1964

Forced convection heat transfer coefficients and induction heating

Max Edwin Light

FORCED CONVECTION HEAT TRANSFER COEFFICIENTS AND INDUCTION HEATING

BY

MAX EDWIN LIGHT

A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Rolla, Missouri

1964

Approved by

(Advisor)

ABSTRACT

The purpose of this study was to design and build an apparatus to experimentally determine the convective heat transfer coefficients for water flowing in a horizontal tube at turbulent flow. Also it was planned to use the apparatus to investigate the spatial dependence of energy deposition by induction heating.

An instrument and measuring techniques were developed that gave reasonable correlations between experimentally determined heat transfer coefficients and values calculated from generally accepted heat transfer relationships developed by other experimenters. Most of the calculated values were within ± 10% of the experimental values for a wide range of flow rates.

It was hoped to determine qualitatively the energy deposition due to induction heating by measuring the steady-state temperature drop across the wall of the stainless steel tube used in the apparatus. Although the temperatures obtained on the outside of the stainless steel tube appeared to be in error, it was concluded from another experiment that the deposition of energy due to induction heating is essentially a surface phenomenon.

ACKNOWLEDGEMENTS

The author expresses his appreciation to Professor A. W. Culp for suggesting this problem, and for his assistance and participation throughout this investigation.

The help given by Professor Robert V. Wolf is hereby acknowledged for his suggestions on suitable methods of test specimen fabrication.

Thanks are due to Doctor H. J. Sauer and Professor S. J. Pagano for their assistance.

Thanks are also due to R. D. Smith, Mechanical Engineering Laboratory Technician, for assistance in operating equipment during the investigation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The main objective of this investigation was to determine suitable methods that would give an acceptable correlation between experimentally determined heat transfer coefficients using an induction heater as the heat source and coefficients calculated from any of the accepted heat transfer coefficient equations.

The secondary objective of this investigation was to qualitatively determine the energy deposition, by an induction heater, in a thick-walled stainless steel tube. The stainless steel tube was split longitudinally and the two sections were cemented around a copper tube. Stainless steel was chosen because of its low thermal conductivity, compared to other metals. This gave a greater temperature drop through the tube wall for a given heat flow. The temperature drop across the stainless tube wall would be considerably greater if the heat is deposited at or near the surface than would be the temperature gradient across the tube wall for a uniform energy deposition. If the depth of energy deposition could be determined, it would permit the calculation of internal temperatures knowing only the external tube surface temperatures.

In order to determine the heat transfer coefficient for convection, the surface temperatures must be known. Attaching a thermocouple, or other temperature measuring instruments, to the inner surface of a tube is at best a very difficult proposition. If a thermocouple is located on the inner surface, it will probably disturb the fluid film which adheres to the surface and thereby affect thermal convection from the surface. In this study, the temperature of the outside surface of a copper tube is measured and it is assumed that the temperature drop through the tube wall is negligible. For the maximum heat flow, the

temperature drop through the tube wall does not exceed 2 F^{o}. The assumption is also made that the energy deposited by the induction heater in the test specimen is completely absorbed by the thick-walled stainless steel tube.

II. NOMENCLATURE

SYMBOL	QUANTITY	UNITS
A	Area	Sq Ft
C_p	Specific heat at constant pressure	Btu/Lb_m-^oF
D	Diameter	Ft
h	Experimental heat transfer coefficient	Btu/Hr-Sq Ft-^oF
h_1	King Heat Transfer Coefficient	Btu/Hr-Sq Ft-^oF
h_2	Colburn Heat Transfer Coefficient	Btu/Hr-Sq Ft-^oF
h_3	Dittus-Boelter Heat Transfer Coefficient	Btu/Hr-Sq Ft-^oF
k	Thermal conductivity	Btu/Hr-Ft-^oF
L	Length of specimen	Ft
Q	Heat transfer rate	Btu/Hr
G	Volumetric heat generation	Btu/Cu Ft-Hr
T_f	Film temperature	^oF
T_b	Bulk temperature	^oF
T_s	Inside surface temperature of copper tube	^oF
V	Fluid velocity	Ft/Hr
μ	Viscosity	Lb_m/Ft-Hr
ρ	Density	Lb_m/Cu Ft

III. SCIENTIFIC BACKGROUND

A. HEAT TRANSFER BY CONDUCTION AND CONVECTION

1. Conduction. Heat flows from a high-temperature region to a lower-temperature region within a solid body by thermal conduction. The particles of matter (molecules, atoms, and electrons) in the high temperature region, which are at higher energy levels, transmit some of their energy to the adjacent lower-temperature regions. In metallic solids, the flow of free electrons is primarily responsible for heat conduction (1). For nonmetals, the conduction of heat is caused by the vibrations of the atoms. This process also occurs in metals but the electron flow in metals is the primary process of thermal conduction. The vibrations of the atoms occur in tiny bunches called phonons (2). A phonon is a pulse of sound waves, comparable to the pulse of water waves from a stone dropped into water. Its name expresses its similarity to the photon, which is a pulse of light waves. The basic quantum nature of matter states that energy occurs only in indivisible little lumps—quanta. Phonons and photons are respectively the quanta of sound waves and light waves. Phonons are the carriers of heat in nonmetallic solids.

The quantity of heat that flows through a solid per unit time is a direct function of the temperature gradient and a property of the solid called the thermal conductivity. Every solid material has its own thermal conductivity and generally, every material that is a good conductor of heat is a good conductor of electricity.

2. Convection. Heat is transferred by thermal convection as a result of fluid motion (3). Cold fluid immediately adjacent to a hot surface receives heat by conduction which it imparts to the bulk of

the cold fluid by thermal conduction and by mixing with it. Free or natural convection occurs when the fluid movement is caused by the change of fluid density. When the fluid is moved by an external force, the heat transfer is said to be due to forced convection.

B. HEAT TRANSFER BETWEEN SOLIDS AND FLUIDS

When a liquid flows through a pipe or tube, the fluid particles in the vicinity of the surface are slowed down due to viscous forces. The fluid particles adjacent to the surface have negligible velocity relative to the surface boundry. Heat is transferred through the walls of the pipe or tube by conduction and through the layer of fluid particles adjacent to the walls by conduction. The heat is then transferred by the moving fluid particles into the main portion of the fluid stream. If the fluid moves in layers, each fluid particle following a smooth and continuous path, the fluid is in laminar or streamline flow. When the flow is increased beyond a certain critical velocity, streamline flow can no longer continue and turbulence takes place. In this range of turbulent flow, innumerable eddies and cross currents occur in the main body of the stream. A radial component of velocity exists for most of the fluid particles. The film adhering to the surface consists of two separate layers. The first layer or sublayer is composed of particles completely without motion clinging to the surface and of particles creeping along in streamline flow with increasing velocity as the distance from the surface is increased. The second layer, much thicker than the first, is a transition zone composed of eddy currents moving at a higher velocity although not so swiftly as the main portion of the fluid stream. The first layer or sublayer is generally termed

the laminar sublayer and the second layer is called the buffer zone. The main portion of the fluid stream is called the turbulent core.

C. SURFACE COEFFICIENT OF FORCED CONVECTION

The heat flow rate, Q, through the fluid film that is assumed to adhere to the surface of any solid in contact with a fluid may be expressed as

$$Q = hA(\Delta t) \tag{1}$$

where Δt is the temperature difference between the surface of the solid and the bulk fluid temperature, h is the surface coefficient for film conductance, and A is the surface area. In order to develop a mathematical expression for a surface coefficient of forced convection, where the flow is assumed to be turbulent, three different means of approach are employed. The first approach is to perform a mathematical analysis of the fluid flow, translated into thermal units through an analogy between fluid friction and heat transfer. The second approach to the problem is to apply the principles of dimensional analysis together with the introduction of numerical constants derived from experimental data. The third approach to the problem, which has less general application, is to represent the experimental data by purely empirical formulas.

The development of an analogy between fluid friction and film conductance had its beginning with the work of Osborne Reynolds in 1874 through his observation that in geometrically similar systems of piping, the transfer of heat by convection was definitely related to the fluid friction. In more recent years, Reynolds' analogy has been progressively extended by a number of experimenters in the attempt to develop an expression that will show close agreement with experimental

results for all fluids of known physical properties throughout the widest ranges of temperatures and velocities.

The expressions devised by rigid mathematical analysis of the analogy between heat transfer and fluid friction are quite involved. The resulting derivations are so much more complicated than the development of an expression by the method of dimensional analysis combined with experimental evaluations that the latter procedure generally has met with great favor.

