Using Finite Element Analysis to Design a New Guarded Hot Plate Apparatus for Measuring the Thermal Conductivity of Insulating Materials

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ABSTRACT

The National Institute of Standards and Technology (NIST) is developing a guarded hot plate apparatus to measure the thermal conductivity of thermal insulation over a temperature range from 90 K to 900 K. The apparatus will create nominal one-dimensional heat flow through a specimen by placing it between two isothermal plates at different temperatures. The thermal conductivity is then calculated from Fourier's Law using the temperatures of the plates, the heat input to the hotter plate, and the thickness of the specimen. In order for this apparatus to provide accurate results, however, each plate must be maintained at a nearly uniform temperature, and the edge of the specimen must be guarded to prevent radial heat flows. Commercially available finite element analysis software helped detect flaws in the design. Temperature profiles throughout the instrument, unwanted heat gains or losses, and the ability of fluid channels to provide adequate cooling were determined using finite element analysis. The resulting temperature variations are estimated to be approximately 38 mK on the meter plate and less than 5 mK on the cold plate for the worst case scenarios of plate operation. Errors in thermal conductivity from extraneous heat flows out the edge of the plate are estimated to be approximately 0.5 % for thick specimens at approximately 900 K but will be significantly less for thinner specimens and at lower temperatures.

Introduction

The National Institute of Standards and Technology (NIST) is designing a guarded hot plate apparatus to measure the thermal conductivity of insulating materials over a temperature range from 90 K to 900 K. The new instrument will greatly expand the ability to measure insulation that is designed for cryogenic applications or for industrial applications at high temperatures. Current test data suggest that the lack of appropriate standards has caused significant variability in measurements, and the design of this plate will address many of the concerns in measuring specimens over a wide temperature range.

A guarded hot plate is an absolute instrument for determining the thermal conductivity of homogeneous flat specimens. This method is recognized by the American Society of Testing and Materials (ASTM) [1] and by the International Organization for Standardization (ISO) [2] as the standard method for obtaining the thermal resistance of building materials. Zarr has recently documented the history of the guarded hot plate apparatus at NIST [3], and similar instruments throughout the world have been described by Pratt [4] and Klarsfield [5].

This paper describes how ANSYS[1] was used to improve the design of the proposed guarded hot plate. Several simulations will be discussed to demonstrate the role of finite element analysis in predicting the performance of the apparatus.

General Overview of Design

Determination of the thermal conductivity is based on Fourier's Law in one dimension:

$$Q = \lambda A \frac{\Delta T}{\Delta z}, \qquad (1)$$

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

where λ is the thermal conductivity, Q is the heat flow through the specimen, Δz is the specimen thickness, A is the area through which heat flows, and ΔT is the temperature difference across the specimen. λ can be determined by measuring the temperatures, heat flow through the specimen, and specimen thickness and applying equation 1.

While the principle behind the measurement may be simple, construction of such an apparatus requires careful attention to detail to ensure that one dimensional heat flow is achieved in the specimen and that temperature measurements closely approximate the true ΔT across the specimen. Figure 1 displays a schematic of the cross-section of a guarded hot plate. The instrument described here consists of a disc-shaped specimen sandwiched between two disc-shaped metal plates. [The apparatus actually tests two specimens at a time, with a mirror image across the plane of symmetry shown in Figure 1; for clarity in this discussion, however, only half of the apparatus will be considered] Insulation and an edge guard surround the specimen to minimize the undesired radial heat transfer to the environment. At steady state, the top plate, termed the hot plate, provides the heat that travels through the specimen. As can be seen in Figure 1, the hot plate consists of an inside disc known as the meter plate, and the annulus surrounding the meter plate is the guard ring. Between these two plates is the guard gap, which is usually filled with insulation. Each of the plates contains electric heaters, and the power into the meter plate is carefully measured to obtain the heat flux through the specimen in the meter section. The proposed design calls for a standard platinum resistance thermometer (SPRT) in the meter plate and the cold plates to obtain the ΔT across the specimen. The purpose of the guard ring is to shield the meter plate and meter area of the specimen from heat gain or loss to the ambient, thus promoting one-dimensional heat flow through the meter area (A). The guard ring is maintained at the same temperature as the meter plate, and the gap between the two plates further prevents any heat flow to or from the meter plate. These steps help to assure that all heat input to the meter plate flows through the specimen in a direction perpendicular to the plates. On the opposite side of each specimen is a cold plate that provides the temperature difference that drives heat through the specimen.

