Utilizing Finite Element Analysis (FEA) for Flexible Heater Designs

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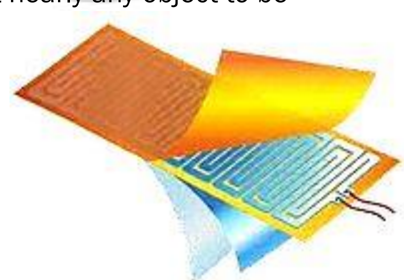
Flexible heaters are commonly utilized in many different heating applications. Generally, these applications are unique and therefore require a similarly unique heater solution. However, the flexible heater solution isn't typically an over-the-counter design. Unique heaters require engineering and design time to ensure proper functioning in the specific application. The design process for a new heater commonly consists of an estimation of power requirements for the customer's specific application followed by prototype builds using a feedback loop approach to determine the final design and power specifications. Finite Element Analysis (FEA) can be implemented into the design process for a new flexible heater to mitigate the time spent in the prototype/feedback loop phase of the heater. FEA is a simulated analysis of a specific component under simulated conditions that represent the real world environment. Multiple simulations using FEA software can dramatically decrease the number of necessary prototypes before confirming final designs and specifications for the heater. To determine the accuracy of FEA software in estimating the power requirements of a flexible heater in a specific application, All Flex conducted several analytical tests and approaches to compare FEA estimations to real-world experimental values. Ultimately the analysis provided by the FEA software was generally within +/- 5 degrees Fahrenheit of experimental values.

Flexible Heaters

Flexible heaters are thin, bendable devices that can be shaped to fit nearly any object to be heated. Most flexible heaters consist of an etched foil sandwiched between layers of dielectric materials which serve as a sleeve or protective covering for the resistive heating element.



Because they are flexible, flexible heaters can be designed in the exact shape and size needed to conform to a piece of equipment or mounting surface. Flexible heaters can be made to mount on a variety of surfaces including flat, irregular shapes, molded three-dimensional, spiral/ropes, and 3-dimensional enclosures.

Applications

Flexible heaters are used in many industries and have a myriad of applications.

- Battery Heating
- Blood Analyzers
- De-icing Equipment
- Heat Sealing
- Incubators
- Laboratory Equipment
- Spacecraft
- Equipment Sterilization

Types of Flexible Heaters

Polyimide Heaters

Polyimide heaters are thin, lightweight, rugged and flexible, providing highly-accurate and reliable performance.

- To provide fast and efficient thermal transfer
- Ideal for applications with space and weight limitations, or where the heater will be exposed to oil, chemicals, or a vacuum
- Capably of an operating temperature range of -200º C to 260º C
- Can bond to metalwork
- Conform reliably to curved and irregular surfaces
- Chemically resistant
- Resistant to cuts and tears
- High dielectric strength

Silicone Rubber Heaters

Silicone rubber heaters are best for large size, industrial and ruggedized applications. Silicone rubber heaters inherently introduce thermal insulation from the heating element outwards. To compensate accordingly, increasing the wattage output of the heater itself is one way to attain the overall thermal goal. Thermal insulation of the silicone rubber insulating layers also impacts the immediacy of thermal changes. The overall thickness of a silicone rubber heater can be as thin as 0.03" and is typically 0.06" thick excluding the backing adhesive.

- Composed of rugged, flexible elastomer material with excellent temperature properties
- Provides a high degree of reliability in a wide range of applications
- Acid, alkali, and water resistant
- Supports higher wattage levels
- Operating temperature range of -45º C to 230º C
- Typically the lowest cost type of flexible heater

The Principle of Joule Heating

Joule heating is the process by which the passage of electric current through a conductor releases heat. The purpose of a flexible heater is to heat an object or environment to a desired temperature and maintain that temperature. Flexible heaters work on the principle of Joule heating by delivering heat through electricity; the amount of heat released is proportional to the square of the current.

Ohm's Law

Ohm's law states that the current through a conductor between two points is directly proportional to the voltage across the two points. One watt (W) is equivalent to one joule per second. One watt (W) is also the rate at which work is done when one ampere (A) of current flows through an electrical potential difference of one volt (V).

$$\frac{V^2}{\Omega} = W = A^2 \cdot \Omega$$

A = amperes
V = Volts
Ω = ohms
W = Watts

Design Requirements

In order to design a flexible heater, the following information is required.

