EQUIPMENT DESIGN TO MEASURE THE FILM COEFFICIENT

OF SUPERHEATED STEAM FLOWING

IN CONDUITS

by

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NOTATION

Symbols:	Description
N_{Nu}	Nusselt number = hd_e/k
N_{Re}	Reynolds number = $Vd_e\rho/\mu$
N_{Pr}	Prandtl number = $C_p\mu/k$
x	Distance from entrance to the point of film coefficient determination in a tube
De	Equivalent diameter
Δx	Incremental length of tube
$q'(x)$	Actual heat transferred to the fluid as a function at position x per unit length of tube
$q(x)$	Heat flow into the tube wall from an external heat source at position x per unit length of tube
q_2	Heat flowing into the element Δx at point x
q_3	Heat flowing out of the element Δx at point $x+\Delta x$
k	Thermal conductivity of the tube
A	Area of tube normal to tube axis
$(dt/dx)_x$	Temperature gradient in the tube in the x direction at point x
$(dt/dx)_{x+\Delta x}$	Temperature gradient in the tube in the x direction at the point $x+\Delta x$
$(d^2t/dx^2)_x$	The rate of change of temperature gradient at the point x
$Q(x)$	Heat added to a fluid flowing in a tube of length x
r_i	Inner radius of tube

L	Length of the tube
h	Film coefficient of the fluid flowing through a tube at the point x
t_s	Inner surface temperature of the tube at position x
t_f	Temperature of the fluid flowing through a tube at position x
t_{f_1}	Temperature of the fluid at the point of entrance to the tube
$\dot{m}$	Mass flow rate of the fluid
c_p	Specific heat of the fluid
dt_f/dx	Temperature gradient in the fluid at position x as it flows through the tube
V	Voltage drop along heater
I	Current flow in heater
Le	End loss term used to include losses due to axial conduction and by radiation
$t_{s_{x+\Delta x}}$	Inside tube surface temperature at point $x+\Delta x$
$t_{s_{x-\Delta x}}$	Inside tube surface temperature at point $x-\Delta x$
t_{s_x}	Inside tube surface temperature at point x
t_{os}	Outside surface temperature of tube
r_o	Outer radius of tube
$q'_a(x)$	Same as $q'(x)$
$q'_m(x)$	Measured heat input into the fluid as a function of tube length x
t_{f_2}	Temperature of the fluid leaving tube of length L

x_1	Point at the entrance to the tube of length L
x_2	Point at the exit of the tube of length L
$t_{f_{x+\Delta x}}$	Temperature of the fluid flowing in the tube at point $x+\Delta x$
$t_{f_{x-\Delta x}}$	Temperature of the fluid flowing in the tube at point $x-\Delta x$
Colburn Equation	$j = (N_{St})(N_{Pr})^{2/3} = 0.023\ (N_{Re})^{-0.2}$

I. INTRODUCTION

Evaluation of forced convection heat transfer to a fluid flowing in a conduit is a difficult problem to solve. All of the heat transferred to the fluid must pass through a stagnant film of fluid that adheres to the conduit wall. It can be shown from dimensional analysis that the film coefficient is dependent on the fluid properties and the geometric configuration of the conduit.

Most of the work done in this field of heat transfer has consisted of studies to determine values for this film coefficient and to develop a means of estimating values of the film coefficient from the dimension of the conduit and the physical properties of the fluid. There are two approaches that can be used to determine the values of the film coefficient: one is the analytical approach, and the other the experimental approach. The experimental method is normally used to prove or disprove the analytical results.

The purpose of this study is to propose a design of a test section to measure the heat transfer to supercritical and subcritical superheated steam flowing through circular tubes of different diameters. No attempt is made herein to actually determine values of the film coefficient or to develop a dimensionless equation to correlate these values. This study, however, includes derivations of several equations which will give values of film coefficient once experimental data has been obtained.

II. REVIEW OF LITERATURE

The determination of the heat transfer film coefficient of fluids in turbulent flow through conduits has been of interest for some years. In 1930, Dittus and Boelter (1) surveyed all the available data on fluids of low to medium viscosity and combined the data into two general dimensionless equations, which are:

$$N_{Nu} = 0.0243(N_{Re})^{0.8}(N_{Pr})^{0.4} \quad \text{(for heating)} \tag{1}$$

$$N_{Nu} = 0.0265(N_{Re})^{0.8}(N_{Pr})^{0.3} \quad \text{(for cooling)} \tag{2}$$

The physical properties are evaluated at the mean bulk temperature. These equations are to be used only for approximation purposes in design of heat exchangers.