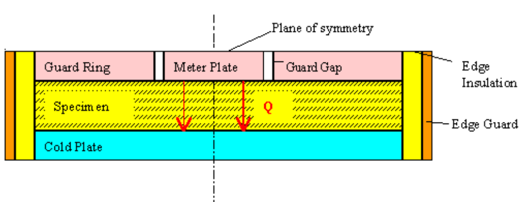

Figure 1. Simplified schematic of Guarded Hot Plate cross section.

A goal in the design of the apparatus is to minimize the uncertainty in measurement of the thermal conductivity of the specimen. In examining equation (1), one can see that the key areas of uncertainty related to the thermal design lie in the measurements of ΔT and Q. The use of ANSYS in evaluating the effect of the design on these uncertainties will be described in the following sections.

While analysis of the complete apparatus would shed a great deal of light on the design, computing and time constraints prevented the designers from accomplishing this task. Instead, individual components of the instrument will be examined and the role of ANSYS in evaluating the design will be discussed.

The designers used ANSYS Mechanical running on a 400 MHz Pentium II® processor with Windows 98® and 256 Mb of RAM. The discussion that follows will describe how a small component of ANSYS effectively assisted in the design of the instrument.

Isothermal temperature distribution on plates

Meter plate

To minimize the uncertainty in temperature measurements, the plates should be held nearly isothermal. Hahn et al. [6] describe a line heat source concept that generates a nearly isothermal profile within a disc-shaped plate. This technique was adopted in ASTM Standard C1043 [7] and served as the basis for the initial design of the meter plate heater layout. This test method suggests that the surface temperature of the plate can be made fairly uniform by placing heater wire in a concentric ring pattern within the plate. Ring heaters can be analyzed mathematically through separation of variables to provide an excellent estimate of the temperature distribution on the surface. For the proposed meter plate, five rings of heater wire were embedded at the mid-plane of the plate. The construction of five separate rings, however, is difficult considering the proposed use of the SPRT for temperature measurement in the plate and is further complicated by the need for wire leads as compared to the ideal situation addressed by ASTM. Modifications to the ring heaters are therefore necessary to get power into the plate and to accommodate the SPRT well. With these modifications, analytical methods of computing the temperature distribution in the plate become cumbersome and, thus, finite element (FE) analysis was needed to evaluate the design.

Initial simulations were run to compare the FE results to analytical results and investigate the ability of ANSYS to provide millikelvin temperature resolution. A two-dimensional, axisymmetric model was generated to determine the temperature distribution resulting from five ideal rings. A schematic of the model is shown in Figure 2. Uniform heat generation was applied to the five heater areas, and a convection boundary condition was applied to the top surface. All other surfaces were maintained as adiabatic. Figure 3 compares the non-dimensional temperature profile predicted by ANSYS at various depths within the plate to the analytical predictions as a function of the distance from the centerline. *V* is the average surface temperature on the surface of the plate, and *v(r,z)* is the local temperature within the plate. The negligible difference between the two sets of predictions provided confidence that ANSYS would fulfill accuracy requirements.

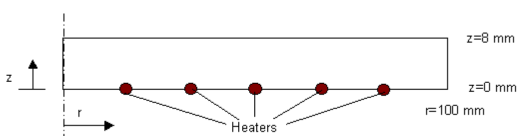

Figure 2. Schematic of axisymmetric, two-dimensional model of meter plate cross-section.

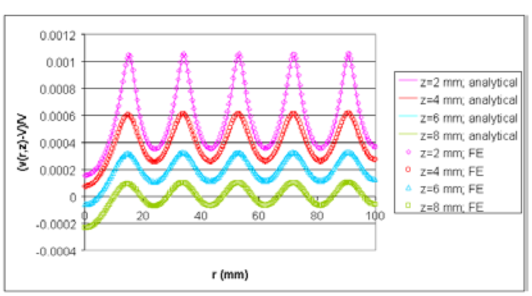

Figure 3. Comparison of analytical predictions to finite element predictions of the non-dimensional temperature in the meter plate.