One method of developing the form of an equation by dimensional analysis is by use of the π theorem. This theorem states that any complete homogeneous equation expressing the relationship between n measurable quantities and r dimensional constants such as (a,b,c ...) in the form f(a,b,c ...)=0 has a solution of the form

$$\phi(\pi_1, \pi_2, \pi_3, \ldots, \pi_{n-r}) = 0 \qquad (2)$$

where the number of π terms is n-r independent products of the terms a,b,c ..., which are dimensionless in the fundamental units. In equation (2), n is the number of physical quantities plus dimensional constants involved and r is the number of fundamental dimensions required to express them. Thus for five physical quantities involved, if they are expressed in terms of three fundamental dimensions, there will be two dimensionless products or π's in the solution.

Taking into consideration all of the variables that effect the convective heat transfer coefficient, the following equation can be derived by the theorem.

$$\phi = \left(\frac{hD}{K}, \frac{DV\rho}{\mu}, \frac{C_p\mu}{K}\right) = 0 \qquad (3)$$

A solution of this equation is

$$\frac{hD}{K} = f_1\left(\frac{DV\rho}{\mu}\right) f_2\left(\frac{C_p\mu}{K}\right) \qquad (4)$$

The form in which the function f_1 and f_2 can readily be expressed has been determined by plotting the results of numerous tests. For most practical applications, these results are well expressed by the equation

$$\frac{hD}{k} = c\left(\frac{DV\rho}{\mu}\right)^b\left(\frac{c_p\mu}{k}\right)^d \qquad (5)$$

This equation is known as Nusselt's equation, and the three dimensionless fractions are known as follows:

$\frac{hD}{k}$, Nusselt number, or modulus (6)

$\frac{DV\rho}{\mu}$, Reynolds number, or modulus (7)

$\frac{c_p\mu}{k}$, Prandtl number, or modulus (8)

From a review of the work of various experimenters, W. H. McAdams has concluded that a fair correlation of their results for the heating and cooling of various nonviscous fluids in turbulent flow in horizontal tubes is given by the equation

$$h = .023\frac{K}{D}\left(\frac{DV\rho}{\mu}\right)^{.8}\left(\frac{C_p\mu}{K}\right)^{.4} \qquad (9)$$

Flow is generally accepted as being turbulent when the Reynolds number is above 2300. Equation (9) applies where the Reynolds number is within the range of 10,000 to 120,000, the Prandtl number is between 0.7 and 120, the length of the tube is at least 60 diameters, and the difference in temperature on the two sides of the film is not large. This equation is widely accepted for the calculation of surface coefficients when the fluid does not have a viscosity greater than that of water.

One of the equations that has been accepted as being one of the better equations for describing turbulent flow in horizontal tubes is the Dittus-Boelter Equation

$$\frac{hD}{K} = .023\left(\frac{VD\rho}{\mu}\right)^{.8}\left(\frac{C_p\mu}{K}\right)^b \qquad (10)$$

where b = .4 for heating and b = .3 for cooling.

When the Reynolds number exceeds 10,000, A. P. Colburn has modified the Dittus-Boelter Equation by changing the exponent on the Prandtl number from .4 for heating to 1/3. It has been well enough accepted to be identified as the Colburn Equation.

$$\frac{hD}{K} = .023 \left(\frac{VD\rho}{\mu}\right)^{.8} \left(\frac{C_p \mu}{K}\right)^{1/3} \qquad (11)$$

The surface coefficient of convection for heating or cooling of water in tubes at temperatures not exceeding 180 °F may be expressed quite accurately by the King Equation

$$h = .00134\,(t + 100)\,\frac{V^{.8}}{D^{.2}} \qquad (12)$$

where t is the average water temperature or if the temperature drop across the inside film is estimated to be more than 10 F°, t should be the film temperature, i. e., the average temperature in the fluid film.

In the application of any empirical equation for forced convection to practical problems it is important to bear in mind that the predicted values of the heat transfer coefficient are not exact. The results obtained by various experimenters, even under carefully controlled conditions, differ appreciably. It has generally been accepted that a correlation within ± 20 per cent is acceptable.

The surface coefficient, h, may be a point value or an average value, i. e., it may apply to a specific point along a tube where the temperature on both sides of the film are known or it may be an average value applying to the entire inside surface of the tube.

All calculations of the surface coefficient made by applying equations such as McAdams', Colburn, etc. involve the evaluation of the physical properties of the fluid at some definite temperature (4). At low rates of heat transfer and turbulent flow, the difference

between the bulk temperature (temperature of the main body of the stream) and that of the surface with which the fluid is in contact may be insignificant. In this case, physical properties are usually evaluated at the bulk temperature of the fluid. At higher rates of heat transfer, the temperature that is usually selected is an intermediate value termed the film temperature. The film temperature is a mean of the bulk fluid temperature and the surface temperature.

$$T_f = \frac{T_B + T_S}{2} \qquad (13)$$

Uniform procedure for the selection of the temperature at which to evaluate the fluid properties has not yet been attained. Usually, the physical properties are evaluated at the bulk temperature when the temperature difference on the two sides of the film is not more than 10 F^o in the case of a liquid or 100 F^o in the case of gases. For larger temperature differences, the film temperature is used.

D. THERMOCOUPLES

T. J. Seebeck discovered the phenomenon of thermoelectricity in 1821 when he found that if a circuit was formed consisting of two dissimilar metallic conductors and if the two junctions of the circuit were maintained at different temperatures, a current flowed in the circuit. The emf producing this current is called the Seebeck thermal emf. It was later found that the voltage Seebeck discovered was brought about by two causes, the Peltier effect and the Thomson effect. In short, Peltier discovered that if a current from an external source is passed through a circuit consisting of two dissimilar materials, one of the junctions would be heated and the other cooled. This effect occured only at the junctions and was reversible. This effect is different

from that of a current flowing through an electrical resistance and varies directly as the square of the current.

The Thomson effect causes a difference of potential along a single homogeneous wire when there is a temperature gradient in it. The Thomson effect, like the Peltier, is reversible.

By inserting a potentiometer into the circuit and measuring the emf generated when the junctions are at known temperatures, a correlation between emf generated and temperature can be established.

To insure continuity of data, the practice is to maintain one of the junctions at a known and reproducible temperature, i. e., the melting point of ice, boiling point of water, boiling point of oxygen, boiling point of sulfur, melting point of silver, or the melting point of gold. In the measurement of temperatures in the range of 0-500 °F, the melting point of ice is usually selected. The emf or difference of potential between the two junctions can be directly related to the difference in temperature between the two junctions.

The hot junction of a thermocouple may be made by soldering or fusing the two metals or by any electrical connection between the two metals. Silver solder is useful at temperatures below 1600 °F, but the best type of junction is made by fusion. The junction of a rare metal couple may be made by using a small oxygen-illuminating gas flame. Acetylene is not desirable, and flux should not be used. It is frequently the practice to twist the two wires because this gives better mechanical strength.

It is not necessary for accuracy to expose the whole length of the element to the temperature to be measured , because the thermo-electric force depends only upon the temperatures of the ends. The cold end,

or junction, should be maintained at a constant temperature.

The four most commonly used thermocouple combinations are: platinum-platinum rhodium, iron-constantan, chromel-alumel, and copper-constantan.

E. INDUCTION HEATING

Induction heating is a means of rasing the temperature of metallic parts by the transfer of electrical energy from a high frequency current-carrying conductor, usually referred to as a heating coil. This coil sets up a field of magnetic flux that energizes the metal workpiece in such a way that current is caused to flow around its surface. The resistance of the work to this flow, or its inability to carry the induced current, causes an immediate heating action to take place (5).