McAdams (2) found from his investigations that the exponent on the Reynolds number remains close to 0.8. Using the results of Sherwood and Petrie (3), McAdams developed the following equation whose physical properties should be evaluated at the arithmetic mean bulk temperature:

$$N_{Nu} = 0.023(N_{Re})^{0.8}(N_{Pr})^{0.4} \tag{3}$$

This equation is to be used for gases and liquids with a viscosity not greater than twice that of water.

McAdams later revised equation (3) to fit that of Colburn and this revision changed the exponent on the Prandtl number to one-third, giving the following equation:

$$N_{Nu} = 0.023(N_{Re})^{0.8}(N_{Pr})^{1/3} \tag{4}$$

The fluid properties of the preceeding equation were evaluated at the film temperature and should be used for gases and liquids with viscosities not greater than twice that of water.

The two differences that can be noted between equations (4) and (3) are the exponent of the Prandtl number and the fact that the properties of the fluids are evaluated at different reference temperatures. Equation (4) henceforth shall be considered the basic equation for the film coefficient as this equation is the one most experimenters have obtained for the experimental data correlations.

In 1950, McAdams, Kennel, and Addoms (4) presented the first published paper on the determination of the heat transfer film coefficient of high-pressure, high-temperature steam. The first equation presented was:

$$N_{Nu} = 0.0126(N_{Re})^{0.89}(N_{Pr})^{1/3}(L/De)^{-0.13} \tag{5}$$

where the properties are evaluated at the film temperature.

There are several changes that can be noted from the basic equation (4); the coefficient is approximately half that in equation (4), the exponent on the Reynolds number is almost 11% higher, and another term, $(L/De)^{-0.13}$, is added to compensate for the fact that the velocity and temperature profiles were not fully developed near the entrance to the test section in this experiment. The $(L/De)^{-0.13}$ term approaches unity as the value of L/De becomes large.

To develop this equation, McAdams, et al. passed the steam through a vertical AISI type 303 stainless steel tube with an inner diameter of

0.383 inches. An electrical heating element was placed inside the tube, forming a thin annulus with an equivalent diameter of 0.131 inches through which passed the superheated steam. The steam entered at right angles to the test section and was almost immediately heated, thus giving no chance for the velocity profile to become fully developed until further along the test section.

As the outer wall was not heated, correction for heat transfer by radiation from the steam to this wall was taken into account. Since little work had been done up to that time on heat transfer from steam by radiation, most of the data used for this correction was extrapolated from existing data.

After McAdams, et al. had developed equation (5) using the Russian data for the thermal conductivity of steam, Keyes and Sandell (5) published a paper in 1950 containing new values for thermal conductivity which showed a large deviation from the Russian data. McAdams, et al. thereupon corrected equation (5) to conform to the new data of Keyes and Sandell. It was later shown by Norwak and Grosh (6) that the Russian data were more reliable, so that the first equation developed by McAdams, et al. is more correct.

Also in 1950, Govier and White (7) published a paper on heat and momentum transfer through steam. Their experiments were conducted on steam at 50 and 100 PSIA and at temperatures of 294-460° F. The equivalent diameter of the test section was 2.526 inches, which is several times larger than the equivalent diameter used by McAdams, et al. This paper closely substantiated the earlier equation developed by McAdams.

The equation developed by Govier and White was:

$$N_{Nu} = 0.022 \, (_{Re})^{0.8} (N_{Pr})^{0.4} \tag{6}$$

which is very close to McAdam's equation (3).

In the late 1950's, the power industry in this country started to use supercritical steam generating units. With the use of these units, it was necessary to be able to predict superheater tube-metal temperature in order to select the type of material to be used and the tube diameter. Thus, knowledge of the steam film heat transfer coefficient in the supercritical region became important. McAdams, <u>et al.</u> had run only a few points in the supercritical region, all at 3500 PSI and at temperatures above 890° F.

In 1957, Dickinson and Welch (8) presented a paper on the "Heat Transfer to Supercritical Water." Their tests were conducted in an AISI type 304 stainless steel tube having an inside diameter of 0.300 inches. This tube was heated by passing an electric current through it. The tube was in a horizontal position. The steam entered the test section parallel to the tube axis and an entrance section of sufficient length was used so that the velocity profile was fully developed. Correction was made for heat loss through the insulation covering the outside of the tube.

Dickinson and Welch found that below bulk temperatures of 660° F., equation (3), developed earlier by McAdams, fits the data within acceptable limits. As the supercritical properties of water are reliable only in the liquid region, it was felt by Dickinson and Welch that a dimensionless correlation using thermal conductivity and viscosity would not be advisable. Instead, a plot of film coefficient versus surface temperature was used as this gave the most consistent reproducibility of points.