Figure 4 shows the first design of the heater layout in the meter plate. The well passing vertically through the middle of the plate shows the location of the SPRT, and the sensitive region of this instrument is shown in pink. To simulate the meter plate, a three-dimensional model was generated. The heater area was created in ANSYS and extruded to form a heater of rectangular cross-section. This volume was partitioned from a disc that was created to simulate the meter plate. Properties of the model are shown in Table 1.

Table 1. Meter plate simulation parameters.

Plate material	Nickel
Plate diameter	200 mm
Plate thickness	8 mm
Heater diameter	3.2 mm
Specimen R-value	0.125 $m^2 \cdot K/W$

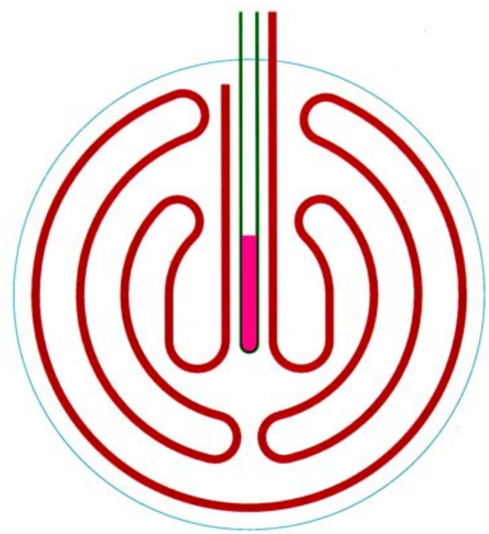

Figure 4. Original meter plate heater design.

The meter plate is isolated from the surrounding guard ring by a guard gap. Under ideal operation, the temperature difference across the guard gap will be zero, so adiabatic conditions were applied along the rim of the meter plate. Because of the plane of symmetry that exists along the axis of the heater as mentioned in Figure 1, adiabatic conditions also apply to the bottom surface of the plate. On the top surface facing the specimen, convection was used to simulate heat flow through the specimen. Analyses were performed to confirm that modeling the heat transfer through the specimen with a convection boundary condition on the surface is equivalent to modeling the full two-body problem. The heat transfer coefficient is the inverse of the thermal resistance of the specimen, and the temperature to which convection occurs is the cold plate temperature. For meshing, SOLID87 elements (10 node tetrahedron) were applied with Smart Sizing of 5 and a global element size equal to 1.5 times the heater diameter. Grid sensitivity studies were performed by decreasing the Smart Sizing values until temperature predictions changed by less than 1 mK. Solution on the final grid was typically performed in approximately five minutes.

Figure 5 displays the temperature contours on the surface of the meter plate facing the specimen. The range of temperatures is quite small for this simulation, but a concern arose because of the cold spot in the lower half of the surface. This cold spot affects the sensitive region of the SPRT. Figure 6 shows the temperature along a path coincident with the axis of the SPRT well from the bottom of the plate to the top. One can see that the cold spot

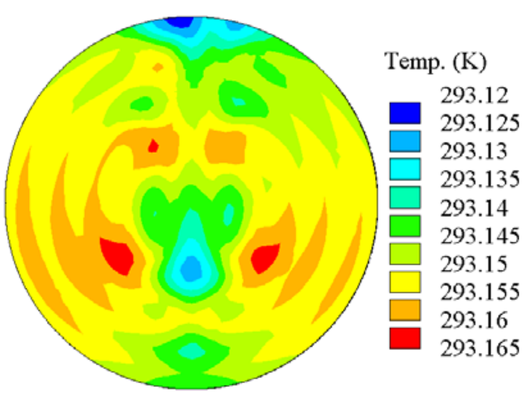

Figure 5. Temperature contours on surface of meter plate for original heater layout.

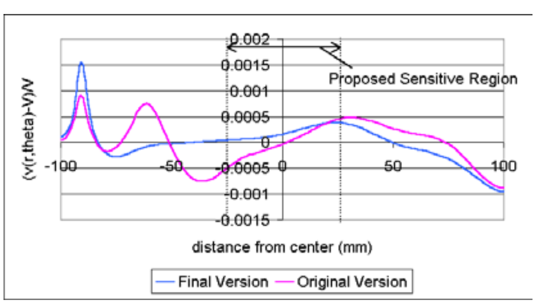

Figure 6. Temperature along path coincident with axis of SPRT for both heater layouts.

encroaches upon the sensitive region of the SPRT. While the overall variation in temperature was small, this perturbation near the SPRT was a concern. The design was modified to help alleviate this problem.