The principle of induction heating is basically the same as that of a transformer. The induction coil would be equivalent to the primary of the transformer and the workpiece to be heated is equivalent to the secondary of the transformer. When the induction coil is energized with alternating current, the current causes magnetic lines of force or flux lines to flow around the coils. Then, as the workpiece is cut by these flux lines, it in turn has induced in it a current that opposes the inducing current. The induced current in the workpiece or secondary tends to flow parallel to primary currents but in the opposite direction. If the workpiece is a magnetic material, it may be assumed to be made up of many small particles which tend to become polarized with a north and south pole lined up with the polarity of the field produced within the coil by the flow of current. The polarity of this field changes many times per second with the alternation of the

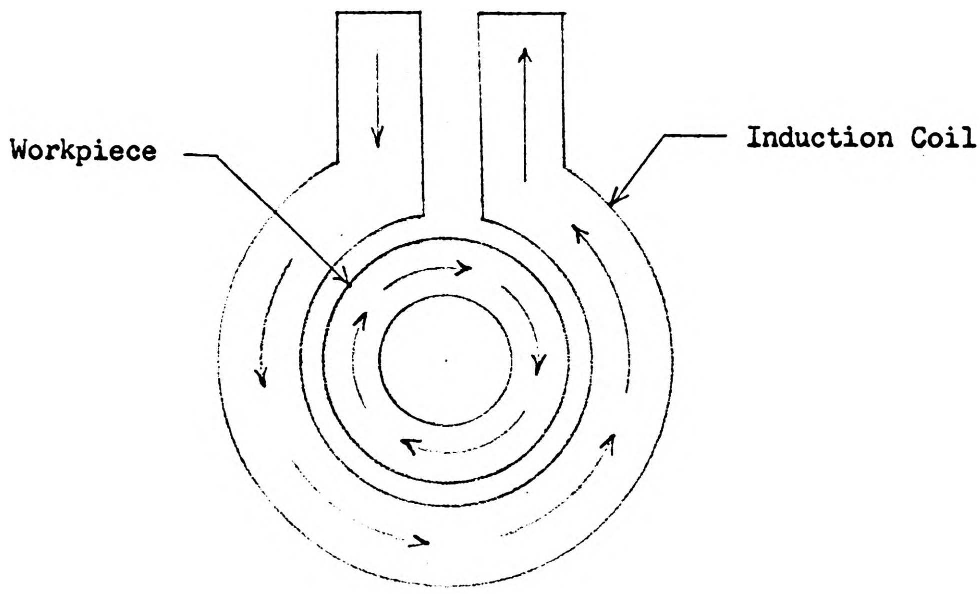


Figure 1. Current in Coil and Workpiece

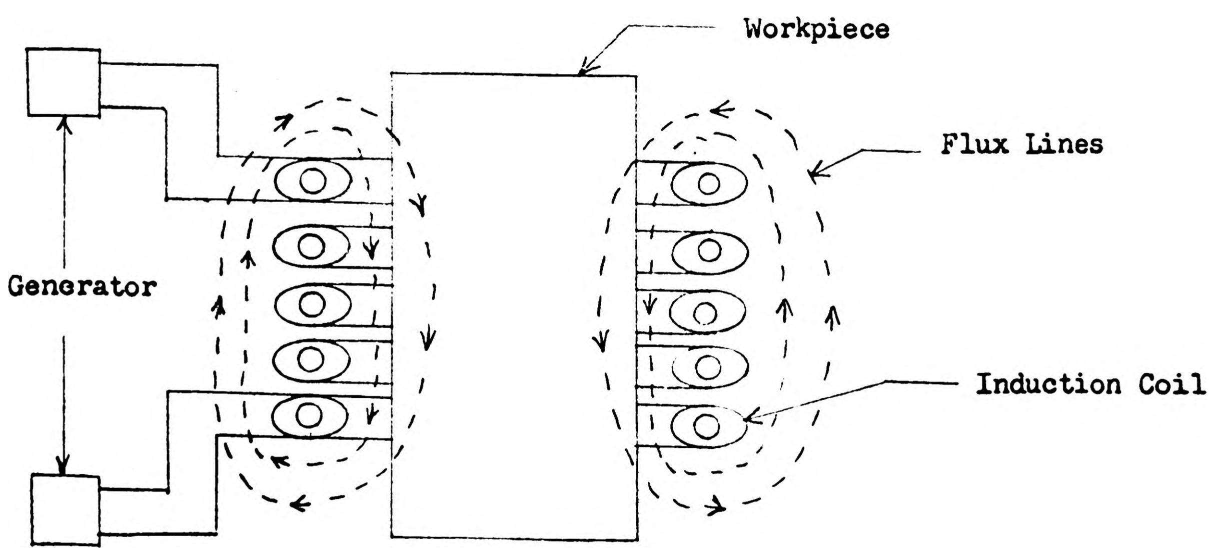


Figure 2. Flux Distribution Around Coils of Induction Heater

current necessary for high frequency heating. The tendency for these small magnets to realign themselves with the changing field polarity is resisted by the metal and internal molecular friction is developed which dissipates itself in the form of heat. This heating effect is due to hysteresis or the hysteresis effect.

Another source of energy deposition is that resulting from the eddy currents which are produced in the area affected because of the intensity of the induced current much the same as the eddy swirls set up along the bank of a rapidly moving stream of water. Since the substance which carries the induced current is acting as a conductor, it also has an electrical resistance to this flow of energy. Thus, induction heating may be compared to ordinary resistance heating and establish it likewise as that heat which is liberated as a result of I^2R losses. That is to say, there is a flow of current (I) and a resistance to this flow of current (R) which, combined, are responsible for the generation of heat. The heat dissipated by the eddy currents is much more significant than heating caused by hysteresis effect for induction heating.

Of great importance in induction heating is the frequency of the A. C. power source. The frequency has a direct influence on the depth of heat penetration. The higher the frequency, up to a certain range, the more pronounced the surface heating effect. A frequency of 2,000 cycles per second may heat a surface to a depth of 0.125 inch, whereas a frequency of 200,000 cycles per second will produce a much shallower heat zone, on the order of 0.020 inch in depth. If deep penetration is desired, frequencies of 2,000 to 10,000 cycles per second usually are applied. Where only surface heating is required, a frequency range

of 200,000 to 500,000 cycles per second is preferable. For extremely thin heat layers, frequencies of 1,000,000 cycles per second may be used.

Three basic types of equipment are used for inductivily heating metallic parts. These equipment are the motor-generator set, the spark-gap converter, and the vacuum-tube or electronic-type generator. In principle they are all alike in that an inductor or heating coil surrounds the work to be heated.

The motor-generator set is used for the lower frequency range of 2,000 to 9,600 cycles per second. These sets are therefore widely used for the heating of parts where deep hardening is required, or for the through heating of bars, such as those required for forging.

For shallow heat penetration applications, the spark-gap converter and vacuum-tube oscillator are employed. The spark-gap converter operates in the frequency range of from 25,000 to 250,000 cycles per second while the vacuum-tube oscillator operates in the range of from 100,000 to 1,000,000 or more cycles per second.

The induction heater used in this study has two output terminals, one for high voltage output and one for low voltage output. The high voltage output terminals on the left are used for feeding multi-turn coils where the loads require relatively low-power densities. The low voltage output on the right is used for feeding single-turn coils and very small multi-turn coils where the loads require relatively high power densities. The high voltage output terminals on the left were used for this study. (See Fig. 5, p. 24)

F. INTERNAL HEAT GENERATION

A number of applications of the principles of heat transfer are

concerned with systems in which heat may be generated internally. Nuclear reactors are one example, electrical conductors and chemically reacting systems are others. The general conduction equation for internal heat generation is

$$\nabla^2 T + \frac{G}{K} = \frac{c\rho}{K} \frac{\partial T}{\partial \theta} \qquad (14)$$

where θ = time and G is the spatially dependent volumetric heat source term. For steady-state conditions, the term on the right side of the equality sign is equal to zero.

Since the heat generation by an induction heater is a volumetric heating effect, equation (14) can be used to determine the steady-state temperature distribution in the member provided the spatial dependence of G is known. Part of this study was aimed at trying to determine the spatial dependence of G by measuring the steady-state temperature distribution in the test apparatus. Solving equation (14) for the steady-state condition of uniform volumetric heating in an infinitely long, annular wall with the external surface insulated, produces the following equation

$$\Delta t_u = \frac{G}{2K} \left[r_2^2 \, Ln \frac{r_2}{r_1} - \frac{1}{2} \left(r_2^2 - r_1^2 \right) \right] \qquad (15)$$

where Δt_u = temperature drop between the outside and inside of the stainless steel tube for uniform heat generation.

If it is assumed that all of the heat is deposited immediately at the external surface of the annular wall, the temperature drop across the tube wall is given as follows

$$\Delta t_s = \frac{Q}{2\pi K L} \, Ln \frac{r_2}{r_1} \qquad (16)$$

where Δt_s is the temperature drop across the tube wall for surface heating and Q is the total steady-state rate of energy deposition in Btu/hr. The total heat transfer rate Q is related to the uniform

volumetric heat rate G by

$$Q = G(\text{volume of tube wall}) = \pi(r_2^2 - r_1^2)LG$$

Substituting this relationship into equation (16), the following equation is obtained

$$\Delta t_s = \frac{G}{2K}(r_2^2 - r_1^2) \ln \frac{r_2}{r_1} \qquad (17)$$

IV. EXPERIMENTAL METHOD

A. TEST EQUIPMENT

1. Thermocouples. The thermocouples used in this investigation were 28 gauge copper-constantan thermocouple wire. The reasons for the selection of this metal combination for the thermocouples are given in the following discussion.

