Optimizing Gridded Heater Arrangements in Anti-/De-icing Systems through Multiphysics Thermal Simulation

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Abstract— **The electro-thermal system in anti-/de-icing systems, known for its reliability, is often favoured despite its notable drawback—high power consumption. Seeking to mitigate this issue, the adoption of a gridded heated surface emerges as a promising avenue for energy optimization. In this study, a finite difference method is employed to meticulously examine heat transfer across a selected surface with defined material properties. The simulation specifically investigates heat conduction under various boundary conditions, considering scenarios where a cold surface is either partially or fully heated in the presence of an ice cover. The discourse in this paper delves into the examination of different geometries of heating elements, assessing their impact on critical parameters such as overall power consumption, heating time, performance, efficiency and other relevant factors. By systematically analysing these variables, the study aims to offer insights into the efficacy of gridded heated surfaces as an energy-efficient alternative within electro-thermal systems. This research contributes to the ongoing quest for more sustainable and resource-conscious solutions, offering a nuanced understanding of how gridded heaters can optimize energy usage while maintaining the robustness associated with electro-thermal heating techniques in anti-/de-icing systems.**

Keywords— ***Finite difference, heat transfer, ice protection, system design, electrothermal***

I. Introduction

Ice accretion in the cold regions impacts onshore [1, 2], offshore [3, 4] and airborne structures [5, 6] rigorously, which necessitates the requirement of heating systems to allow for proper functioning of machines, stability of structures, and ventilation [7]. In Arctic regions, heating systems are part of common household necessities like car to commercial jetliners to avoid icing problems. A range of techniques exist that convert an available source of energy into thermal energy based upon the application, e.g.: photothermal, electrothermal, geothermal and thermochemical. Electrothermal heating among them is widely used for its efficiency, system portability, reliability, and safety – as no combustion or gas leakage risk is involved.

A conceptual idea to design an economical ice protection system was presented by Yousuf et al. [8] in which basic idea is to use active infrared thermography for ice detection purpose and gridded heaters for ice mitigation. Before moving on for system design implementation phase, preliminary heat transfer simulations are carried out to lay a foundation for an energy efficient heating strategy. Literature review was conducted in this domain to study about thermal analysis for different surfaces and aerofoil structures. Khawaja et al. [9] and Taimur et al. [10] performed dedicated research on simulation leading to experimental verification for thermal signature of fresh water and saline ice cube. Mohseni et al. [11] made a comparative numerical heat transfer study for two different patterns of anti-icing heating elements (wires) that were embedded in polymer composite of aerofoil. Zhu et al. [12] assessed the performance of electrothermal de-icing system using 2D numerical approach; they simulated ice-water phase transition process via enthalpy method and studied AUX method for conductive heat transfer. Bennani et al. [13] conducted a detailed numerical study coupling unsteady ice accretion, heat conduction via electrothermal system, melting of ice, and boundary-layer flow.

Current paper is an extension of previous research conducted by Khawaja et al. [14-17] presents a 2D conductive numerical heat transfer simulation over a supposed aluminium surface holding heating elements from the perspective of heat flow and energy conservation. It is postulated that a gridded heated surface can offer a better optimization instead of a large heating surface. Two different test cases are presented in order to assess the proposition.

II. Numerical Study Of Conductive Heat Transfer

Temperature is a measure of heat energy and the variation of temperature (distribution of heat energy) in a given region of space over the transition of time is expressed by partial differential equation. This partial differential heat equation in 2-D in terms of diffusion coefficient (α) is expressed as:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right); \begin{cases} t \geq 0 \\ 0 \leq x \leq L \\ 0 \leq y \leq W \end{cases}$$

where T is the temperature, t is time, (x, y) are spatial dimensions for length (L) and width (W), and α is the diffusion coefficient which is a material property.

The solution for this transient heat equation can be obtained for a finite time if initial conditions (at $t = 0$) and boundary conditions at (x, y) = (0,0) and (x, y) = (L, W) are known. To solve this partial differential equation is discretized using Finite Difference Method. Since the heat equation involves both first and second derivatives, it can be solved by Forward Time Centred Space (FTCS) discretization [18]. FTCS is employed for the purpose of this study by using forward difference for (time) transient term and central difference for spatial terms, i.e.:

$$\frac{T_{i,j}^{t+1}-T_{i,j}^{t}}{\Delta t}=\alpha\left(\frac{T_{i+1,j}^{t}-2T_{i,j}^{t}+T_{i-1,j}^{t}}{(\Delta x)^2}+\frac{T_{i,j+1}^{t}-2T_{i,j}^{t}+T_{i,j-1}^{t}}{(\Delta y)^2}\right)$$

where: subscript i, j denote computational points in spatial domain (x, y). $(\Delta x, \Delta y)$ formulate the mesh spacing, and Δt is the time step for simulation.

