THE UNIVERSITY OF MANITOBA

CONDUCTION HEAT TRANSFER IN A TUBULAR RESISTANCE HEATER WITH A HELICAL RESISTANCE COIL

by

J. R. Lion

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements for the Degree
of Master of Science

Department of Mechanical Engineering

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ABSTRACT

The design of electrical tubular resistance heaters has in the past been hampered by a lack of knowledge of resistance wire temperature as a function of geometry. This study provides a method of determining the conduction heat transfer between the helical resistance wire coil and the metal sheath material. From this the wire temperature may be calculated.

Shape factors for conduction from the wire to the sheath were found by using a finite element computer program which modeled each turn of the resistance wire helix as a torus of revolution. After computing shape factors for a wide range of geometries, the model was tested using an electrical analog technique.

Through the use of these predetermined shape factors, resistance wire temperature can be calculated for a particular geometry given only the sheath surface temperature, thermal conductivity of the insulating medium, and the watt density on the resistance wire.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A	area
b	odds
d	diameter
D	dimensionless diameter
E	electrical potential
G	shape factor
h	convective heat transfer co-efficient
i	electrical current
K	thermal conductivity
L	length
m	mean
p	helix pitch
P	dimensionless pitch
Q	heat flux
R	electrical or thermal resistance
t	wall thickness of sheath material
T	temperature

Greek Symbols

ρ	electrical resistivity
Δ	difference
θ	helix lead angle
π	3.14

ℓ	length
ω	uncertainty interval
ν	independent variable

Subscripts

a	ambient or helix inside
i	inner
o	outer
s	surface or sheath
std	standard
w	wire

CHAPTER I

INTRODUCTION

1.1 Background Information

Since not everyone is familiar with the construction of electrical tubular resistance heaters, a brief outline of the processes and materials involved is presented. It is hoped that the reader will gain a clearer understanding of the main part of this presentation after reading this background material. However, this information is not intended as a precise description of all the different manufacturing techniques used. Rather, it is only a brief description of the general characteristics of a tubular resistance heater.

1.1.1 Basic Heater Description

An electric tubular resistance heater is composed of three basic parts; the resistance wire helix, the electrical insulating medium, and a tubular metal sheath.

Resistance wire is most commonly made from 80-20 nickel-chromium alloy with traces of iron and silicon. However, other resistance wire alloys are widely used; for example, alloys of chromium, aluminum, and iron.

The resistance wire helix must be protected electrically by a non-conductor from the tubular metal sheath. This insulating material must have both high dielectric strength and good thermal conductance. Although other materials may be used for this purpose, granular magnesium oxide is most common.

The resistance wire helix and insulating material are enclosed in a thin walled metal tube of copper, stainless or mild steel, nickel alloys, aluminum, or other material, depending on the final application. The metal tubing provides protection against the environment and allows a means of increasing the density of the insulating material, the importance of which will be discussed below.