It was discovered that only the constantan lead need be located at the point where the temperature was to be determined when measuring temperatures along copper tubing by means of copper-constantan thermocouples. This was accomplished by letting the copper tube act as the conductor to a common copper wire, which can be located at any convienient point along the tube. To prove that the copper tube would conduct the current to the copper lead, and that impurities in the copper tube would not alter the reading, a test was devised to measure the boiling and ice temperatures of water. When the temperature of boiling water was measured, both the mercury thermometer and the potentiometer indicated a reading of + 211 °F, although the temperature of the copper connection was approximately 80 °F. When the boiling water was replaced by ice and water, the mercury thermometer and the potentiometer indicated a reading of + 32 °F. Therefore, it was concluded that this method gave accurate results. This method was better than the conventional way of attaching thermocouple leads because the copper lead could be located away from the coils of the induction heater. This reduced the possibility of extraneous current being induced in the thermocouple circuits used to measure the copper tube temperature.

The 28 gauge thermocouple wire was selected because the smaller

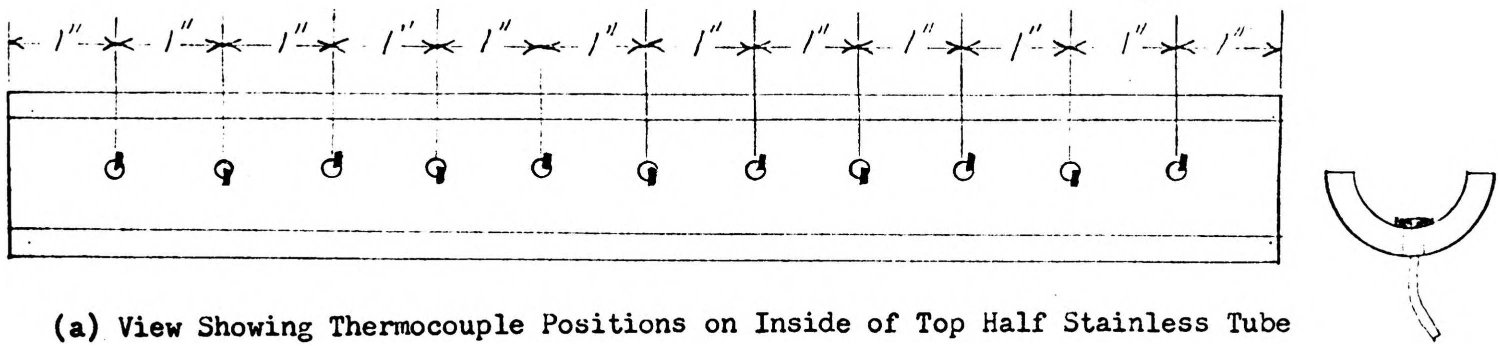
size leads could be attatched with a minimum amount of solder. A large build-up of solder around a thermocouple connection, when exposed to a magnetic field induction, could give an erroneous temperature reading due to the excess mass cutting more flux lines thus indicating a higher temperature. Also, the large mass of solder creates an electrical junction between the thermocouple metals that measures a temperature other than at the desired point.

2. Test Specimen. The test specimen constructed for this investigation is shown in Figure 5b.

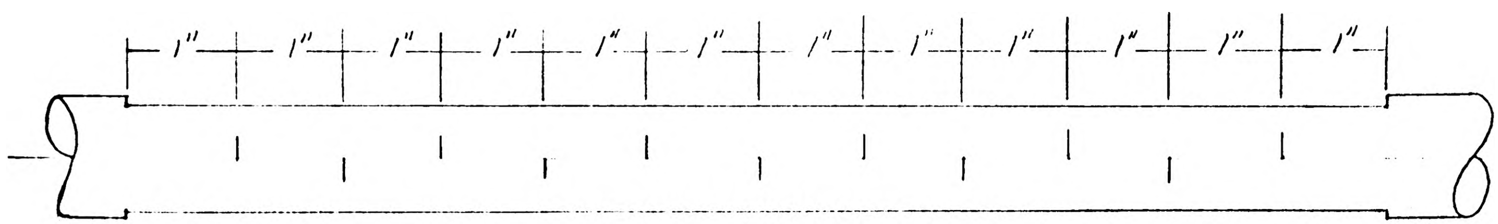
The test specimen was prepared by longitudinally sawing a twelve inch section of type 304 stainless steel tubing into two halves. Eleven 1/16 inch diameter holes were drilled along a straight line through one of the pieces of tubing. A 28 inch section of 5/8 inch I. D. copper tubing was next selected. The O. D. of the copper tube was reduced starting at a point four inches from one end of the tube and extending twelve inches toward the other end. The reason for reducing the O. D. of the copper tubing was to obtain a sufficient amount of bonding agent between the copper tube and the two halves of the stainless steel tube. Also, this would insure that the two halves of the stainless steel tube would fit as closely as possible around the reduced O. D. section of copper tube. The reason for mating the two halves of the stainless tube as closely as possible around the copper tube was that a temperature build-up can occur at a sharp break in the surface of the test specimen because of the change of the path of eddy currents. A straight line was scribed along the twelve inch section of copper tube which had the O. D. reduced. Eleven insulated constantan thermocouple leads were soldered on alternate sides of the scribed line at one inch

intervals. (See Fig. 3b) Copper-constantan thermocouple junctions were run through the 1/16 inch diameter holes in the stainless tube section and soldered to the I. D. of this section. (See Fig. 3a) The copper tubing was slightly dented where the insulated thermocouple wire, fastened to the stainless tube I. D., would rest on the copper tube. It is believed that denting the copper tube had the effect of increasing the calculated heat transfer coefficients due to increased turbulence induced by the dents in the tubing. The constantan therocouple leads on the copper tube were put through the 1/16 inch diameter holes in the top section of the stainless tube. (See Fig. 4a) A two part epoxy resin cement was mixed and applied to the inside of the two halves of the stainless tube. The two halves were then clamped around the copper tubing and the epoxy cement allowed to cure for two days. The epoxy resin cement was selected as the bonding agent because no bonding agent could easily be obtained which would properly wet the surface of the stainless tubing at low temperatures. The critical temperature being the melting point of the solder used to fasten the thermocouples to the stainless and copper tubing. Therefore, no bonding agent could be used which would have to be applied at a temperature which could disturb the position of the thermocouples. A sample of the epoxy was obtained and used to bond a small section of copper tube to stainless tube as would be done for the actual test specimen. This small specimen was exposed to temperatures (200-300^{o}F) which would be encountered in actual testing and the bonding strength of the epoxy at these temperatures was considered adequate.

After the epoxy cement had cured for two days, thermocouples were attatched to the O. D. of the stainless tube. (See Fig. 4a) The test

