented in Figure 48. Computational and experimental data are compared in Figure 49. In the experimental test, station B was close to the heat source (hot air) due to which the temperature values were higher compared to station A. In computational test case, span locations 6-in and 18-in
corresponded to station A and B defined in experimental test. However, temperature values at span location 6-in and 18-in were similar in computational results due to uniform heat distribution. The heater activation time was 22 seconds.

Figure 49 presents LE wing skin temperature at stations A and B after heater element modification. The temperature distribution along the chord matched well for warm hold test case in Figure 49-a. In cold hold test case, skin temperature values obtained from computation were low. However, a green trend line shows an increment in temperature profile and matched well with the experimental data. This increment in temperature values was obtained due to increased heater activation time. The heater was activated for 25 seconds.

48-a. Warm Hold test 48-b. Cold Hold test

Figure 48. Wing skin temperature contours; Warm Hold and Cold Hold test cases
Figure 49. LE wing skin temperatures at station A and B

49-a. Warm Hold test

49-b. Cold Hold test
CHAPTER 8
ENGINE INLET ICING TESTS

Chapter 8 presents numerical and experimental results for full scale commercial jet transport engine equipped with an electro-thermal ice protection system. The experimental data are from laboratory tests performed at WSU and icing tunnel tests performed at the NASA John H. Glenn Icing Research Tunnel (IRT). Sections 8.1, 8.2, and 8.3 describe the tests performed at WSU, the IRT test facility and icing tests performed at NASA respectively. Section 8.4 provides details of the simulation performed to compute skin temperatures resulting from the activation of the inlet ETIPS. Section 8.5 discusses comparison of experimental and computational results. The comparison is divided into three parts as follows:

i. WSU Laboratory Test Part I

ii. WSU Laboratory Test Part II

iii. IRT Icing Test

8.1 Experimental Setup

Figure 50 presents the experimental setup used at WSU prior to the IRT tests to test the electrical heaters. During testing of each heater at WSU laboratory test part I and II, four T-type thermocouples were used to monitor the temperature of the inlet (exterior) skin over the heated area, and two thermocouples were used to monitor the temperature of the heater surface. Of the four thermocouples attached to the inlet skin, one pair was connected to thermocouple readers while the other pair was connected to a PC based Data Acquisition System. Temperatures at two locations of the inlet leading edge were measured, one near the center of a heater segment and the other approximately 2-inches from the heater lead wires. The two thermocouples connecting the TC reader and the DAS at each test location were positioned less than 2 cm (0.8 in) apart. For
the inner surface heaters (with two segments), the center heater thermocouple was placed on heater segment 2 near its cable connectors. For the outer surface heaters (with four segments), the center heater thermocouple was placed on approximately center of heater segment 3. The data acquisition system and LabView software used in the tests are shown in Figure 50-b.

50-a Thermocouple attachment location
50-b DAS with LabView program

Figure 50. Experimental setup for electric heater performance tests at WSU

An inlet model was installed in the IRT test section as shown in Figure 51. The inlet was rotated by 90 degrees about its longitudinal axis so that the inlet upper and lower (thicker) lips were parallel to the tunnel side walls. This was done to allow for change in inlet angle of attack through rotation of the IRT turntable.
8.2 IRT Test Facility

The NASA Glenn Icing Research Tunnel test facility is shown in Figure 52. The IRT has a 6-ft × 9-ft (1.83-m × 2.74-m) test section that measures 20-ft (6.1-m) long and can attain a maximum speed of 390 mph (174.35 m/s) when it is empty. The IRT is a closed-looped refrigerated facility with a test section total temperature controllable from -22°F (-30°C) to +33°F (+0.56°C). The operational static pressure at the tunnel test section is near or below the atmospheric value. Two sets of nozzles (the standard and MOD-1 types) are utilized in the IRT spray system, which consists of 10 spray bars with 54 nozzle locations per bar. Depending on spray cloud conditions, 165 standard-type or 90 MOD-1 type nozzles were used during the inlet
tests. The IRT spray system is capable of simulating icing clouds with MVDs in the range of 14 \(\mu m\) to 40 \(\mu m\), and liquid water content (LWC) of 0.3 g/m\(^3\) to 3 g/m\(^3\).

![Figure 52. NASA Glenn Icing Research Tunnel; 6-ft by 9-ft test section](image)

**8.3 Experimental Procedure and Icing Tests**

All heaters were powered with 120 VAC and heater activation/deactivation was controlled manually using an ON/OFF switch. The test procedure involved activating one heater at a time until the temperature of the inlet skin was raised by approximately 60°F or 70°F at which point the heater was deactivated. During heater activation, the thermocouple readers and the DAS LabView program recorded real-time measurements from all thermocouples attached to the inlet skin and heater surfaces. The video of the temperature history data from the TC readers were saved on the video camera memory card, while data recorded by the DAS was saved on the DAS PC.