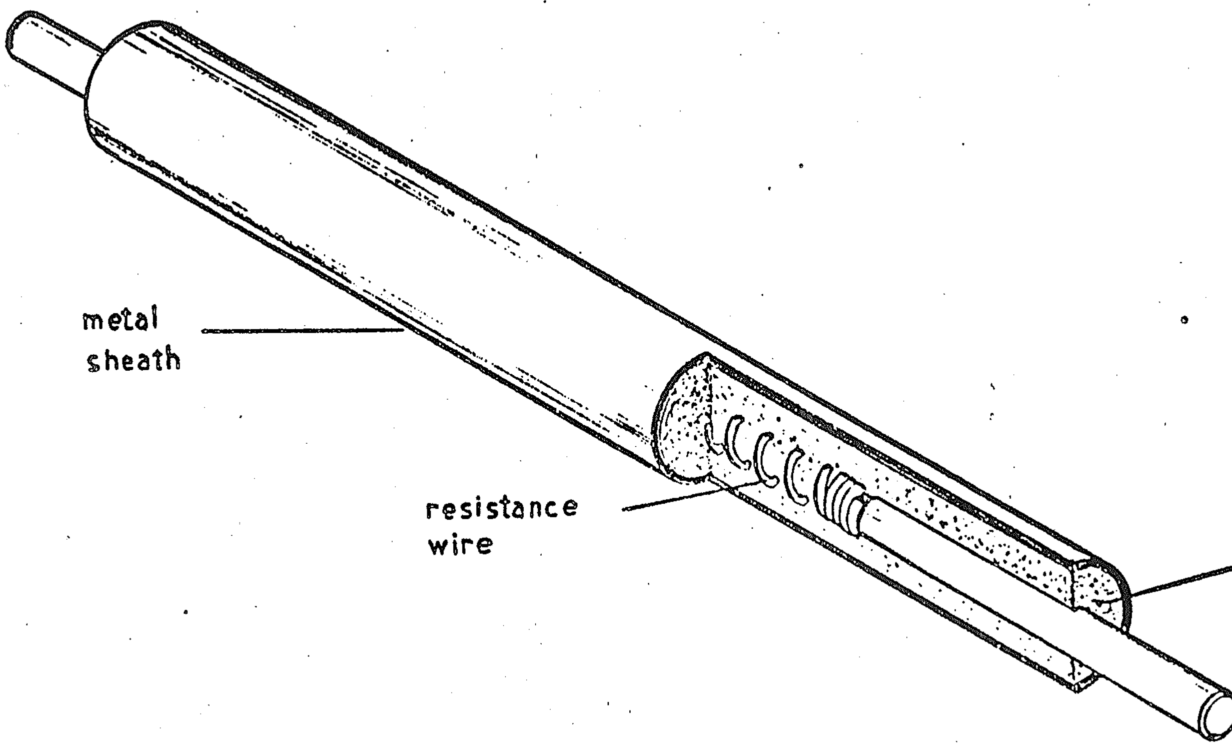
Figure (1.1) is a schematic of the components of an electrical tubular resistance heater.

1.1.2 Manufacturing Processes

The following is a brief description of the various stages in the manufacturing of an electrical tubular resistance heater.

The obvious first step in producing a heating element is its initial design. The main design criterion is the rate at which an element must produce heat to fit its final application. For a given voltage this is determined solely by the total electrical resistance of the resistance wire helix. As there are many ways of obtaining the required

FIGURE 1.1
SCHEMATIC OF AN ELECTRIC TUBULAR RESISTANCE HEATER



resistance, a specific geometry for heater construction must be chosen. The geometric variables of a heating element are; resistance wire diameter, arbor diameter, helix pitch, and heater element outside diameter. Then, before construction begins, other design decisions are made, such as; the length and type of terminal pins, overall heater length, and the type of sheath material.

The first construction process is that of winding the resistance wire into a helix of the required length. Winding may be done mechanically on a machine that draws the wire around a stationary cylinder into a continuous helix. The helix is then automatically cut to the desired length. Alternately, winding may be accomplished by turning a length of drill rod in a variable speed drill and manually feeding the the wire onto the rod. An ohmmeter may then be used to measure the desired electrical resistance therefore determining the helix length.

It should be noted that the helix now has a pitch equal to one wire diameter. That is, the helix is close wound with one turn touching another rather than stretched to a larger pitch as in the finished heater. The inside diameter is now the sum of the arbor diameter, the diameter of the cylinder on which it was wound, and the wire "springback". The springback is caused by the elasticity in the resistance wire and its effect is to cause the helix to unwind somewhat. Thus the inside diameter of helix is slightly larger than the arbor cylinder diameter. This phenomenon usually causes an increase in diameter of only a few thousandths of an inch.

The next step in the production process is to fasten terminal pins to both ends of the helix. This may be done in various ways. One way is to push a number of turns of the helix around the cylindrical terminal pin and make a spot resistance weld, thus fusing the helix to the terminal pin. Another method is crimping the helix to the pin. Again a few turns of the helix are pushed over the end of the terminal pin. This assembly is then held in a die while a stamping operation deforms the wire thus fastening the helix to the terminal pin. Yet another method is to use threaded terminal pins and simply thread the helix onto the pin.