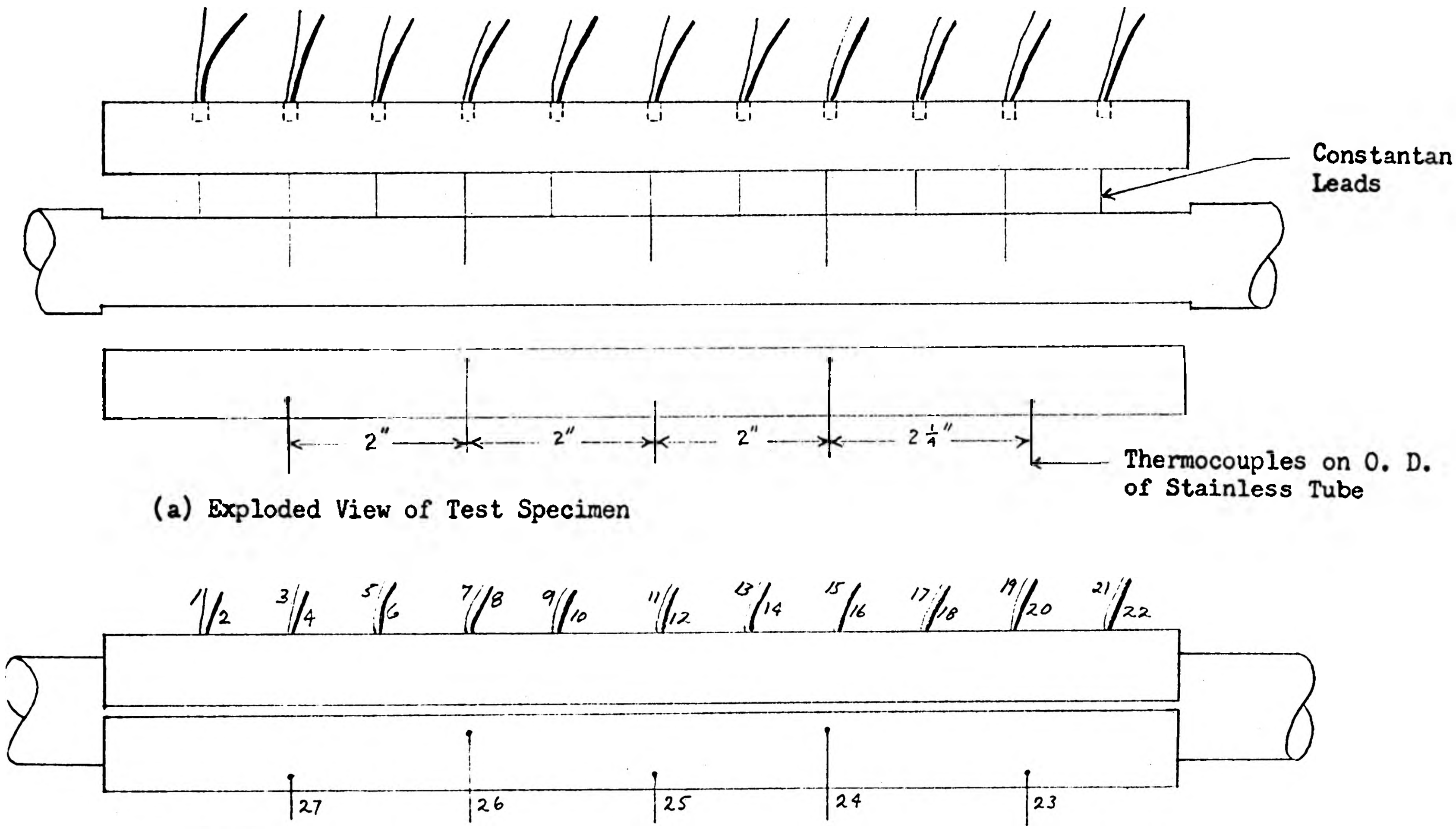


(a) View Showing Thermocouple Positions on Inside of Top Half Stainless Tube



(b) Top View of Copper Tube Showing Position of Constantan Leads

Figure 3. Construction



(a) Exploded View of Test Specimen

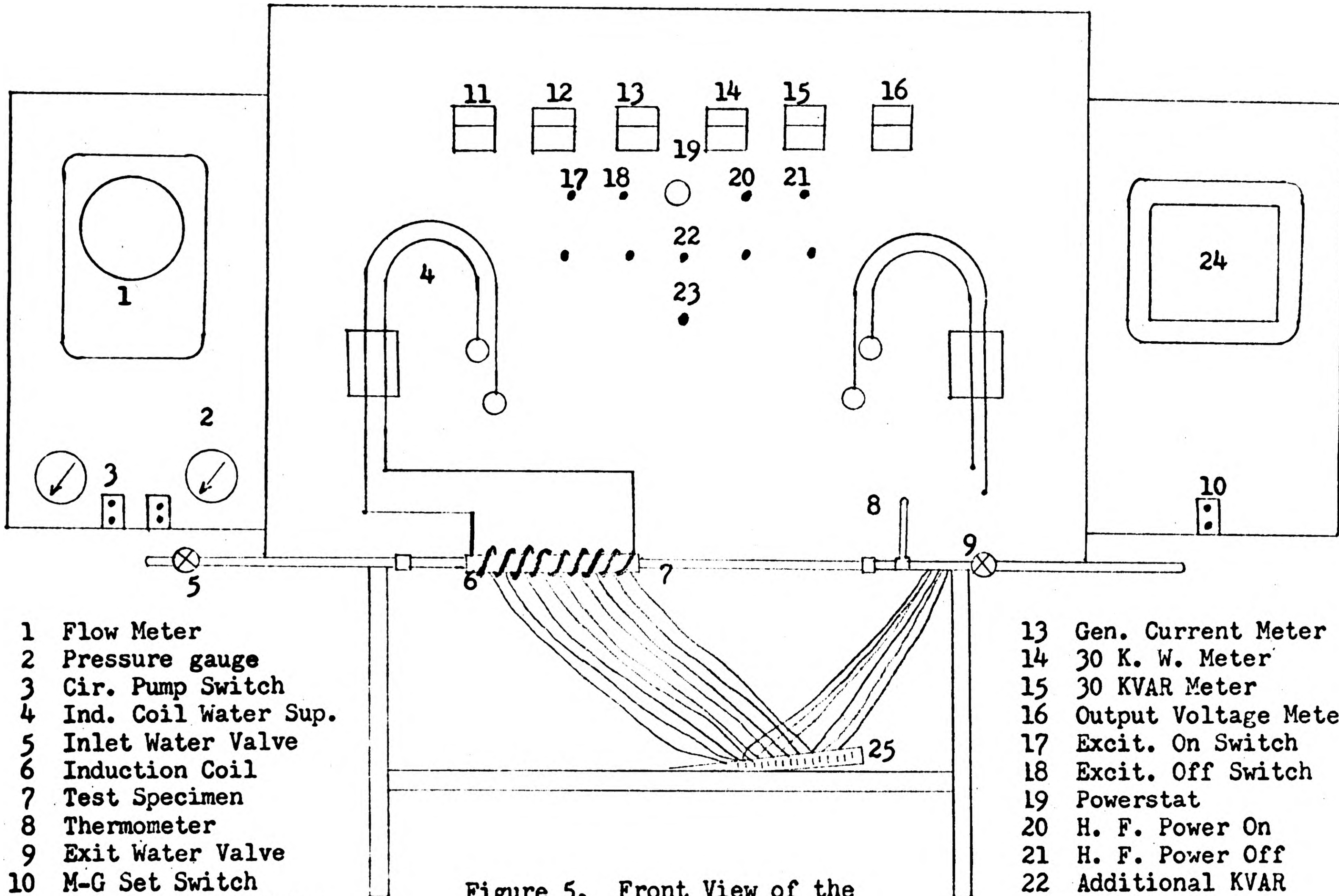
(b) Complete Test Specimen

Figure 4. Construction of Test Specimen

specimen was wrapped in asbestos cloth to prevent the specimen from touching the coils of the induction heater which would cause a heat build-up at the point of contact and produce uneven heating of the test specimen. Also, the asbestos cloth was applied to reduce heat transfer from the external surface. Slits were made in the asbestos cloth to permit the thermocouples to project out radially between the coils of the induction heater.

3. Induction Heater. The induction heater used in this experiment was a Westinghouse single phase multipurpose heater. (See Fig. 5) It is composed of a motor-generator set with a fixed frequency of 9600 cycles per second. The motor-generator set is cooled by circulating water obtained from the Missouri School of Mines power plant. It is protected from overheating by relays located in the motor which automatically shut off the set when the water reaches a temperature of about 90°F, or the water gauge pressure falls below forty pounds per square inch. The motor-generator is capable of supplying voltage over a range of 12 1/2 to 800 volts. The induction coil used is made of 3/8 inch diameter copper tubing, consisting of 14 turns, and was approximately 12 inches long. The tubing of the induction coil is connected to the coolant water supply to keep the tubing from overheating during operation.

4. Recorder. The recorder used in this study is a Wheelco continuous null balance type D. C. potentiometer. The recorder is equipped with circuitry and automatic switches to monitor sixteen thermocouples. The output siginals are printed on a continuously moving chart. The reference circuit consisted of a thermocouple placed in series with the input signal circuitry and immersing it in



1 Flow Meter
2 Pressure gauge
3 Cir. Pump Switch
4 Ind. Coil Water Sup.
5 Inlet Water Valve
6 Induction Coil
7 Test Specimen
8 Thermometer
9 Exit Water Valve
10 M-G Set Switch
11 Field Current Meter
12 Gen. Voltage Meter
13 Gen. Current Meter
14 30 K. W. Meter
15 30 KVAR Meter
16 Output Voltage Meter
17 Excit. On Switch
18 Excit. Off Switch
19 Powerstat
20 H. F. Power On
21 H. F. Power Off
22 Additional KVAR
23 Cap. Off Switch
24 Recorder
25 Terminal Strip

Figure 5. Front View of the Induction Heater and Test Specimen

an ice bath.

A capacitor was installed in each lead of the reference circuit and was grounded. This was done to filter out extraneously induced emfs that might be generated by the induction coil in the thermocouples. These capacitors reduced the electrical noise in the input signal.

A test was conducted to see if the induction heater was generating any extraneous emfs in the thermocouples. This was done by connecting a five turn copper coil to the induction heater. The axis of the coil was in the vertical position. A beaker with a small cylinder of steel in it was filled with water and placed in the coil. The induction heater was started and the powerstat adjusted until the water began to boil. A thermocouple junction was immersed in the boiling water and the recorder indicated 211°F. From this experiment, it was concluded that the induced emfs in the thermocouple by the induction heater did not seriously affect the recorder reading.

B. PROCESS COOLANT WATER

The following features were considered essential in the coolant water used for this study.