- Power required (Watts)
- Start temperature
- Operating control temperature
- Warm up time to reach operating temperature
- Material and configuration of the mounting surface
- Available space for measuring heater temperature (resistance temperature detector, thermistor, thermocouple, thermostat, thermal cutoff, thermal fuse)
- Controller for controlling the temperature of the flexible heater
- Identification if a heat sink be needed
- Determination of how the flexible heater will assembled/integrated
- Method of mounting the flexible heater

Power Requirements

The total amount of power required for an application is the larger of:

- Warm up power + heat lost during warm up
- Process heat + heat lost during steady state

Warm up power, which is measured in watts (W), is the power required to elevate the temperature of a substance in a given amount of time.

$$\frac{mC\ (T_f - T_i)}{t} = W$$

W = Watts
M = Mass of object (g)
C_p = Specific heat of the material (J/g˚C)
T_f = Final Temperature of the object (J/g˚C)
T_i = Initial Temperature of the object (J/g˚C)
t = Warm up time (seconds)

Process heat is the heat required to maintain a steady state when the heater is performing useful work.

Power Requirement Example:

- A plastic forming operation requires eight pounds of plastic to be processed per hour
  - The plastic has a specific heat of 0.46 BTU/lb_m°F
  - The plastic reaches a pliable state at 325°F
  - Two steel platens must be preheated to 325°F in 15 minutes
    - Each platen weighs 205 pounds
    - Measuring 24 inches long by 12 inches wide by 2.5 inches thick
    - The platens are not insulated
    - The platens have a specific heat of 0.12 BTU/lb_m°F
    - Warm up is accomplished with the platens closed
  - Heat loss during warm up and during operation is 140 watts per square foot
  - Ambient room temperature is 70°F
  - Total exposed surface area is 7 square feet $A = \pi r^2$
  - 1 kWh = 3412 BTU

- Calculate warm up power

$$4.42\ kW = \frac{205\ pounds \cdot 2\ platens \cdot 0.12\ BTU/lb_m \text{°F} \cdot (325\text{°F} - 70\text{°F})}{3412\ \ BTU/kWh\ \cdot \left(\frac{15}{60}\right) minutes/hr}$$

- Calculate heat loss during warm up

$$.98\ kW = \frac{7\ sq\ ft \cdot (140\ W/ft^2)}{1000W/kW}$$

- Calculate process heat required

$$0.275\ kW = \frac{8\ lbs\ of\ plastic\ \cdot\ 0.46\ BTU/lb_m\text{°F}\ \cdot\ (325\text{°F} - 70\text{°F})}{3412\ BTU/kWh\ \cdot 1\ hr}$$

- Calculate heat loss during operation

$$.98\ kW = \frac{7\ sq\ ft \cdot (140\ W/ft^2)}{1000W/kW}$$

- Calculate power required

$$15.40\ kW = 14.42\ kW + 0.98\ kW\ >\ .275\ kW +\ .98\ kW$$

Always add a safety factor when calculating power requirements. The less accurate the modeling of the thermal environment, the greater the safety factor should be. It is common to add a safety factor of 20-25%. Using the example above, a factor of safety of 25% is added.

- Add a safety factor to determine the new required power

$$19.25\ kW = 15.4\ kW \cdot 1.25$$

Watt Density/Thermal Uniformity

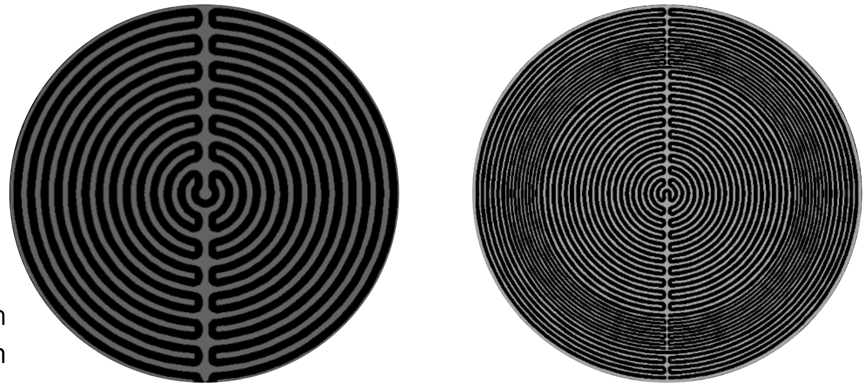


Figure 1: Uniform Heater Trace Layout (Left), Profiled Heater Trace Layout (Right)