In the next production step, the helix and terminal pin assembly is held concentrically in a length of the metal tubing chosen for sheath material. The helix is stretched to a predetermined length so that the terminal pins protrude slightly from both ends of the tubing. Next the insulating medium is vibrated into the metal sheath and falls around the terminal pins as well as around and between the turns of the resistance wire helix. The helix and terminal pin assembly is thus electrically insulated from the metal sheath material. There are various ways of producing the above configuration. Perhaps the most common is a batch process in which the helix and terminal pin assembly is held stationary on a machine. The length of metal tubing for sheath material is then mechanically moved down around the helix assembly and at the same time stretches the helix to its required length. The insulating medium, usually magnesium oxide, is then vibrated into the tubing. The vibration serves to increase the density of the magnesium oxide which results in a higher thermal conductance.

Thermal conductance increases exponentially with increasing density in most granular insulating materials used in heater elements. Since it is desirable to have as little thermal resistance as possible between the resistance wire helix and the tubular metal sheath, operations are performed to increase the density of the insulating medium. One way to achieve this is to draw the metal tube containing the insulating material through a set of rolls. For powdered magnesium oxide, a significant diameter reduction compresses the powder into a granular solid. At this point the tubular resistance heater is a straight cylinder with a work hardened metal sheath, the basic electrical tubular resistance heater.

1.2 Statement Of The Problem

The lack of knowledge of the maximum heat flux that may be prescribed for a particular geometry has hindered designers of tubular heating elements. That is, what resistance wire or sheath watt density may be prescribed and still allow the resistance wire to remain at a temperature low enough to ensure a long heater service life.

Many problems are encountered in measuring resistance wire temperature. For example, thermocouple probes inserted into heating elements give limited accuracy since the measurement is only local. Furthermore, heat is conducted away through the thermocouple faster than through the insulating medium. Also the geometry of the heater may be easily disturbed by inserting the probe. F. S. Epstein (ref. 1) describes a method of determining resistance wire temperature by using the helix as a resistance thermometer. Although his method allows accurate determination of wire temperature for a particular heater, it does not enable the determination of a reuseable shape factor since the thermal conductivity of the insulating material remains unknown. Therefore, the scope of this approach is limited to single geometries and a single insulating material having a standard density.

1.3 Scope Of The Thesis

The study presented here utilized a simplified model of the resistance wire helix and a finite element computer analysis of the heat transfer. The model's geometry was varied, thereby simulating a wide range of tubular heating elements. Shape factors were determined over a range of variables which covered most of the heater geometries commonly manufactured. Dimensionless variables were used in plotting the data to allow the user to easily identify the correct shape factor for the geometry in question.

The computer simulation was tested using a steady state electrical analog technique with a liquid conductor. This was found to be preferable to determining the shape factor from an actual heater because of the difficulty in accurately obtaining the thermal conductivity of the insulating medium. The analog measurements agreed well with the results found in the computer study.

CHAPTER II

COMPUTER SIMULATION

2.1 The Model

In order to compute the conduction heat transfer between the resistance wire helix and the outer sheath material, a simplified model was constructed. This model allowed solution by the numerical finite element technique.

Since there were four geometric variables, three of them were non-dimensionalized by dividing them by the wire diameter. The computed shape factor is presented as a function of these non-dimensionalized variables in sets of curves that cover the range of values encountered in common heater geometries.

2.1.1 Simplification

The resistance wire helix was modeled as a series of doughnut shaped elements or tori. Each turn of wire in the helix was modeled as a torus of revolution having helix inside diameter the same as the torus inside diameter. The pitch of the helix, the axial length for one turn of wire, was modeled as the center to center axial length between two adjacent tori. The wire diameter of the helix and torus circle diameter of the model were the same.

The outside diameter of the heating element, the sheath diameter, was the same in the torus model as it was in the real heater. Figures (2.1.1) and (2.1.2) illustrate the helix and the model described above.