1. Reasonably free of air or other gases.
2. Low temperature.
3. Constant temperature.

The cistern of the Mechanical Engineering Building was considered the best source of process coolant water available. The cistern is maintained at a depth of six feet and contains sufficient water for all the Mechanical Engineering Department power plant laboratory work. This water is kept in continuous storage and additions made only when the water level is at a minimum level. Because of the continuous

storage, this water was considered to be relatively free of gases. The cistern water was used throughout this study to cool the test specimen. The observed temperature variations for the cistern water were less than one F^o during the first part of the investigation. During the latter part of the investigation, additional water had to be added to the cistern and the observed temperature variations for the remainder of the experiment were less than three F^o.

C. FLOW MEASUREMENT

The magnitude of the flow was measured for each run by weighing the amount of water that would flow, in a given time interval (2 min.), into a barrel setting on a platform scale. By this method, the flow was calculated in pounds per hour.

D. WATER TEMPERATURE MEASUREMENT

Inlet and outlet test specimen water temperatures were measured by mercury thermometers. One thermometer was placed in the weir tank. It was assumed that the water in the weir tank was at the same temperature as the water pumped to the test specimen inlet since water was supplied to both places by a common pump. A thermometer was also placed in a tee downstream from the test specimen.

At the start of each run, before the induction heater was turned on, water was allowed to flow through the test specimen from two to three minutes then the thermometer mounted in the tee was read and recorded as the inlet temperature. This reading was checked with the reading obtained from the thermometer in the weir tank. The observed temperatures from these two thermometers were in perfect agreement throughout the study. After the induction heater was turned on and steady-state conditions were reached for the particular run, the

thermometer in the tee was again read and this was recorded as the outlet temperature.

E. TEST PROCEDURE

The general procedure was to start the induction heater and adjust the coolant flow to the desired flow rate. No data was recorded for use in this study until the thermocouple chart recorder indicated steady-state conditions were reached. After the data for a particular run was recorded, the flow rate was adjusted to the next reading and the procedure was repeated.

V. RESULTS

A. COMPARISON OF MEASURED AND CALCULATED HEAT TRANSFER COEFFICIENTS

The measured values of the heat transfer coefficient were obtained by the following equation

$$h = \frac{Q}{A \Delta t}$$

where Δt = the difference between the average copper tube surface temperature and the average water temperature and A is the inside surface area of the copper tube.

The values calculated by the King Equation (12) were within acceptable limits when compared to the measured values for both runs one and two. For low heat fluxes, the range of error of the calculated coefficients was + 3.4% to + 16.2% while the range for high heat fluxes was - 1.9% to + 11.6%. The magnitude of deviation was about the same, 12.8% for run one and 13.5% for run two.

The best correlation between measured and calculated results was obtained when the Colburn Equation (11) was used to obtain the calculated values. The range of deviation for run one was - 4.8% to + 7.5% and for run two it was - 9.2% to + 3.2%. The magnitude of deviation for both runs is almost the same.

The largest deviation between measured and calculated results was obtained from the Dittus-Boelter Equation (10) although the results were still within acceptable limits. The range of deviation for runs one and two were + 6.2% to + 19.1% and + 0.7% to + 15.2% respectively.

B. DEPTH OF ENERGY PENETRATION

It was assumed that the heat penetration, caused by the coil of the induction heater, started at the outside of the stainless tube

and flowed inward. During the course of this study, the thermocouples on the O. D. of the stainless tube indicated a significantly lower temperature than the thermocouples on the I. D. of the stainless tube. After the test runs were completed, the asbestos cloth was removed and inspection of the test specimen showed that two of the five thermocouples had come loose from the O. D. of the stainless tube. This condition raised doubts as to the validity of any of the thermocouples on the O. D. of the stainless tube.

Another test was conducted to qualitatively determine where the transformation of electrical energy to thermal energy occured. A small solid steel cylinder was immersed in a beaker partially filled with water and the beaker was placed in the coil of the induction heater. The powerstat of the induction heater was adjusted until the water began to boil. The beaker of water had been placed on a balance scale so that the time to boil away a predetermined weight of water could be determined. The temperature on the inside of the steel cylinder was measured by means of a thermocouple located in the center of the cylinder at the midpoint along the axis of the cylinder. The inside temperature of the steel cylinder was assumed to remain constant. The temperature of the outside surface of the cylinder was assumed to be 212^{o}F. By knowing the time to boil away a given amount of water, the rate of internal energy generation was calculated by

$$Q = m\, h_{fg}$$

where m = rate of water boiled away and h_{fg} = the enthalpy of vaporazation of water. The volumetric energy release, assuming a uniform energy deposition rate, was calculated by dividing Q by the volume of the cylinder. The following equation was obtained from the works of

Carslaw and Jaeger. (6)

$$\Delta t = \frac{A_0 z (L-z)}{2K} - \frac{4L^2 A_0}{K\pi^3} \sum_{n=0}^{\infty} \frac{I_0[(2n+1)\pi r/L]}{(2n+1)^3 I_0[(2n+1)\pi/L]} \frac{\sin(2n+1)\pi z}{L} \quad (18)$$

A_0 = constant rate of heat production per unit volume

L = length of cylinder

z = distance between L = 0 and L

Δt = difference between outside and center temperatures

Using equation (18), the calculated temperature difference for the experimental run assuming a uniform heat generation was 14 F^o whereas the measured temperature difference was only 4 F^o. It was concluded from this comparison that the calculated temperature difference could possibly indicate that the energy transformation was far from a uniform volumetric process but rather a surface or near surface phenomenon. According to Osborn (7)

> "The magnetic lines of force which induce the flow of energy are more concentrated at the mid point of the width of the inductor (coil of the induction heater) and near its inside face. But the unusual characteristic of high frequency heating (1,000 cycles per second and above) upon which all surface hardening applications depend is its tendency to concentrate on the surface of the conductor through which it flows."

From the above statement by Osborn, it is concluded that energy transformation due to induction heating is a surface or near surface phenomenon at these frequencies and that the thermocouples on the O. D. of the stainless steel tube gave erroneous temperature readings

TABLE I

RECORDED DATA, LOW HEAT FLUXES

Run No.	Flow Lb/Hr	Water Temp. °F t(in)	t(out)	T_{21}	T_{19}	T_{17}	[illegible]face T[illegible] °F T_{15}	T_{11}	T_9	T_7	T_5	T_3
1-A	900	76.0	80.0	111	122	122	122	113	117	115	143	112
1-B	1200	76.0	79.0	103	112	110	110	106	106	108	135	104
1-C	1455	76.0	79.7	111	126	122	122	114	115	116	125	117
1-D	1590	76.6	80.1	114	131	124	126	118	122	116	-	116
1-E	1800	76.6	79.5	108	117	119	120	116	112	110	131	112

TABLE II

CALCULATED DATA, LOW HEAT FLUXES

Run No.	Q Btu/Hr	Heat Transfer Coefficients Btu/Hr-Ft^2-°F h	h_1	h_2	h_3	Avg. Water Temp. °F	Avg. Copper Tube Surface Temp. °F
1-A	3594	525	558	527	583	78.0	119.6
1-B	3593	666	692	638	710	77.5	110.4
1-C	5360	800	827	766	850	77.9	118.6
1-D	5550	800	885	823	910	78.3	120.8
1-E	5210	836	971	899	996	78.1	116.1

TABLE III

RECORDED DATA, HIGH HEAT FLUXES

Run	Flow	Water Temp. °F		Copper Tube Surface Temperatures °F								
No.	Lb/Hr	t(in)	t(out)	T_{21}	T_{19}	T_{17}	T_{15}	T_{11}	T_9	T_7	T_5	T_3
2-A	877.5	69.8	78.8	150	160	166	168	-	158	143	143	147
2-B	1070	71.7	76.5	121	132	133	133	125	126	118	115	121
2-C	1425	71.7	75.0	112	121	122	124	-	117	107	105	100
2-D	1635	71.7	74.8	100	120	120	121	-	117	107	107	108
2-E	1830	71.7	74.5	104	112	112	113	-	100	99	102	103

TABLE IV

CALCULATED DATA, HIGH HEAT FLUXES

Run No.	Q Btu/Hr	Heat Transfer Coefficients Btu/Hr-Ft^2-^{o}F h	h_1	h_2	h_3	Avg. Water Temp. ^{o}F	Avg. Copper Tube Surface Temp. ^{o}F
2-A	7900	601	592	553	605	74.3	154.4
2-B	5130	615	645	606	670	74.1	124.9
2-C	4690	713	789	729	813	73.4	113.5
2-D	5050	785	876	810	904	73.3	112.5
2-E	5100	958	940	870	968	73.1	105.6