Watt density determines how quickly the heater can transfer heat to a heated surface. Watt density is the amount of electrical power applied divided by the effective area of the flexible heater. Watt density is typically expressed in W/cm^2 or W/in^2. The maximum permitted applied power for each type of flexible heater depends on the insulation material, the heat sink control temperature, and the mounting method. If the watt density exceeds the maximum rating, the heater is in danger of overheating and premature failure. High watt density heaters are required for higher operating temperatures.

Temperature gradients exist in every thermal system and are necessary for heat flow. Temperature decreases as the distance from the heat source increases. To compensate for losses, additional wattage is often added to the system. Large temperature differences cause problems with control and unnecessarily high heater temperatures.

Thermal losses are apparent in nearly all flexible heater applications. Thermal losses in flexible heaters stem from a combination of factors that include edge losses (convection), heat sinks (conduction), and the heater watt density profile. Most commonly, thermal uniformity is desired in a flexible heater application. To accommodate thermal uniformity, the design of the flexible heater needs to counteract the thermal losses mentioned above (convection, conduction). Profiling the flexible heater element design to have multiple independent zones of varying watt density is a design technique commonly employed to ensure thermal uniformity throughout the heated workpiece. It is important to note that the power requirements are most often higher with a profiled flexible heater vs. a uniform flexible heater.

Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a technique often used during the engineering design process of a product. FEA is a simulated analysis of a specific component under simulated real world conditions. FEA gives flexible heater manufacturers the ability to efficiently evaluate a heaters performance in a specific application before a physical prototype is built. Implementing FEA in the design process of a flexible heater cuts down on prototype cycles and developmental costs. Multiple tests can be simulated quickly with design changes implemented almost instantaneously.

Modeling/Material Selection

The groundwork of any FEA simulation requires modeling of the component or assembly in question. In a flexible heater application, this would most commonly include modeling of the heater and any other components that directly interface with the heater (heatsinks for instance). For the specific example of this analysis, a simulation was completed for the same profiled and uniform flexible heaters from figure 1 on the previous page with both mounted on identical 6" diameter and 0.5" thick borosilicate glass discs. In addition to modeling the components in question, it is necessary to provide the FEA simulation software with material characteristics for all components being simulated. For heat transfer simulations, it is critical that the software is using the correct density and thermal conductivity value for each material.

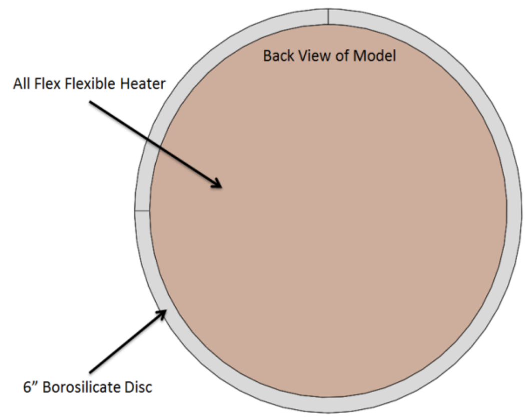


Figure 2: Model of Flexible Heater and Borosilicate Glass Disc

Testing Parameters

In an effort to effectively compare the FEA simulation to real-world values, the following testing parameters were utilized in both the real-world experiment as well as the FEA simulation.