The final heater layout is given in Figure 7, and the resulting temperature profile is displayed in Figure 8. The temperature fluctuations along the surface of the plate are similar to the previous design, but the cold spot near the SPRT has been removed. The use of ANSYS provided insight to modify the heater layout so that measured temperatures will give a better indication of the average surface temperature.

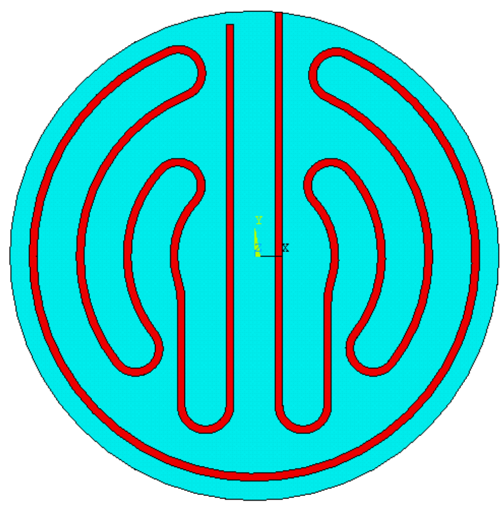

Figure 7. Final heater layout in meter plate.

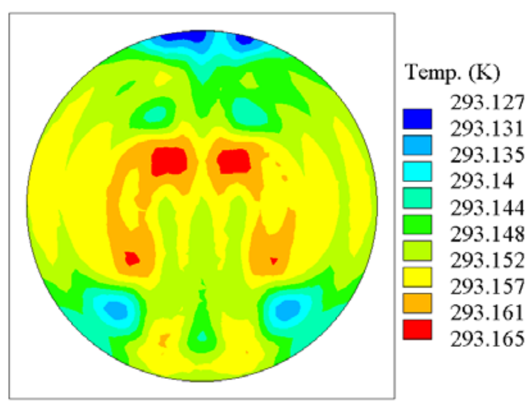

Figure 8. Temperature contours on surface of meter plate for final heater layout.

Cold Plate

As the thermal sink nearest to the environment, the cold plate provides the bulk of the heating or cooling to change the average specimen temperature. The cold plate needs coolant tubes to reach approximately 90K and heating elements to achieve 900 K. To achieve a nearly uniform temperature profile along the surface, a composite design was developed. The cross-section of the design is shown in Figure 9, consisting of (top to bottom) the thermometry plate, the heater plate, and the coolant plate. Figure 9 shows a more detailed schematic of the cold plate shown in the guarded hot plate schematic of Figure 1. Thermal insulation will be placed between the three plates to diminish temperature fluctuations and to prevent the heating elements from battling with the coolant tubes when both are operating. Behind the plate is auxiliary insulation and a water jacket to maintain the outer shell at room temperature. Analysis of this complex array would be difficult with typical analytical techniques.

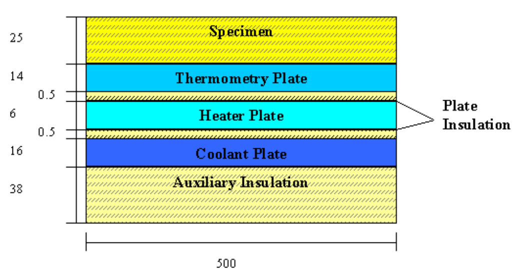

Figure 9. Schematic of composite cold plate (not to scale, dimensions in mm).

In addition to the composite geometry, another difficulty in the analysis of the cold plate is the presence of the fluid flowing through the coolant tubes. Since this fluid will gain heat flowing through the tubes, maintaining an isothermal thermometry plate is a challenge. ANSYS was used to simulate various layouts of the coolant tubes to determine if the resulting surface temperature profile was sufficient. The following sections will discuss the analysis of fluid channels using ANSYS Mechanical.

Instead of using a full computational fluid dynamics (CFD) code to simulate the channels, efforts were focused on using the Mechanical module, which was more familiar to analysts. FLUID116 elements were thus used to model the flow. These pipe elements are line elements that have either two or four nodes. The four-node option allows the user to model the fluid with two nodes and the wall of the tube with the other two. The element handles the convective coupling between the fluid and solid. The two wall nodes are also used in meshing the solid, creating a connection between the fluid in the coolant tubes and the solid.