Figure 6. Axial Temperature Distribution

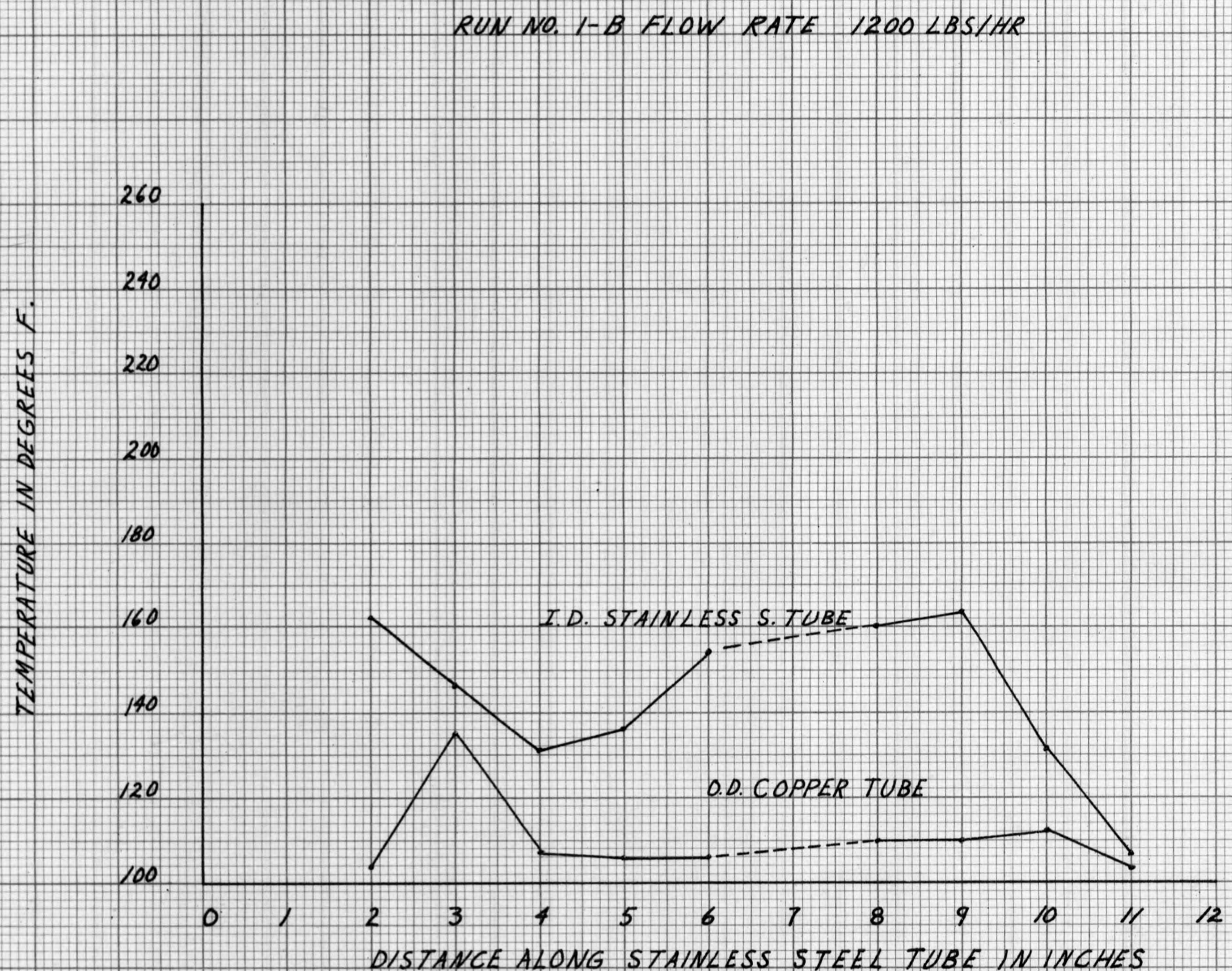


Figure 7. Axial Temperature Distribution

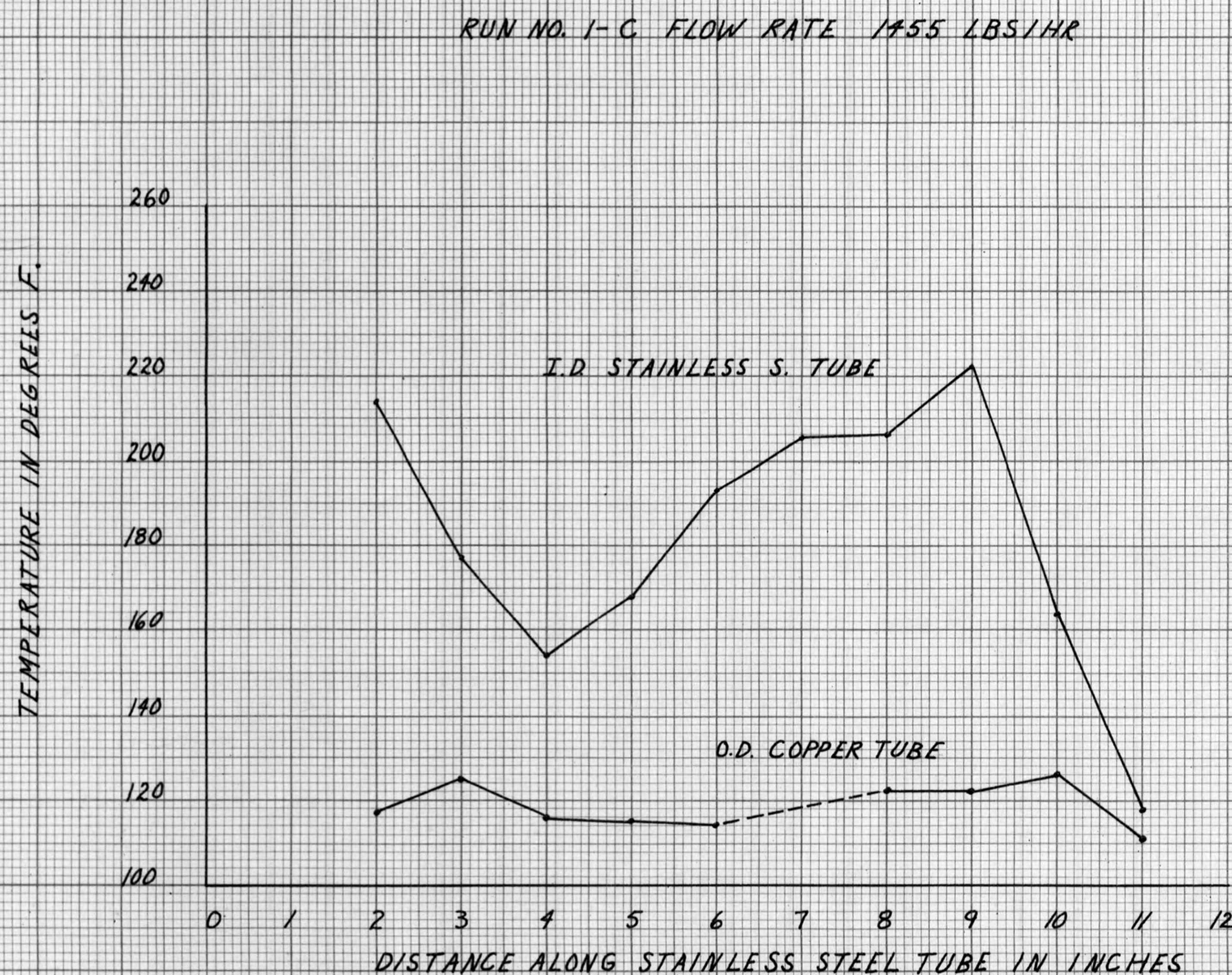


Figure 8. Axial Temperature Distribution

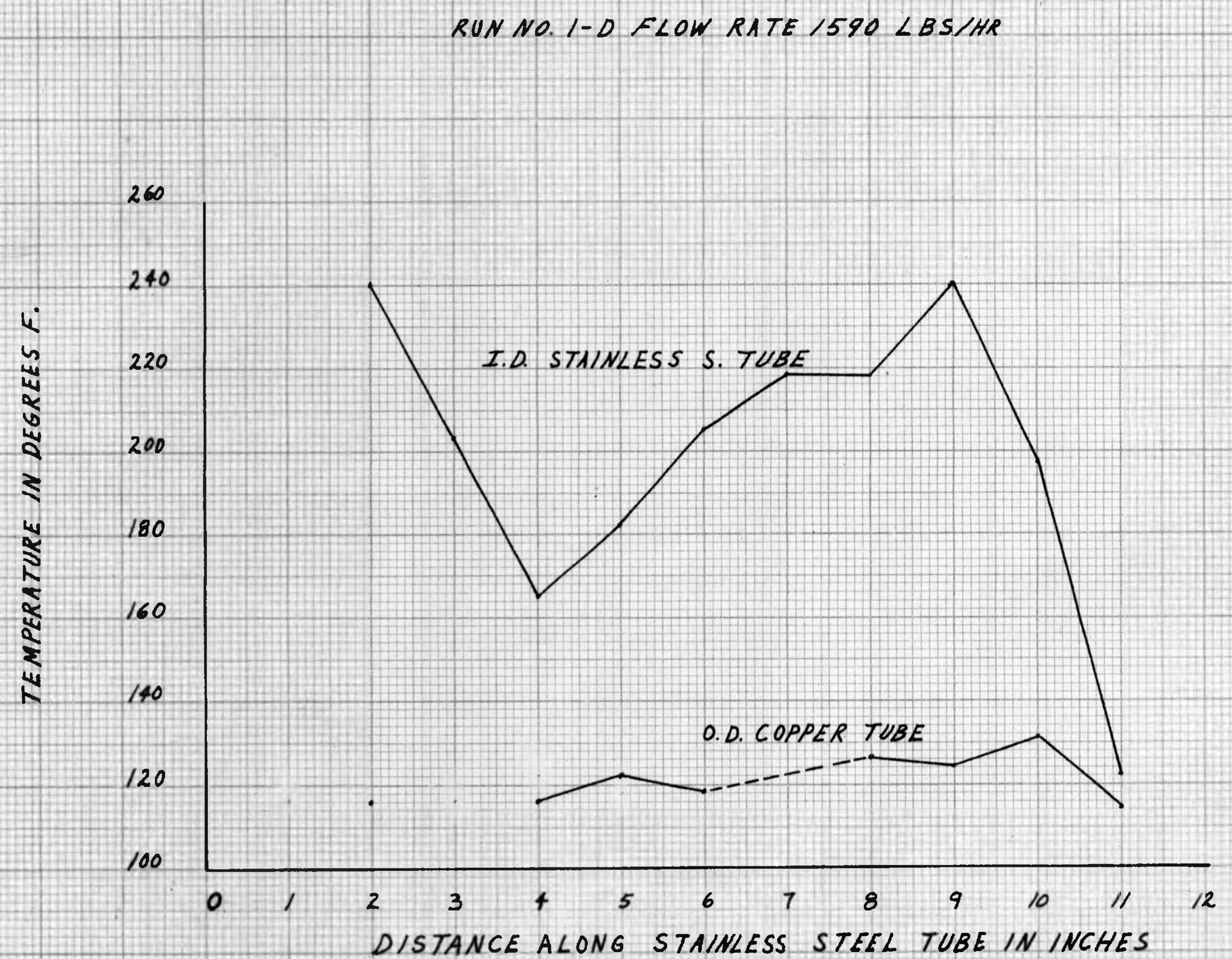


Figure 9. Axial Temperature Distribution

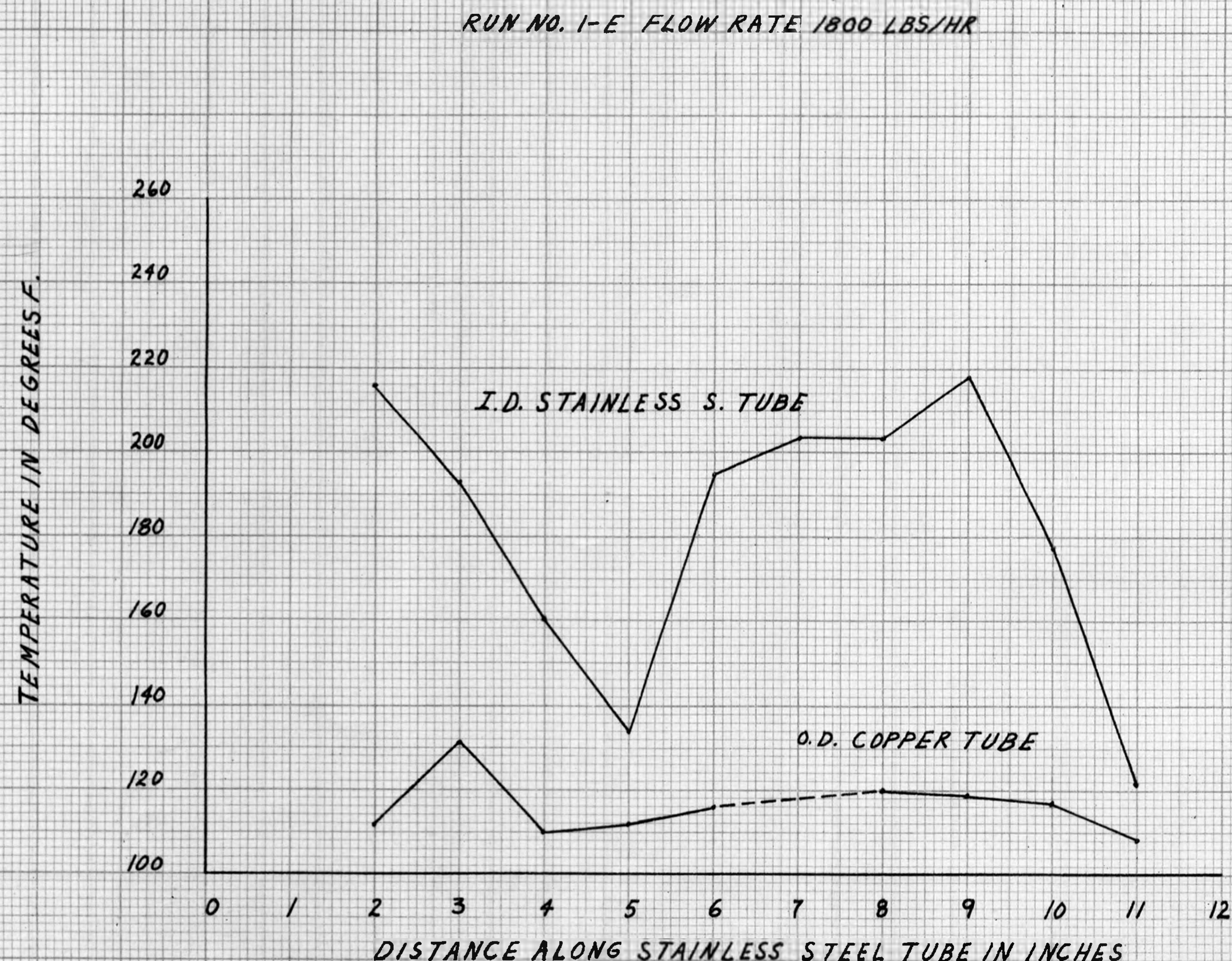


Figure 10. Axial Temperature Distribution

VI. CONCLUSIONS

The following conclusions were drawn from the results of this study.

A satisfactory correlation of experimental and empirical heat transfer coefficients can be obtained using the induction heater as the heat source without directly measuring the inside surface temperatures of the copper tube.

The results obtained from this study for the correlation of heat transfer coefficients compare satisfactorily with the results obtained by accepted heat transfer correlations.

It is concluded that the transformation of electrical energy to thermal energy in the test specimen is essentially a surface phenomenon.

REFERENCES

(1) BROWN, AUDREY I. and MARCO, SALVATORE M. (1958) Introduction to Heat Transfer. McGraw-Hill, New York, p. 2.

(2) SPROULL, ROBERT L. (1962) The Conduction of Heat in Solids. Scientific American, Vol. 207, p. 94.