In preparation for icing tests at the NASA Glenn Icing Research tunnel facility, a preliminary test matrix was developed and was presented to the industry partners for review. Inlet test conditions included airspeed of 200 kts (230 mph), angle of attack (AOA) of 0° and
inlet capture area ratio (CAR) of approximately 0.58. These conditions were representative of holding flight in icing conditions.

8.4 Computation Setup

8.4.1 Geometry and Materials

A CAD import module was used to import the engine inlet model. In COMSOL, the engine inlet simulation model was designed with heaters placed circumferentially around the inlet lip to match the model tested. The material defined for the inlet and heater is defined in Table 1 in section 5.2.

8.4.2 Meshing and Physics setup

The inlet was meshed using mapped and swept meshing methods. Mapping involved creation of quadrilateral elements on the depth/ thickness of the heater and skin surface and then opting sweeping method to circumferentially create hexahedral elements. The mesh of the inlet is shown in Figure 53.

In Joule heating physics setup, heat flux boundary condition was defined to heater boundaries individually. This meant, while simulating heater performance at 90° inlet section, heat watt density was assigned to that particular heater boundary alone. The heaters were deactivated at time (seconds) when temperature difference, $\Delta T=60^\circ F$ and $\Delta T=70^\circ F$ was obtained during experimental tests. The initial temperature values and time taken are listed in Table 10.

The heater watt densities for inner and outer heaters were different due to their relative size. Watt density was calculated by dividing the total heater power by effective area. The effective area is where the heat flux is defined to the whole region.
TABLE 10
WSU TEST CONDITIONS PART I

<table>
<thead>
<tr>
<th>Run #</th>
<th>Initial Temperature (°F)</th>
<th>Inlet station (degree)</th>
<th>Heater Watt density (W/in²)</th>
<th>Mesh elements</th>
<th>Heater Thickness (inches)</th>
<th>Inlet Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>76</td>
<td>90°</td>
<td>Inner heater 9.2</td>
<td>22428</td>
<td>0.005</td>
<td>0.054</td>
</tr>
<tr>
<td>32</td>
<td>74</td>
<td>180°</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>73</td>
<td>90°</td>
<td>Outer heater 8.8</td>
<td>23400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>76</td>
<td>180°</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.5 Comparison of Experimental and Computational Results

8.5.1 WSU Test Part I

In part one; test performed at WSU consisted of performance assessment of the inner and outer heaters installed on the engine inlet. Figure 54 shows surface temperature contours during inner and outer heater activated times at different inlet stations. Experimental and computational time-temperature histories obtained at all circumferential stations are presented in Figures 55 and
56 for the inner and outer surface heaters, respectively. A summary of test results showing the
time required for the heater to raise the temperature of the inlet skin by a minimum 60°F is
shown in Table 11. The results shown are from temperature readings obtained with
thermocouples attached near the center of each heater.

To raise the temperature of the inlet skin by at least 70°F, near the center of the heater, the
inner station (I. S) heaters took an average of 19 seconds for an average initial skin
temperature of 74.5°F. The outer station (O. S) heaters took an average of 19.5 seconds to do so
for an average initial skin temperature of 72.5°F. During heater activation, the O.S. heaters had a
steeper temperature gradient (Figure 56) compared to that of the I.S. heaters (Figure 55).

### TABLE 11

SUMMARY OF TEST RESULTS FOR THE ELECTRIC HEATERS INSTALLED ON ALUMINUM INLET LIP – TC LOCATED AT APPROXIMATELY CENTER OF HEATER SEGMENT

<table>
<thead>
<tr>
<th>Inlet Station</th>
<th>Start Temp (°F)</th>
<th>Time Taken: ΔT=60°F (s)</th>
<th>Time Taken: ΔT=70°F (s)</th>
<th>Inlet Station</th>
<th>Start Temp (°F)</th>
<th>Time Taken: ΔT=60°F (s)</th>
<th>Time Taken: ΔT=70°F (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90° inner</td>
<td>76.0</td>
<td>15</td>
<td>19</td>
<td>90° outer</td>
<td>72.5</td>
<td>16.0</td>
<td>19</td>
</tr>
<tr>
<td>180° inner</td>
<td>74.0</td>
<td>18.5</td>
<td>24.5</td>
<td>180° outer</td>
<td>76.0</td>
<td>16.0</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Figure 54. Temperature contour of inner heater at 90° (left) and outer heater at 180° (right) inlet stations
8.5.2 WSU Test Part II

The second part of WSU tests involved installation and evaluation of leading edge heaters in addition to inner and outer heaters tested during Part 1 of the laboratory tests. The
properties of the heaters and initial temperature values are shown in Table 12. All heaters were activated and deactivated at the same time interval.