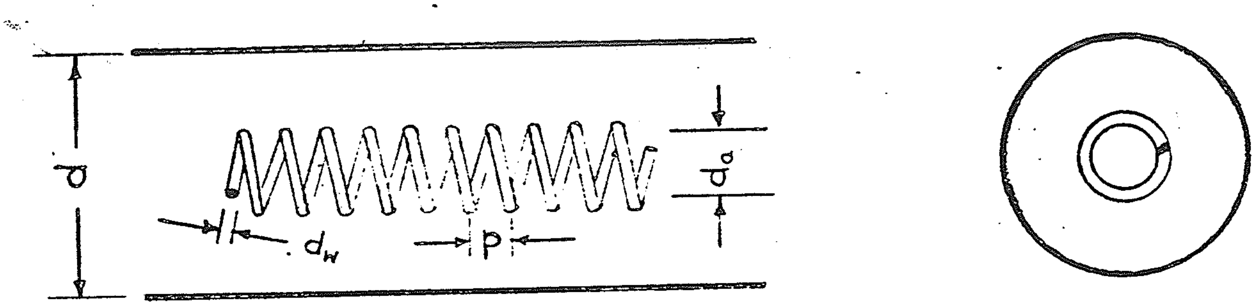
As can be seen from Figure (2.1.2) the geometry becomes axisymmetric when modeled in this way. A single element has a disk shape such as would be made by rotating the wedge shown in Figure (2.2.1) to fill the entire 360^{o}. The volume normally filled by the resistance wire was omitted as will be explained below. Figure (2.2.2) shows an infinitesimally thin slice of the wedge shown in Figure (2.2.1). The dimensions, "p", "d_w", "d_a", and "d" fully describe a heater geometry when modeled as a series of tori of revolution.

2.1.2 Assumptions And Boundary Conditions

Heat flux and temperature boundary conditions were applied to the axisymmetric shape as shown in Figure (2.2.2).

In the torus model the temperature field is a function of the axial and radial co-ordinates and is not a function of the angular co-ordinate. Therefore, the adiabatic sides shown are found by symmetry from adjoining identical elements. The bottom of the element is obviously adiabatic since it is the axis of symmetry.