Ambient Environmental Temperature	68 *F
Voltage Supplied to Heater	5 volts
Emissivity Value for Thermal Imaging Camera	0.94
Warm-Up Duration	10 minutes (600 seconds)

Table 1: Testing Parameters

Size	6 in. Diameter
Area	28.27 sq. in.
Voltage	5 volts
Wattage	3.12 watts
Current	0.633 amps
Resistance	7.89 ohms

Table 2: Uniform Heater Specifications

Size	6 in. diameter
Area	28.27 sq. in.
Voltage	5 volts
Outer Zone Wattage	1.60 watts
Outer Zone Current	0.32 amps
Outer Zone Resistance	15.66 ohms
Middle Zone Wattage	0.871 watts
Middle Zone Current	.174 amps
Middle Zone Resistance	28.71 ohms
Inner Zone Wattage	1.41 watts
Inner Zone Current	0.282 amps
Inner Zone Resistance	17.76 ohms

Table 3: Profiled Heater Specifications

Test Setup

Both the uniform flexible heater and the profiled flexible heater were mounted to the backside of each 6" borosilicate glass disc. The glass discs were mounted to four ceramic stands with minimal contact to mitigate heat transfer from the glass discs to the stands holding the disc. The front face of the glass discs were coated with a matte black paint to ensure a clear image with the thermal imaging camera. The heaters were simultaneously supplied with 5 volts and warmed-up for a total time of ten minutes (600 seconds). At ten minutes, thermal images of the front face were taken of both the uniform and profile heater – the thermal images are a representation of the heat transferred through the glass disc from the heater to the front face of the glass disc.

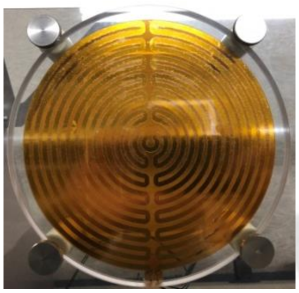


Figure 3: Heater Mounted with Standoffs to Back Face of Disc

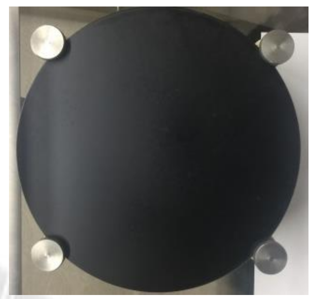


Figure 4: Front Face of Disc Coated with Matte Black

Forward Looking InfraRED (FLIR) Thermal Imaging/Emissivity

FLIR thermal imaging devices convert infrared wavelength energy into a visual display that operates in the visual light spectrum. Infrared wavelength energy is typically radiated infrared energy emitted by a heat source. Emissivity is one of the leading causes of confusion when using any FLIR thermal imaging camera or software. Emissivity represents the efficiency that a specific material has at radiating thermal energy. Emissivity values on thermal imaging devices can be tweaked to better match the reflective characteristics of the material – for shiny or low-emissivity materials; it is common practice to cover the surface with electrical tape or coat the surface with a matte black paint. Electrical tape and matte black paint raise the emissivity correction to 0.94. For reference, human skin has an emissivity value of 0.98 while clean aluminum has a value of 0.10. For this analysis, the glass was coated with a matte black paint; the uncoated glass that the heaters mounted to was not a high-emissivity target for the thermal imaging camera.

Results: FEA vs. Thermal Imaging

An FEA simulation was conducted for both the uniform flexible heater as well as the profiled flexible heater. The results of the simulations are documented below in Figures 5 and 7. Similarly, the thermal imaging camera was used to capture a thermal image of the profiled flexible heater mounted to the borosilicate glass disc. For a relevant comparison, the thermal image was captured after a 10 min warm-up period to match the 10 min timed simulation.