The solution for FTCS methodology resembles to that of a parabolic differential equation, that can become unstable for certain values of α, Δx, Δt. Collecting these terms in above heat equation solution gives: $c_x = \alpha \frac{\Delta t}{\Delta x^2}; c_y = \alpha \frac{\Delta t}{\Delta y^2}$. These values (cx, cy) related to mesh sizing or mesh quality are called Courant numbers, and the stability criteria is defined as Courant–Friedrichs–Lewy (CFL condition) [19]. As per this criteria, they should be limited by a maximum value (typically less than 1) [20]. For this study, the values of α, Δx, and Δt were chosen so that the Courant number was about 0.1.

III. Simulation Setup

To study the conductive heat transfer over a surface from the perspective of heat flow and energy conservation, it is postulated that a gridded heated surface can offer a better optimization. To assess this conjecture a two-dimensional aluminium surface (100cm×50cm) subjected to icing and then de-icing, is simulated in MATLAB® and its heat transfer pattern is studied. For this purpose, two cases are chosen to analyse qualitatively: (i) comparison of a single heat source and gridded heaters (ii) comparison of heaters geometry. The simulations run for 500 sec and heater(s) turn on at t=5s. Assumed constant values related to mesh sizing and initial & boundary conditions are tabulated below in TABLE I and brief case description is given in TABLE II.

Some assumptions have been made while running the simulation:

a) Heat transfer is occurring only through conduction.
b) No heat loss is taking place via any face of rectangular sheet.
c) Heaters turn ON as a step function.
d) Presence of ice is simulated as a surface region with 253K (-20°C) temperature and its thickness is neglected so as to consider a 2D scenario.

TABLE I. Different Parameters considered during MATLAB simulation for Heat Transfer

Constant Parameters	
Diffusion Constant (α)	0.1 cm^2s^{-1}
Time Step (Δt)	1 s
Spatial Domain Step (Δx, Δy)	(1s, 1s)
Initial Conditions	
Metal Sheet Temp.	255 K (-18°C)
Boundary Conditions	
Ambient Air Temp. (all 4 sides)	258 K (-15°C)
Other Constants	
Heater Temp	400 K (673°C)
Heater Turn ON Instant	t = 5s (& onwards)
Aluminum Specific Heat	0.90 $J/(g.°C)^{-1}$

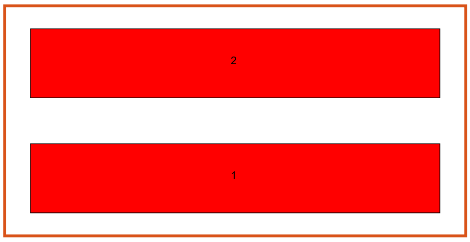
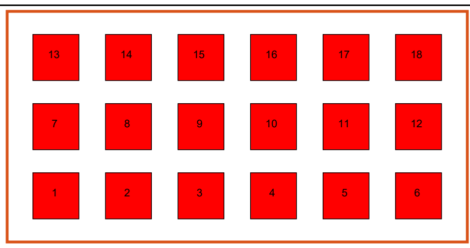
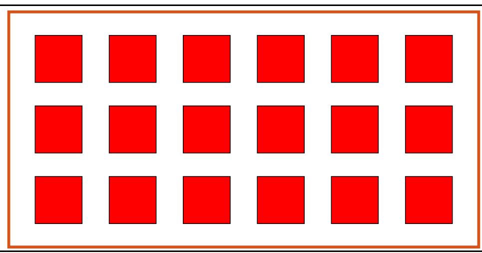
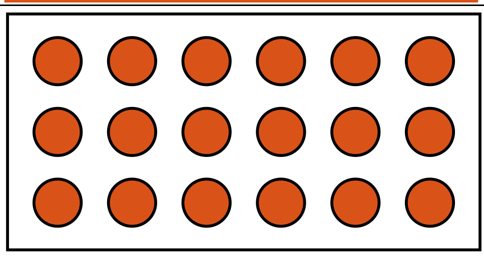
With the conditions described in Table-I, the same heating pattern is obtained in all test cases for the first 4 secs when the heaters are off. So, they are separately shown in Figure-1. The rectangular contour in the centre of the upper plot is iced region at 253K and surrounding zone describes metal temperature at 255K. In the elapsed time till 4s, heat diffuses from hot region (sheet) to the cold region (ice block) which appears as a thermal gradient shaded according to colour bar and chosen palette. Similarly, the contours on the outer border describe heat flow from boundary (hot air) towards metal sheet (cold zone).