**TABLE 12**

WSU TEST CONDITIONS PART II

<table>
<thead>
<tr>
<th>Run #</th>
<th>Avg. initial Temperature (°F)</th>
<th>Heater Type</th>
<th>Heater Watt Density (W/in²)</th>
<th>Heater Thickness (inches)</th>
<th>Inlet Thickness (inches)</th>
<th>Mesh elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>76</td>
<td>inner</td>
<td>9.2</td>
<td>0.005</td>
<td>0.054</td>
<td>56236</td>
</tr>
<tr>
<td></td>
<td>74</td>
<td>outer</td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>leading edge</td>
<td>9.5</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ambient test performance was assessed for the electric heaters based on the experimental setup. Temperature contours of inlet lip at time intervals t=9 secs and t=15 secs are shown in Figure 57. These time intervals are selected to show heater performance during mid-initial stage and maximum temperature performance before the heater was deactivated.

![Temperature contour of inlet lip at time 9secs and 15secs respectively; Front view (left) and side view (right)](image)

Figure 57. Temperature contour of inlet lip at time 9secs and 15secs respectively; Front view (left) and side view (right)

Time-temperature history were noted and tabulated for experimental and computational tests. It should be noted that experimental values for the outer heater at station 180 was not available and
no heat flux was applied at that station during computational run. Hence temperature was not probed at that station. However, temperature readings on the inlet skin surface (outer) at different sections on the inner, outer and leading edge heater activated regions were available from the experimental data and were probed likewise in simulation test.

About 30 to 34°F skin temperature was considered to be sufficient to cause ice debonding at the interface between the ice layer and inlet skin and likewise the heater was deactivated when the maximum temperature reading reached value of 110°F, an increment of 34°F above ambient temperature value. The inner and outer heaters took approximately 7 to 7.5 seconds to reach this maximum temperature reading.

Figure 58 shows inlet skin surface time-temperature distributions on inner heater activated region at stations 11°, 101° and 281° respectively. Comparison of experimental and computational temperature profiles during heater ON time show good agreement. However after the heater was deactivated the drop in temperature in the experimental data was higher than that predicted by the simulation.
Figure 59 shows comparison of experimental and computational results for the outer heater region. At station 11°, the heater took a second or two longer during testing to raise the temperature of the inlet skin surface to 110°F compared to analysis data. The time taken by the outer heater to raise the outer inlet skin temperature of 110°F was about 7.5 seconds.
An electric heater with watt density 9.5 W/in² defined based on heater effective area was used at leading edge of the engine inlet for the simulation study. The thickness of the leading edge heater was thicker than the heaters installed at inner and outer stations. Temperature contour at the leading edge strip can be seen in Figure 60. A linear temperature profile was obtained during heater ON time from computational results. A temperature difference, $\Delta T = 7^\circ F$ was observed between experimental and computational results at station 9° and 279° respectively. Likewise $\Delta T = 10^\circ F$ at station 99° was obtained. A faster heater response was observed in the computation.
8.5.3 IRT Icing Tests

This section consists of cold temperature tests conducted at static free stream temperatures of 26°F, -4°F, and -22°F. Figure 61 shows ice on the engine inlet with the ice protection off. Ice accretion on the inlet lip can result in severe engine performance losses and
ice shed from the inlet lip can result in engine damage. Thus, ice protection is necessary to maintain the inlet lip free of ice during flight in icing conditions.

Figure 61. Ice accretion on engine inlet

Initial Temperature value of 26 °F

Cold temperature (26°F) test on engine inlet was performed at NASA IRT to assess the performance of the electro-thermal ice protection system (ETIPS). Inlet geometry and heater configuration and placement were the same as the one used in the WSU laboratory tests.