To simulate the coolant tubes, lines were created along the path of the fluid. Initial attempts to simply mesh these lines with the FLUID116 elements using the Mesh Tool were unsuccessful because elements were not necessarily oriented in the correct manner. Proper orientation is vital for these elements because flow directions are dependent on the manner in which the elements are defined. It was found that the use of the Mesh Tool resulted in elements with opposing flow directions, thereby ruining the simulations. To alleviate this problem, a file was created to manually generate the elements. The steps that were taken to simulate the fluid flowing through the solid are as follows:

1) Create keypoints along the path of the fluid channel.
2) Connect keypoints to form a line.
3) Create a circle to represent the outside of plate.
4) Create two areas from the "fluid channel" line and circle.
5) Extrude areas to form the solid plate
6) Create nodes at the keypoints making up the fluid channel.
7) Copy those nodes at an arbitrary distance from the original nodes. The new nodes will be the "fluid" nodes, while the original nodes will be the "solid" nodes.
8) Define FLUID116 elements using the nodes generated in steps 6 & 7.
9) Mesh the solid using conventional methods (SOLID87 elements).
10) Merge coincident nodes to glue the FLUID116 elements to the solid elements.

The FLUID116 elements require real constants to be assigned for the hydraulic diameter and cross-sectional area of the pipe. While the user has the option of specifying a convection correlation, a constant heat transfer coefficient was applied in this simulation as part of the fluid properties. Viscous heat generation was also included as a material property.

The resulting layout of the elements simulating the coolant tubes is shown in Figure 10. Coolant enters on the left side, spirals into the center and then back out until its exit on the right side. For temperatures slightly below ambient, the design called for ethanol as the coolant, while liquid nitrogen or gaseous nitrogen would be used as temperatures approach 90 K.

To determine the heat transfer coefficient and the viscous heating term, separate calculations were performed. The optimal flow rate was estimated as the flow rate at which the rise in fluid temperature from inlet to outlet in a channel with isothermal walls was minimized. At low flow rates, heat from the plate increased the temperature of the fluid severely. At extremely high flow rates, viscous heat generation causes the temperature of the fluid to rise. The optimum was found using classical heat transfer calculations, and the accompanying heat transfer coefficient and heat generation rate were used in the finite element model.

The flow rate was input as a heat flux boundary condition on the elements. The inlet temperature was fixed by applying a temperature boundary condition on the fluid node at the inlet. Heat flow through both the auxiliary insulation and the specimen was modeled as convection. The edges of the plate were assumed to be adiabatic. Table 2 lists the parameters of the cold plate simulations. Each simulation required approximately 45 minutes of computation time.

Table 2. Parameters for cold plate simulation.

Thermometry plate, heater plate, and coolant plate material	Nickel
Plate insulation	Alumina fiber
Auxiliary insulation	Alumina board
Overall plate thickness	41.5 mm
Specimen R-value	$0.125\ m^2 \cdot K/W$
Auxiliary R-value	$0.63\ m^2 \cdot K/W$
Hydraulic Diameter	9.81 mm
Channel Area	$1.3 \times 10^{-4}\ m^2$
Ethanol	
Mass flow rate	0.10 kg/s
Inlet Temperature	250 K
Hot Plate Temperature	270 K
Nitrogen Gas	
Mass flow rate	0.00776 kg/s
Inlet Temperature	80 K
Hot Plate Temperature	100 K

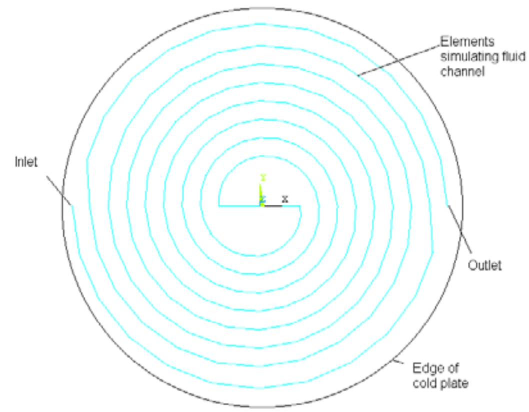

Figure 10. Fluid elements in cold plate

The major result output was the surface temperature contours facing the specimen. As can be seen in Figure 11, the predicted temperature variation on the surface of the cold plate is extremely small for ethanol coolant. The liquid maintains its temperature throughout its passage through the coolant tubes.