The resistance wire was assumed isothermal since its



d — heater outside diameter

d_a — helix inside diameter

d_w — wire diameter

p — pitch

FIGURE 2.1.1

HELIX AS IN ACTUAL HEATER

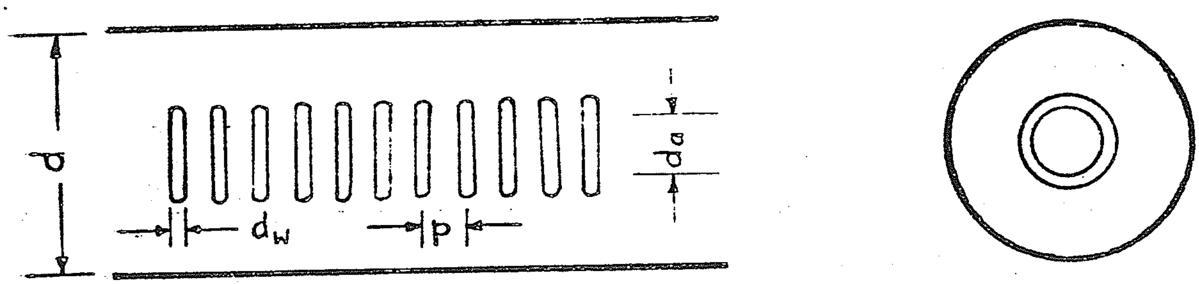


FIGURE 2.1.2

TORUS MODEL

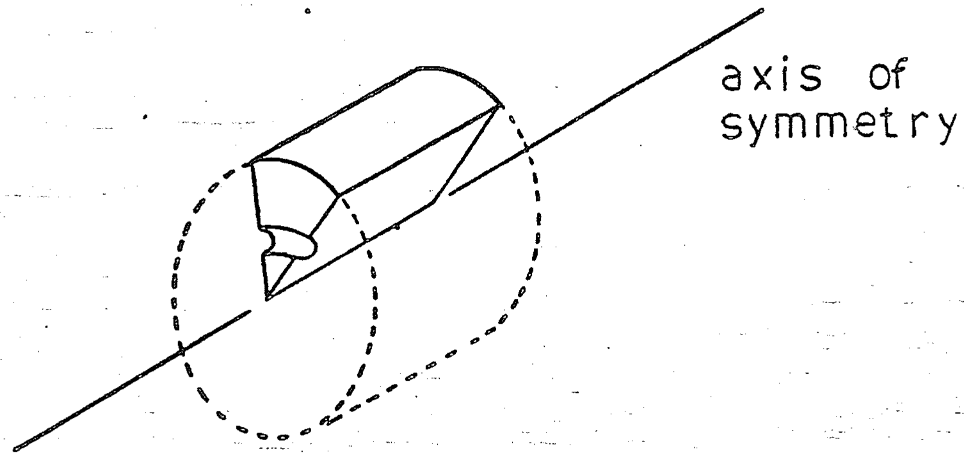


FIGURE 2.2.1

ELEMENTAL VOLUME

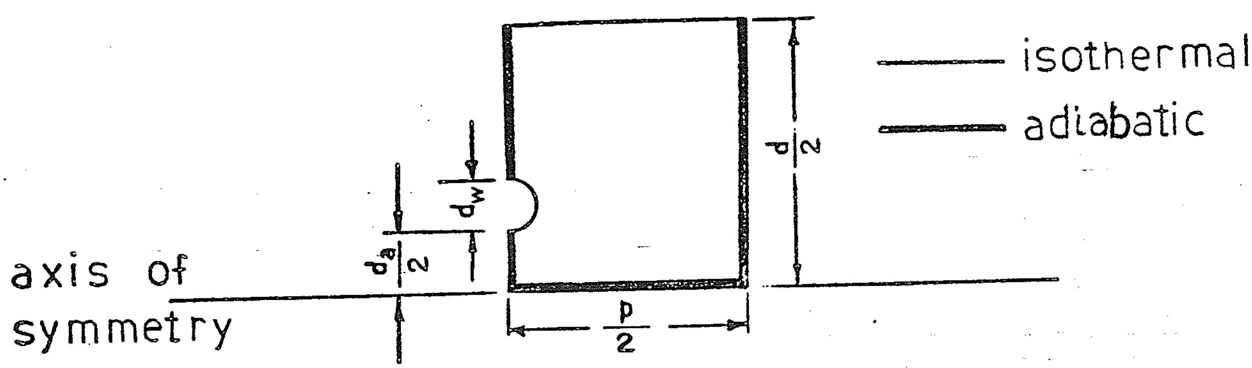


FIGURE 2.2.2

COMPUTER MODEL

thermal conductivity is fifty to one hundred times greater than that of the electrical insulating material. This assumption was further verified by a finite element computer analysis in which the resistance wire was part of the elemental volume. The resistance wire was assumed to have uniform heat generation. It was found that the temperature differences between any two points in the resistance wire were negligible. Therefore, the semi-circular region shown in Figure (2.2.2) was considered isothermal.

For similar reasons the comparatively thin layer of sheath material was not included as part of the grid for the final computer program. Common sheath materials such as copper and mild steel have thermal conductivities fifty to four hundred times greater than that of the electrical insulating material. A preliminary finite element analysis showed that the sheath material was nearly isothermal in both axial and radial directions. The absence of the sheath material in the elemental volume also greatly simplified the manipulation of input for the computer program because the elemental volume was composed of one material only.

2.1.3 Changing Geometry

The basic finite element grid which was drawn on the shape shown in Figure (2.2.2), is presented in Figure (2.3). As numerous heater geometries were studied various alterations were made to the basic grid to accommodate particular geometries. For example, for larger arbor diameters blocks of insulating material had to be added to the bottom of the shape shown in Figure (2.3). Similarly, for larger heater outside diameters blocks of insulating material were added to the top of the grid. To allow for changes in pitch or stretch ratio of the helix, insulating material was added in the axial direction. A computer program was written to produce punched input data for the many different geometries. Since the grid contained a single material, obtaining computer run input data for the varied geometries was accomplished with comparative ease.