The heater activation time was extended to attain sufficient heat on the inlet skin surface to prevent the formation of ice accretion. The values of the convective cooling due to external flow were obtained from FLUENT software. An average of convective cooling data was calculated for a range of temperature starting from 30°F to 120°F. Values of -833.96 W/m², -510 W/m², and -1034.16 W/m², corresponding to inner, outer and LE heater position, were assigned on the outer surface of the inlet as a boundary condition. The negative sign indicates convective „cooling” condition. A maximum skin temperature of about 120°F was used in the selected tests and the heaters were deactivated after the outside skin surface attained this maximum temperature. Temperature difference ΔT of 50°F is shown in Figure 62, marked from 70°F to 120°F, warm enough to prevent ice accretion. Slopes matched well at the maximum skin
temperature readings of computational and experimental results although about 5°F difference was found after the heater power was shut off. However this difference is not important since it has no impact on ETIPS effectiveness.

Experimental and simulation results of surface skin temperatures on outer heater activated region at 11°, 101° and 281° stations were in good agreement as shown in Figure 63. The outer heaters
took an average of 12 seconds to bring the outer inlet skin surface to a temperature of 120°F from a temperature of 70°F.

Electric heaters at the leading edge region took about 3 seconds longer than heaters at inner and outer regions to raise the skin temperature to 120°F starting from a temperature of 70°F.
Experimental and computational results for the leading edge heaters presented in Figure 64 demonstrated good agreement.

Figure 64. Surface time-temperature distribution of LE heater

- a. Leading edge, 9° station
- b. Leading edge, 99° station
- c. Leading edge, 279° station

*Initial temperature value of -4°F*

In order to estimate heater performance at a colder temperature of -4°F additional computations were performed. Computational results are presented in Figures 65, 66 and 67. There were no experimental results available for this case. Watt density and heater activation
time were kept same as for the 26°F case. The values of the convective cooling due to external flow were -852.92 W/m², -606.2 W/m², and -1058.16 W/m². These values were defined on the outer surface of the inlet model where inner, outer and LE heaters were installed respectively.

Electric heaters at all three regions, inner, outer and leading edge, took approximately 16.5 to 17.5 seconds to bring the outer inlet skin surface to a temperature of 70°F from an initial temperature of -4°F.

![Figure 65. Surface time-temperature distribution of inner heater](image)

a. Inner, 90° station  
b. Inner, 270° station

Figure 65. Surface time-temperature distribution of inner heater

![Figure 66. Surface time-temperature distribution of outer heater](image)

a. Outer, 0° station  
b. Outer, 101° station

Figure 66. Surface time-temperature distribution of outer heater
From the Figure 67, it can be said that after the heater was deactivated the inlet outer skin surface temperature was still high and did not drop instantly.

![Figure 67: Surface time-temperature distribution of LE heater](image)

**Initial Temperature value of -22°F**

Inlet model was simulated for ambient temperature of -22°F because it is the lowest temperature limit in the icing envelope. Also this test was performed to assess ETIPS performance in the extreme case. No experimental results were available for this case. Figure 68 shows temperature profile of the inlet model with all heaters activated.
It can be said that for lower ambient temperature, energy of higher watt density for longer time period is required to heat the outside surface skin temperature in order to breakup or prevent the ice formation. The convective cooling values calculated due to external flow were -829.52 W/m$^2$, -588.08 W/m$^2$, and -1029.6 W/m$^2$. These values were defined as a boundary condition on the outer surface of the inlet model where inner, outer and LE heaters respectively were installed.

Figure 69. Surface time-temperature distribution of inner heater
All the electric heaters were activated and deactivated at the same time interval. The heaters were shut off at 30 seconds. Inner heaters raised the temperature of the inlet skin surface to about 80°F while outer and leading edge heaters raised about 15°F higher than the inner heaters.
CHAPTER 9
SUMMARY AND CONCLUSIONS

The main objective of the thesis study was to develop a numerical methodology for the assessment of Electro-thermal ice protection system (ETIPS) for aircraft de-icing. Finite element analysis based software; COMSOL Multiphysics was utilized to perform the heat transfer analysis. A rectangular box model with an electric heater attached to the bottom surface of the box lid was initially used to develop the numerical methodology. Parametric studies were performed to assess the performance of the numerical model over a range of conditions, aerospace materials (metallic and composite) and heater configurations. Both ambient and cold temperature tests were used in the simulations and the heaters were found to meet the desired electro-thermal ice protection system requirements in terms of heater response time (time to raise skin temperature sufficient to melt the ice).

Next, the heater element operational characteristics were evaluated using a two-dimensional wing model to test the methodology on curved surfaces. The heater watt density and the heater shut off time period was similar to the ones used in the analysis performed with the box. Next simulation methodology was used to replace a bleed air system of a business jet wing model tested in an icing tunnel facility with an ETIPS. Temperature distributions obtained with the ETIPS were compared with corresponding bleed air system results and showed good agreement. The difference between experimental and computational results was about 2.6% for warm case and 3.4% for cold case.