IV. Simulation Results

A. Case-1: Heaters Quantity

Conventional approach for commercial anti-icing and de-icing systems is to use a single heating element that spans across the target surface, for instance in case of leading edge of aileron for conduction. To assess the concept of gridded heaters for a rectangular sheet, a case of two heaters spanning across its length is compared to a matrix of 18 heaters (3×6). Two heaters are considered instead of single heater so that heat transfer can be studied better visually because otherwise single heater would maintain 400K temperature on a larger area of the sheet for whole duration when it turns on.

TABLE II. Test Cases Considered to Analyse Gridded Heaters Concept

Case-1: Comparison of fewer heaters spanning a surface vs multiple gridded heater


Case-2: Comparison of heaters geometry – square vs circular heaters



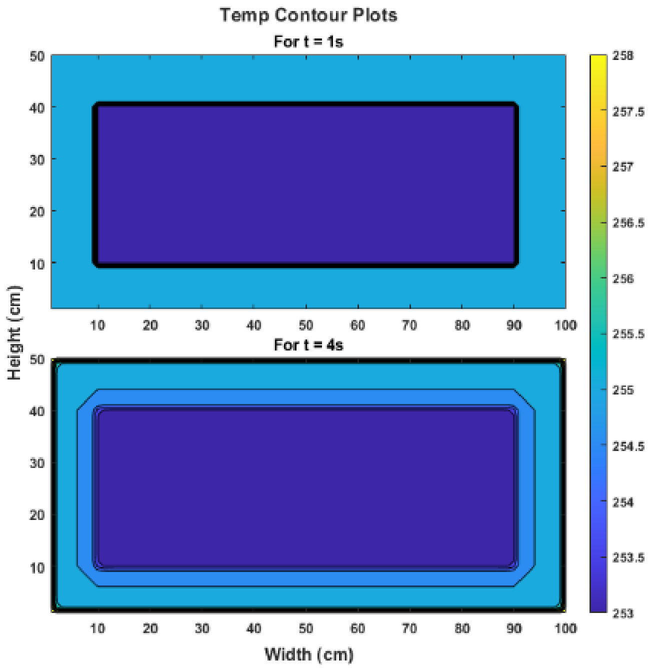


Fig. 1 Thermal contour plots for t = 1s and t = 4s.

Figure 1 shows the heating pattern for the two spanning heaters and Figure 2 shows its corresponding gridded heaters concept. Although the two heaters maintain the temperature across the covered area, the gaps in between the heaters exhibit low temperature zones till at least $t = 150s$.

B. *Case-2: Heaters Geometry*

In this case 18 square and circular heating elements are simulated with dimensions 10 cm length and 10 cm diameter respectively. Horizontal and vertical spacing between heaters is set as 5.6cm and 5cm respectively, and same values are considered for horizontal and vertical border margins as well. Figure 3 and Figure 4 below describe the heating patterns for square and circular heaters in which it is quite evident that former ones reach thermal equilibrium at much greater rate than the latter case, i.e., square heaters achieved it at around 150s and after that the temperature transition is almost at steady state. Cold temperature zones are present between heaters in both the cases till at least 80s however due to less area occupied by a circle ($(5\times5)\pi = 78.5$ cm^2) than a square ($10\times10 = 100$ cm^2), circular heaters have to work more. In other words, if pulse heating is to be used then on-time for circular heaters will be more than square ones. Some interesting and opposing patterns are observed in both the cases, for example at t = 80s: in case of square heaters the centre of aluminium sheet will acquire equilibrium late as compared to the left/right sides. This pattern is totally opposite in case of circular heaters.