2.1.4 Computer Program

The finite element computer program, "NLHEAT", that was used for this study was developed by Hsu and Bertels (ref. 2), using a method described by Wilson and Nickell, (ref. 3).

The computer program was flexible and handled both axisymmetric and planar geometries. It allowed the speci-

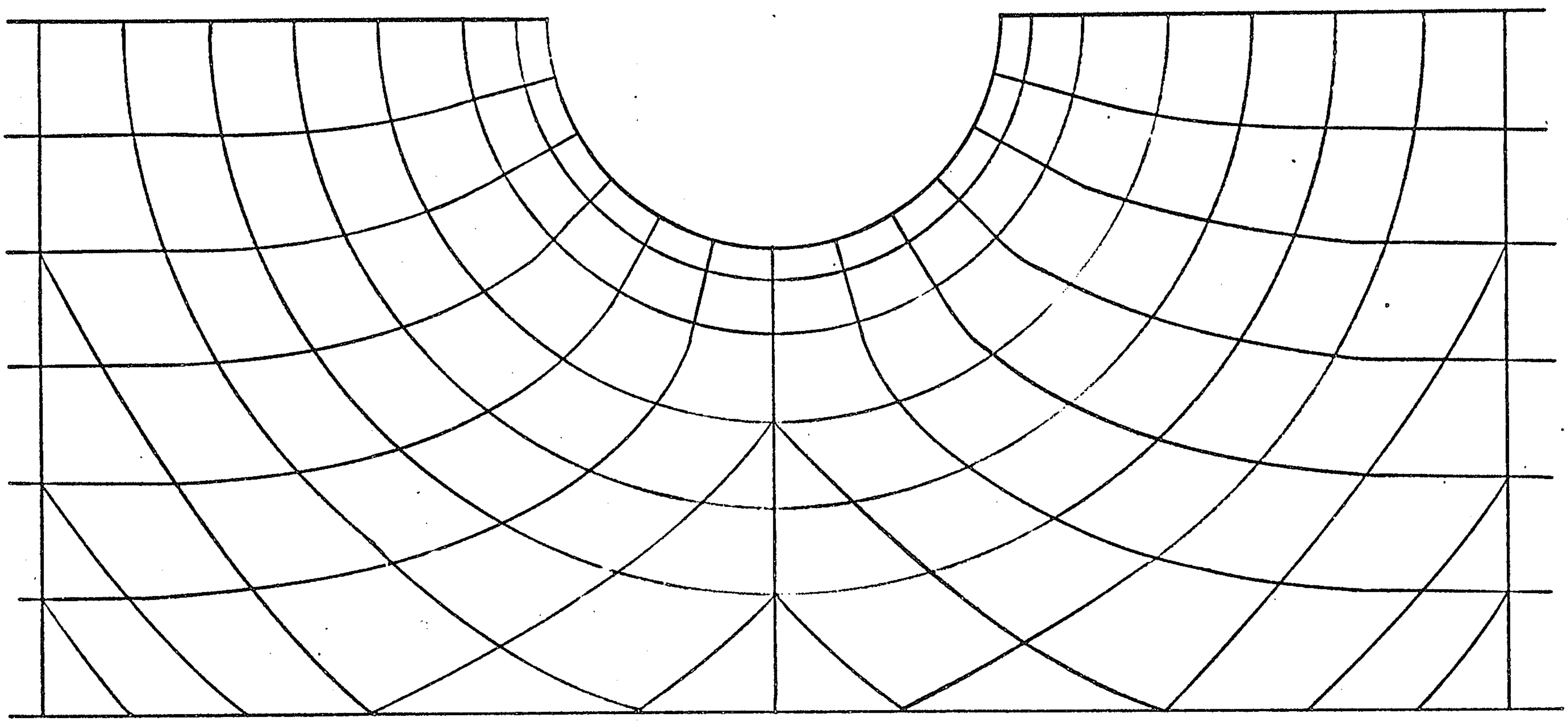


FIGURE 2.3
FINITE ELEMENT GRID

fication of isothermal and adiabatic boundaries. Material properties and heat transfer co-efficients could be made to vary with temperature, time, and position. The computer program calculated and returned node point temperatures for any specified set of conditions.