Finally the simulation method was applied to simulate the ETIPS performance of a full scale engine inlet ETIPS that was tested at WSU and also at the NASA IRT facility. The ETIPS consisted of four inner and four outer electric heater elements installed downstream of the inlet
leading edge providing 360° coverage. The heater watt densities were based on total heater power used in the experiments and effective inlet surface area. Subsequently, additional heater elements were installed at the leading edge region to match the experimental setup. The simulations were performed using boundary conditions (convective cooling) representative of the icing tunnel test conditions. During the simulation tests, all heater elements were activated and deactivated according to the ETIPS operation used in the experiments.

Following are comments and key findings based on the work performed and results obtained during the course of this research.

- The tests showed that the silicone encapsulated heater element was able to raise the temperature at the center of the 9-inch x 6-inch x 0.0625-inch aluminum plate test article by about 80°F (45°C) from an initial temperature of 70°F (21°C) in approximately 18 seconds. For subfreezing conditions, the heater took 16 seconds to raise the temperature at the aluminum flat plate by about 80°F (44°C) from an initial temperature of approximately -10°F (-23°C).

- For Kapton encapsulated etched foil heater element, tests showed that the heater element was able to raise the temperature at the center of the 9-inch x 6-inch x 0.0625-inch aluminum plate test article by about 80°F (45°C) from an initial temperature of 70°F (21°C) in approximately 16 seconds. For subfreezing conditions, the heater took 15 seconds to raise the temperature at the aluminum flat plate by about 80°F (44°C) from an initial temperature of approximately -10°F (-23°C).

- The time step and grid resolution studies conducted with Kapton heater and box geometry showed that for numerical time step intervals of 0.025 s, 0.05 s and 0.1 s no significant changes in the computed skin temperature values was observed. The grid
densities, 32817, 43096, 52863 used showed no significant impact on the computational results.

- Rectangular 3 in x 4 in Kapton heater elements with watt densities 5 W/in\(^2\) and 20 W/in\(^2\) were tested and simulated on a 9-inch x 6-inch x 0.1-inch aluminum plate. Computational results matched experiment results from laboratory tests performed with 5 W/in\(^2\) and 20 W/in\(^2\) power densities. A difference of 5°F to 10°F in maximum skin surface temperature between experimental and computational results was obtained.

- A Kapton heater of watt density 2.5 W/in\(^2\) was experimentally tested on a graphite-epoxy composite material. The test was conducted at ambient temperature of 72°F and the heater was deactivated after 10 minutes. The results depicted similar slope trends for experimental and computational runs however due to the heat losses occurred during experimental testing the maximum surface temperature was lower than the computational result.

- A computational study was carried out to evaluate heater performance on different types of composite. The results were plotted against previously tested aluminum metal element. For corresponding ON and OFF times, the composite materials showed better response by attaining higher surface temperatures in a given time.

- An electro-thermal ice protection system was developed for a business jet wing to replace a bleed air system that was tested in an icing tunnel facility. Analysis showed that by tailoring heater power density in the chordwise direction from 27.4 W/in\(^2\) near the leading edge to 15 W/in\(^2\) downstream of the leading edge the ETIPS matched the performance of the bleed air system in terms of skin temperature distribution. Activation
times for the electric heaters ranged from 22 to 25 seconds which meet requirements for ETIPS cycling times.

- The simulation methodology developed was tested using an ETIPS developed for a full-scale engine inlet. The inlet ETIPS was tested at WSU and in an icing tunnel facility. Computational results obtained for both inner and outer heaters matched well with the experimental results in both WSU tests I and II. A temperature difference $\Delta T$ of 7°F was obtained between computational and experimental results for the leading edge heaters.

- For cold temperature test conducted at the NASA icing tunnel facility at static free stream temperatures of 26°F, computational results for all heaters (inner, outer and LE) of the inlet electro-thermal system showed that the heaters were able to raise the inlet skin temperature to 70°F within 12 seconds. These results were in good agreement with results obtained from icing tests. Computational tests performed at initial temperatures of -4°F and -22°F, showed that a heater response time of approximately 30 seconds was required to attain a maximum skin surface temperature of 110°F.

In this research, the simulation methodology developed to evaluate the performance of ETIPS for various geometries was successfully validated with experimental results. In future, this numerical approach can be used to support the design and performance assessment of ETIPS for fixed wing aircraft prior to certification testing. This will reduce the time and costs associated with the development and certification of electro-thermal ice protection systems.
REFERENCES
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