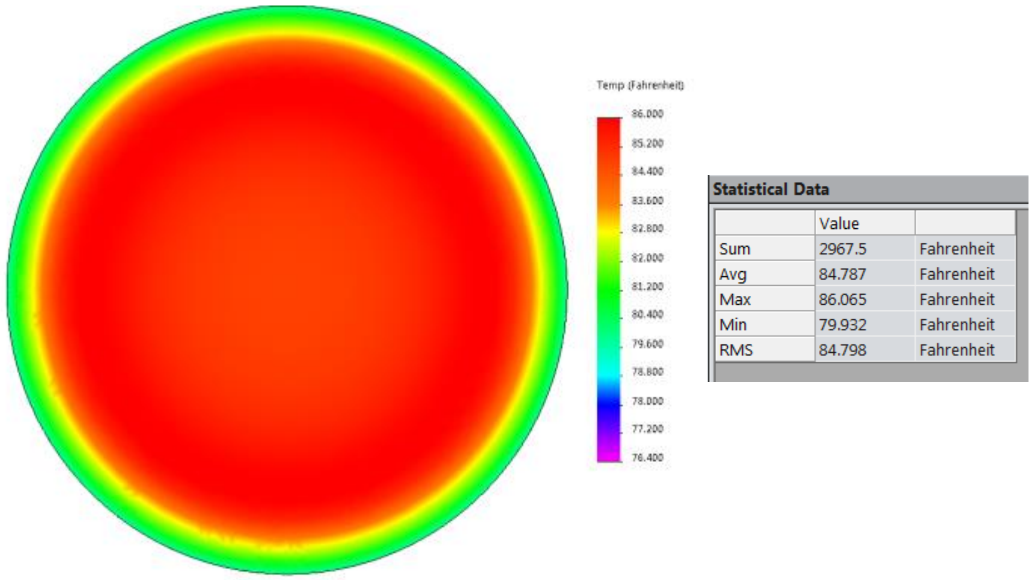


Figure 5: Profiled heater simulation results after 10 minutes and 5 volts input voltage

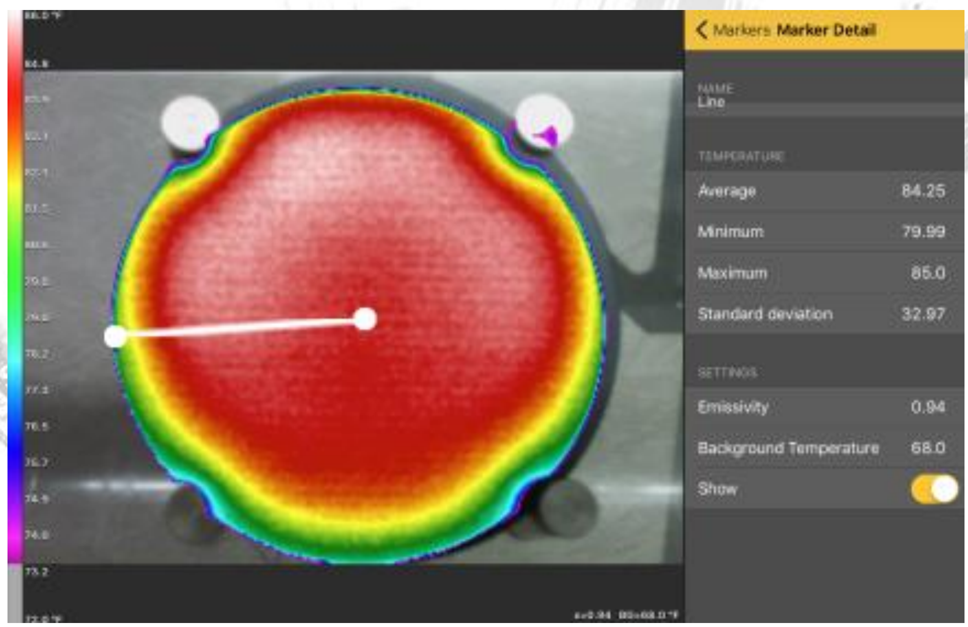


Figure 6: Thermal image of profiled heater after 10 minutes and 5 volts input voltage

Profiled Heater			
	FEA	Thermal Image	Delta
Min Temp [˚F]	79.93	79.99	0.06
Max Temp [˚F]	86.07	85.00	1.07
Ave. Temp [˚F]	84.79	84.25	0.54