For the torus model the following set of specifications or boundary conditions were applied. Referring again to Figure (2.2.2), the semi-circular boundary representing the wire surface was given a prescribed temperature. The upper horizontal boundary which represents the outer surface of the heating element was given a prescribed uniform convective heat transfer co-efficient. In the case of the adiabatic boundaries, there was no prescribed heat transfer co-efficient and, therefore, no heat could be transferred through those boundaries. The insulating material was given a uniform thermal conductivity which was approximately the value of thermal conductivity of compacted magnesium oxide found in heating elements. As previously mentioned, a preliminary analysis showed that even for a heater with a large helix inside diameter and a convective heat transfer co-efficient of 1 Btu./ft.^{2} - hr. - ^oF, the outer surface of the heater was found to be isothermal within two degrees Fahrenheit.

Before using the computer program on the torus model, it was checked for accuracy by using known geometries such as the plane wall and concentric cylinder. It was found that the numerical solution compared to five significant figures with the exact analytical solution.

Several different grid sizes were used when the torus model was analyzed. It was found that enlarging the grid size did not significantly change the computer results for the same geometry.

2.1.5 Calculating A Shape Factor

The method used to determine a single shape factor from the results of the computer program was as follows:

A shape factor describes the influence of geometry between two isothermal surfaces in heat conduction problems. Since the resistance wire was modeled as an isothermal surface and the outside heater surface was found to be almost isothermal from computer results, the use of shape factors was feasible. The conduction equation for this case is:

$$Q = G K (T_w - T_s) \qquad \text{..........} \qquad 2.1$$

where

Q = heat loss (Btu./hr.)

G = shape factor (ft.)

K = thermal conductivity of insulating material (Btu./hr. - ft. - ^{o}F)

T_w = resistance wire temperature prescribed in computer program (°F)

T_s = surface or sheath temperature calculated by the computer program (°F)

In equation 2.1, G is the shape factor having units of length and is equal to a representative area divided by a representative length. The shape factor is a function of geometry only.

Since this is a steady state heat transfer process, the total heat flux from the resistance wire is equal to the total heat flux from the heater surface for the elemental volume shown in Figure (2.2.1). The surface heat loss is given by:

$$Q = h_s A \ (T_s - T_a) \quad \ldots\ldots\ldots\ldots \quad 2.2$$

where

h_s = convective heat transfer co-efficient prescribed in the computer program (Btu./hr. - ft.^{2} - °F)

T_a = ambient temperature prescribed in the computer program (°F)

A = heater surface area (ft.^{2})

The area, A, for the torus model is equal to the product of the circumference and half the pitch.

The shape factor, G, per unit axial length of heater can then be found by rearranging equation 2.1 to the form:

$$G = \frac{Q}{\frac{1}{2} \, p \, K \, (T_w - T_s)} \quad \ldots\ldots\ldots\ldots \quad 2.3$$

where

p = is the axial pitch between two adjacent tori (ft.)

and evaluated by substituting the value of Q from equation 2.2. Equation 2.3 is divided by ½ p because the elemental volume under consideration has that axial length as shown in Figure (2.2.2).

2.2 Results Of The Computer Study

In this section the results of the computer study are presented. A sample calculation is also presented to indicate how these results may be used on a real heater.

2.2.1 Presentation Of The Data

Over five hundred computer runs were made to encompass common heater geometries and a shape factor calculated for each geometry by the method described in section 2.1.5.

As previously mentioned, the heater geometry of the torus model is fully described by: resistance wire diameter, d_w; helix inside diameter, d_a; heater outside diameter, d; and pitch, p. These variables were non-dimensionalized in order to reduce the number of curves required to show the results of the computer study. That is, a four dimensional plot was reduced to three dimensions by dividing the heater diameter, helix inside diameter, and pitch by the wire diameter. Therefore, any torus model geometry is described