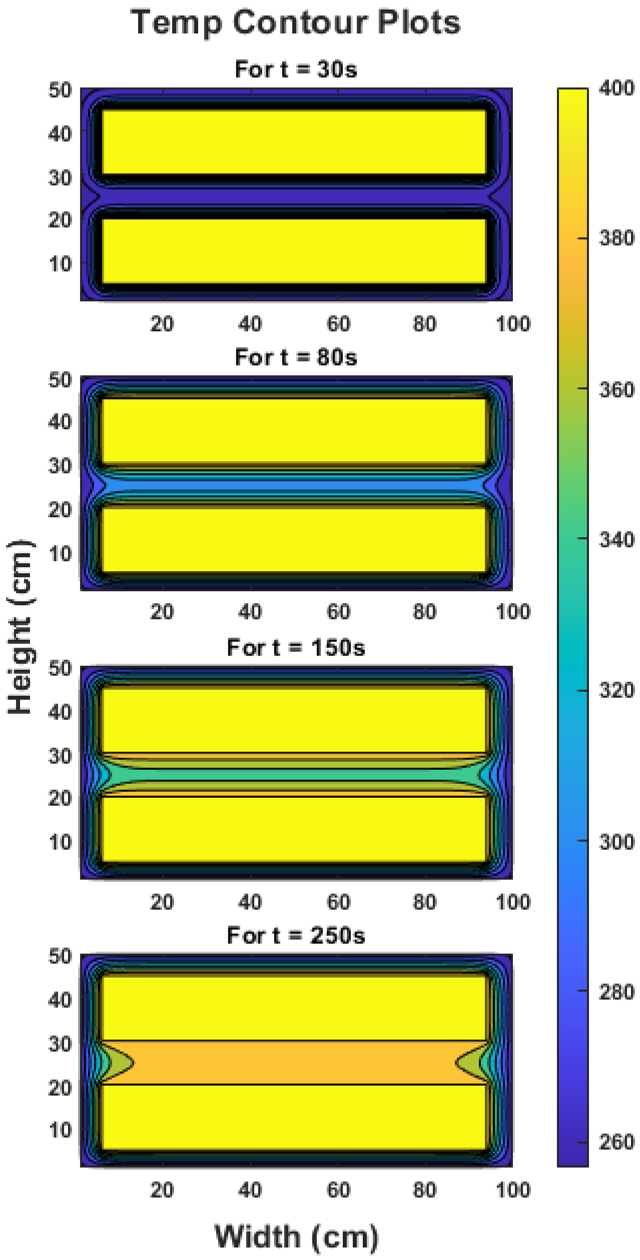


Fig. 2 Heating pattern for the case of heaters spanning across the sheet.

It can also be observed at later time instants: t = 150s and 250s that temperature evolution follows the order: centre – (then) left/right – (then) centre left/centre right of the sheet. The contours around the border attain almost similar pattern throughout the simulation for both geometries as fixed boundary conditions for atmospheric temperature are assumed.

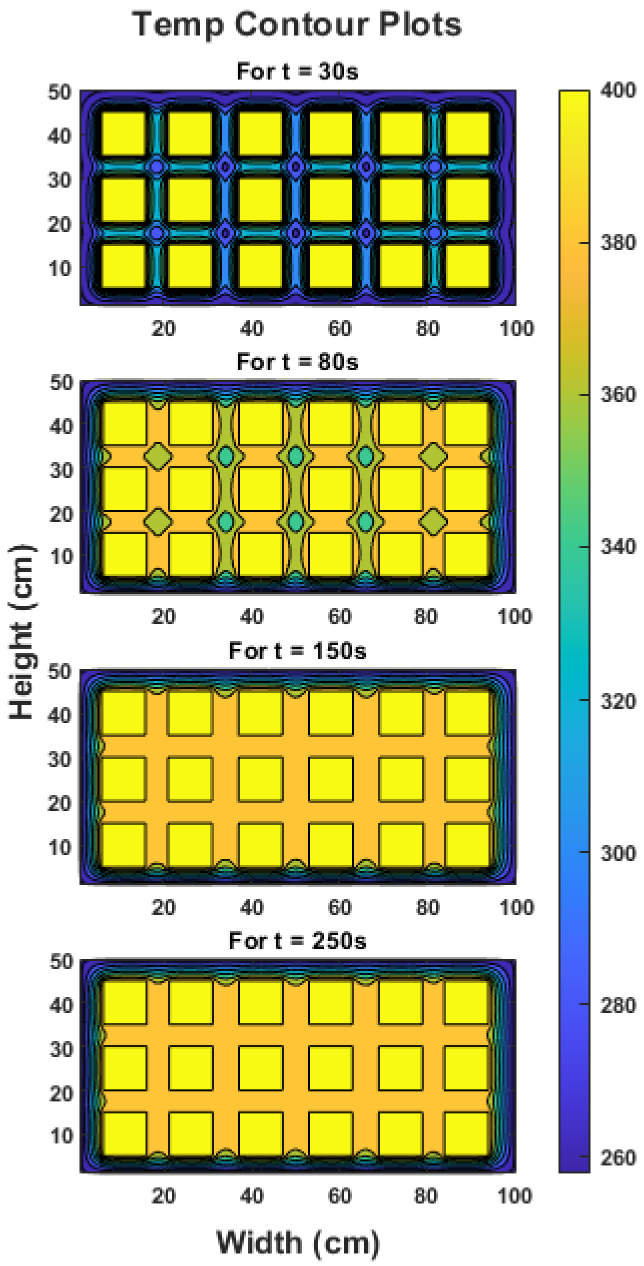


Fig. 3 Heating pattern for square heaters.