(3) KERN, DONALD Q. (1950) Process Heat Transfer. McGraw-Hill, New York, p. 25.

(4) BROWN, AUDREY I. and MARCO, SALVATORE M. op. cit. p. 137.

(5) CURTIS, FRANK W. (1944) High-Frequency Induction Heating. McGraw-Hill, New York, p. 1.

(6) CARSLAW, H. S. and JAEGER, J. C. (1959) Conduction of Heat in Solids. Oxford, p. 223.

(7) OSBORN, H. B. Jr., BRACE, P. H., JOHNSON, W. G., CABLE, J. W., and EAGAN, T. E. (1946) Induction Heating. American Society for Metals, Cleveland, Ohio, p. 7.

VITA

The author was born on March 9, 1938 at Aurora, Missouri. He attended high school in Aurora, Missouri and graduated in May 1956.

In September of 1956, he enrolled at the Missouri School of Mines and Metallurgy and received the degree of Bachelor of Science in Mechanical Engineering in January 1961.

Upon graduation the author worked one and one-half years with Mueller Company as an assistant project engineer in their research department.

In September 1962, he enrolled in the Missouri School of Mines and Metallurgy as a graduate student in Mechanical Engineering and was appointed a Graduate Assistant in the Mechanical Engineering Department for the spring semester of 1963.