For cryogenic temperatures, the initial design called for nitrogen gas as the coolant. Figure 12, however, shows that the low-density gas resulted in significant temperature variations on the surface of the cold plate. Plots of the nodal temperatures of the fluid indicated that the fluid temperature rises quickly to the plate temperature, and the remaining passage through the tube (approximately ¾ of total length) provided essentially no cooling.

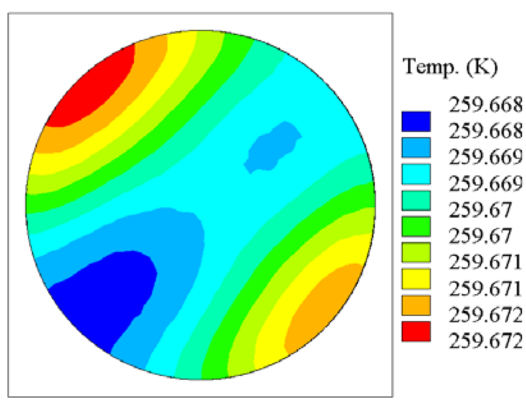

Figure 11. Temperature contours on surface of cold plate; ethanol as coolant.

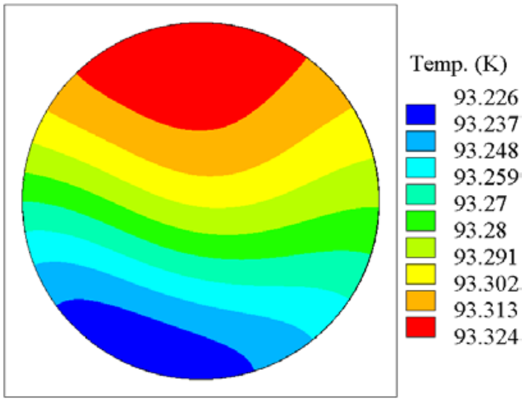

Figure 12. Temperature contours on surface of cold plate; nitrogen gas as coolant.

From these results, it was decided that liquid nitrogen was needed as the coolant medium at low temperatures. To obtain temperatures above that of liquid nitrogen, power is added from the heater plate (Figure 9). Temperature variations with the liquid nitrogen are similar to those found with ethanol. With these liquids, the plate can be operated over the desired range. The use of ANSYS to model the effect of cooling channels in the plate was extremely helpful in determining the temperature profiles resulting from different fluids and from different channel configurations. Furthermore, these simulations did not require a full-fledged CFD analysis, yet the results provided insight on the physics of the problem.

Ensuring 1-D heat flow

Another major focus of the finite element analysis was to ensure that the design effectively decreased the amount of heat flowing in or out of the meter region in the radial direction. For this purpose, the design calls for a guard around the periphery of the specimen that is controlled near the temperature of the specimen. Figure 13 shows a cross-section of one-quarter of the plate. Because of symmetry, the entire plate can be simulated with this two-dimensional axisymmetric model. This model shows a bit more detail than the simple schematic of Figure 1, while the cold plate construction is simplified slightly from that shown in Figure 9. The cold plate in Figure 13 consists of two pieces with a thin layer of insulation between them. Heat is generated uniformly in the lower plate. With this arrangement, temperature fluctuations on the surface of the cold plate are greatly diminished.

Auxiliary insulation on the outside of the plate decreases heat transfer to the environment, and the outside border is cooled with a water jacket for safety and for better control of environmental conditions. The specimen in Figure 13 is 100 mm thick (maximum design thickness); the unusual shape of the lower auxiliary insulation is meant to accommodate thinner specimens. The edge guard is modeled as a thin strip of metal with a specified temperature. The purpose of these studies was to determine the effectiveness of the edge guard in preventing radial heat flow from the meter section.

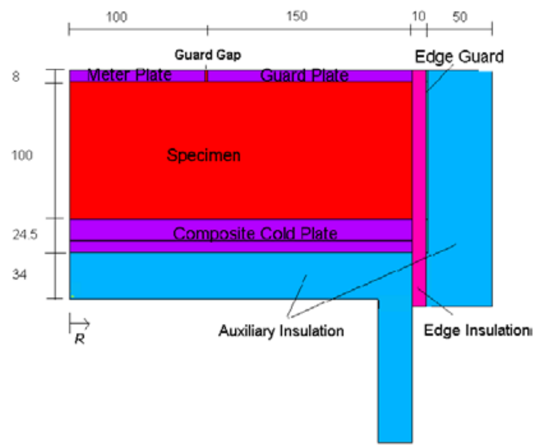

Figure 13. One quarter cross section of Guarded Hot plate for analyzing heat flow within the specimen; dimensions in mm.