Table 4: Profiled Heater Results: FEA vs. Thermal Image

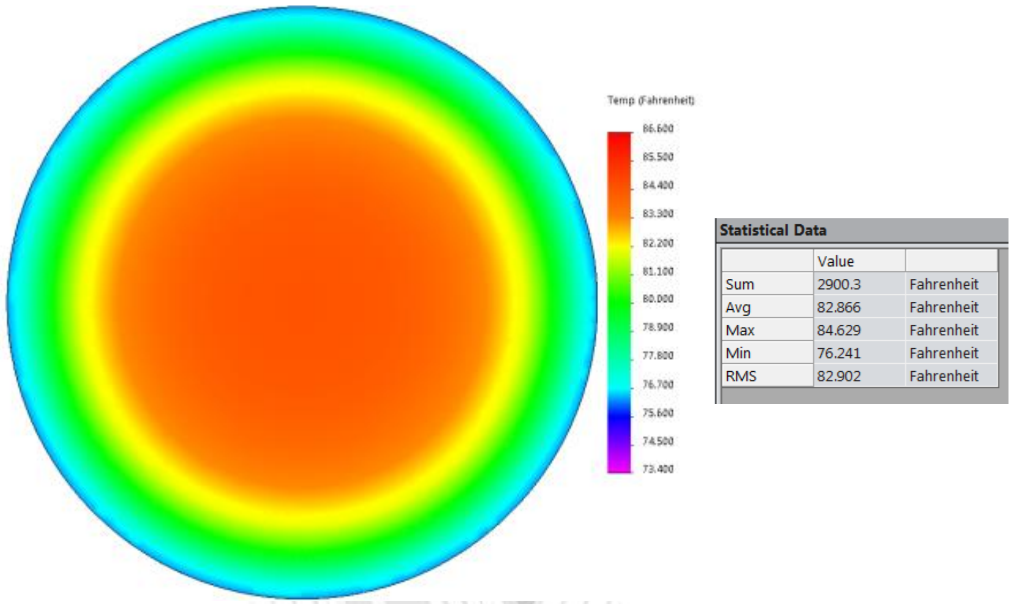


Figure 7: Uniform Heater Simulation Results after 10 minutes and 5 volts Input Voltage

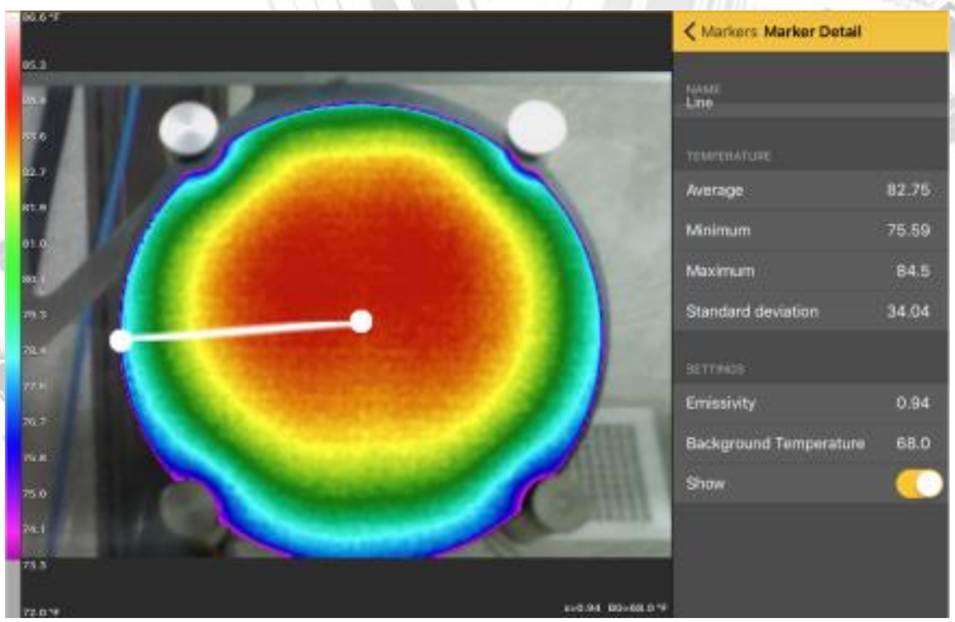


Figure 8: Thermal Image of Uniform Heater after 10 minutes and 5 volts Input Voltage

Uniform Heater			
	FEA	Thermal Image	Delta
Min Temp [˚F]	76.24	75.59	0.65
Max Temp [˚F]	84.63	84.50	0.13
Ave. Temp [˚F]	82.87	82.75	0.12

Table 5: Uniform Heater Results: FEA vs. Thermal Image

Conclusion

The demonstrated comparison of FEA heater simulations to real-world heaters shown above provides valuable evidence in the argument to implement FEA simulations into the heater design process for flexible heaters. Assuming the FEA simulation is provided with the proper input variables to mimic the real-world application, there appears to be no obvious reason that the FEA simulation can't accurately hypothesize the thermal uniformity and power requirements with an uncertainty of less than 5%. Utilizing FEA simulations throughout the design process of a flexible heater can greatly decrease the number of prototyping cycles required to build a heater that meets the needs of a specific application while mitigating developmental costs and manufacturing time.