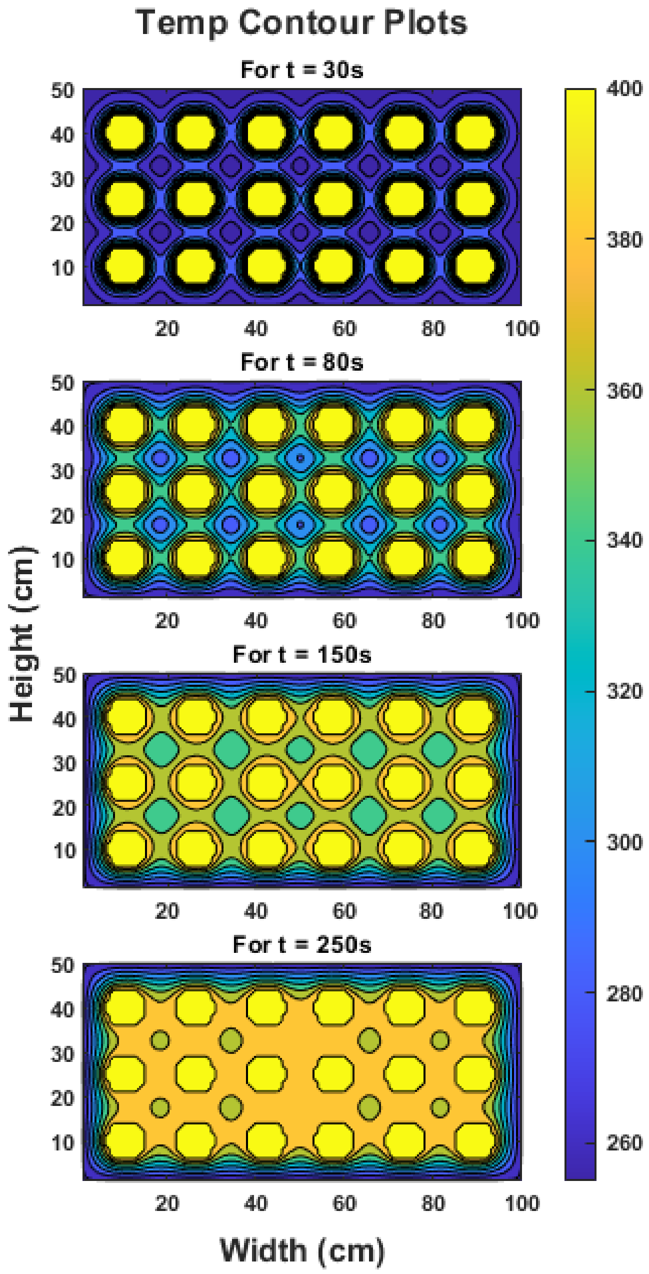


Fig. 4 Heating pattern for circular heaters.

V. Conclusion

Despite the evident disadvantage of high-power consumption of electrothermal heating systems in general, their comparatively high efficiency, safety, reduced weight, and possibility to implant or embed in different materials still makes them a choice for certain applications. This study presents the concept of a gridded heated surface created through small heaters against a conventional approach in which whole surface is heated by large heater. Two dimensional simulations for conductive heat transfer are carried out in MATLAB using finite difference method. Two test cases are considered concerning the overall concept of gridded heaters and their geometry. Results suggest that gridded heaters allow the thermal equilibrium to be reached earlier and consume low power per unit mass. They also allow more control to the user for heating a specific portion of target surface. In case of geometrical shape, heat transfer for square and circular heaters revealed opposite patterns: for square heaters thermal gradient is established from lateral sides towards the centre, whereas for circular heaters its direction is from the centre and lateral sides of sheet towards their in-between space. Nonetheless overall heat transfer rate is high for square heaters but the expense of more power per unit mass. Selection of suitable heating elements may depend upon various factors, such as financial/maintenance cost, application, and shape of target surface. So, the study does not intend to reject one geometry for the other for any general case study. The simulation work is a preliminary step towards the development of actual hardware setup for an energy optimized ice protection system.

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