The model shown in Figure 13 was meshed with PLANE77 elements (8-node quads). Most areas were meshed with mapped meshing, but the specimen area required a free mesh owing to the awkward geometry near the guard gap. Mesh refinement in the specimen was made near the guard gap to resolve the temperature effects in that region. The thermal conductivities of the auxiliary insulation, edge insulation, and specimen are temperature dependent. For the final design, the edge guard is controlled at a uniform temperature matching the mean temperature of the specimen. Heat generation was applied to each of the meter plate, guard ring, and cold plate. Though the actual plate is heated with carefully spaced wires, the model was simplified here by applying uniform generation to the entire area of the plates.

Determination of the proper heat generation rates required an iterative process. Three independent quantities needed to be controlled. To determine the proper values, three parameters were selected as output to gauge the effectiveness of the power selections. First, the temperature difference across the specimen needed to reach the desired value. Second, the desired mean temperature of the specimen is known and should be matched to the temperature specified on the edge guard. The last condition to be met is that the temperature difference across the guard gap should be zero to prevent unwanted radial heat flow to or from the meter plate. Hand calculations determined the first estimate for powers, and several perturbations of those values were then run. To tune the optimal value for the powers, linear regressions were performed for each of the output variables as a function of the three input powers. These regressions were used to predict the optimal powers in each plate to achieve the desired output. After several iterations, the correct powers for the three plate areas were obtained. Table 3 describes the final parameters for this simulation. Solution typically required approximately 10 minutes; though the model was two-dimensional, the temperature dependent properties of the insulation required iterative solutions.

Figure 14 shows the resulting temperature profile for a 100 mm specimen at an average temperature of 910 K and a temperature difference across the specimen of 40 K. The isotherms in the meter region are nearly parallel, indicating that the heat flow is largely one-dimensional in this region. Without sufficient guarding, the curves in the isotherms at the edge of the specimen would creep into the meter region, indicating that some of the heat from the meter plate would flow out the side of the specimen instead of directly to the cold plate. Estimates of the error in measurement due to this

Table 3. Edge Guard Simulation Parameters

Plate material	Nickel
Edge guard material	Nickel alloy
Specimen material	Fiberglass batt
Aux. insulation material	Alumina board
Edge insulation material	Ceramic Fiber
Edge guard temperature	910 K
Ambient temperature	298 K
Generation rates	
Meter plate	4919 W/m^3
Guard Ring	12412 W/m^3
Cold Plate	2.00×10^5 W/m^3

edge guard are approximately 0.5 %. For thinner specimens and at temperatures closer to room temperature, these errors would be greatly diminished, so this error is a worst-case scenario for edge guarding. While the numbers cannot be taken literally, the ANSYS analyses provided confidence that the edge guard would sufficiently protect the specimen from unwanted heat gains and losses.

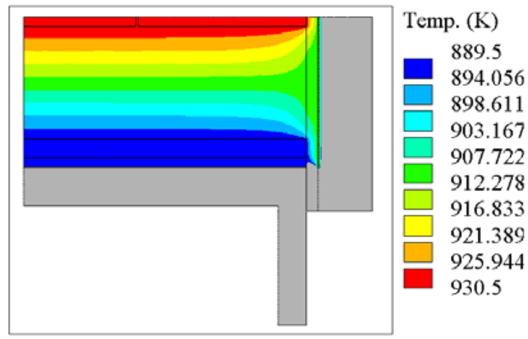

Figure 14. Temperature contours in 100 mm specimen for a temperature difference of 40 K at a mean temperature of 910 K.

Conclusion

ANSYS was used to supplement analytical methods in the design of a new Guarded Hot Plate apparatus to measure the thermal conductivity of thermal insulation. The finite element simulations enabled designers to determine whether heater and coolant tube layouts would generate a uniform temperature profile on surfaces facing the specimen. Analyses also assured designers that one-dimensional heat transfer would be present in the meter section of the specimen. The use of ANSYS has provided greater insight into the physics of the apparatus and will enable NIST to make measurements with greater accuracy.

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