At the surface temperature range of 750-850° F. and at pressures above critical, the film coefficient was found to be very large. As the surface temperature increased in the direction of flow, the film coefficient increased until the above mentioned temperature region was passed, and then started to decrease with increasing surface temperature. This was the case for all mass flows and pressures. Thus it can be concluded that the exact means of heat transfer in this range of surface temperature is not known. From a surface temperature of 800-1000° F., it was concluded by Dickinson and Welch that a constant Stanton number of 0.00189 can be used with an accuracy of 10% to predict the film coefficient.

A comparison was made by Dickinson and Welch between the dimensionless correlation of McAdams, <u>et al.</u>, the theoretical equations developed by Deissler (9) and Goldman (10) to predict the film coefficient, and results of the Dickinson and Welch investigation. The comparison showed that the values of the heat transfer film coefficient obtained by Dickinson and Welch were sometimes twice as large as those obtained by the use of the formulas developed by McAdams, <u>et al.</u>, Deissler, and Goldmann. The greatest deviation between the other three correlations and Dickinson and Welch's values were at a surface temperature of 800° F.

During the fifties, the nuclear reactor started to play an ever-increasing part in the generation of electrical power in this country. More and more power companies were starting to use this form of energy to produce electrical power. All of the early nuclear reactor power generators used a heat transfer loop between the reactor core and the steam generating unit. This heat transfer loop usually used sodium, high pressure water, or some other medium to transfer heat.

The idea to generate the superheated steam used in the turbine within the reactor core itself, and not in a separate unit, was advanced near the end of the fifties. This would reduce the amount of equipment necessary and the intermediate heat transfer loop. Because of the high heat fluxes that existed in nuclear reactors and the fact that superheated steam is a less effective medium to remove heat from the nuclear reactors than the conventional mediums, more research was necessary on steam film heat transfer coefficient to be sure burn-out conditions would not develop in the reactor from lack of heat removal.

In September 1960, Heineman (11) presented a paper on heat transfer to superheated steam. His experiments were conducted using both tubes and rectangular channels. The tube was an AISI type 304 stainless steel tube with a 0.333 inch inner diameter. The rectangular test section was made of AISI type 304 stainless steel plates formed to give a configuration 1.25 by 0.047 inches on the inside. There was an unheated entrance length for the tube of 16 equivalent diameters and 13 equivalent diameters for the rectangular duct. Both of the test sections were set in a vertical position.

From the data obtained, Heinemann developed the following equations:

$$N_{Nu} = 0.0157(N_{Re})^{0.84}(N_{Pr})^{1/3}(L/De)^{-0.04} \quad \text{for } (6 < L/De < 60) \tag{7}$$

and

$$N_{Nu} = 0.0133\ (N_{Re})^{0.84}(N_{Pr})^{1/3} \quad \text{for } (L/De > 60) \tag{8}$$

All fluid properties are to be evaluated at the film temperature. These equations were developed from the experimental data obtained.

No apparent difference was noted by Heinemann between the film coefficient of the rectangular duct and the tube for $L/De > 60$. Thus the equation (8) can be used with both rectangular ducts and tubes. The equation (7) should be used only for tubes.

Although there was a difference between the coefficient and the exponent values in the equations of McAdams, et al. and Heinemann, Heinemann stated that this was probably due to the fact of the difference in the unheated entrance section used by him and that used by McAdams, et al. With this allowance, Heinemann stated that his experimental data substantiates the work of McAdams, et al. within $\pm 5\%$.

It can be seen that the coefficient and the exponent on the Reynolds number in both equations (8) and (9) are different from those of the basic equation (4), but closer than the same terms in equation (5), developed by McAdams, et al.

At the 1961-1962 Heat Transfer Conference, J. C. Collier and P. M. C. Lacey (12) presented a paper on "Heat Transfer to High Pressure Superheated Steam in an Annulus." Their experiment was conducted in an annulus with an inner diameter of 0.375 inches and an outer diameter of 0.553 inches with the test section held in a vertical plane and the steam passing from bottom to top. Only the inner tube was heated, as in the McAdams, et al. experiment, and had a traveling thermocouple within. There was an unheated entrance section of L/De = 18.2.

Two tests were run with the steam pressure fixed at 20 PSIA but with equivalent diameter different for each test. Another test was conducted with the same equivalent diameter as one of those used during the low pressure runs for a pressure range from 155 to 1075 PSIA.

When the authors combined all their data into a dimensionless equation, the results obtained were:

$$N_{Nu} = 0.0058\,(N_{Re})^{0.945}(N_{Pr})^{1/3}(L/De)^{-0.1} \qquad (9)$$

or

$$N_{Nu} = 0.0035\,(N_{Re})^{0.945}(N_{Pr})^{1/3}(1+4.56De/L) \qquad (10)$$

where the properties are evaluated at the film temperature for both of these equations.

The authors stated that these equations were "offered with some reservations, because the slope for intermediate values of L/De are heavily weighted by the low pressure results, which were at the lower Reynolds number."[1/]

1/ Collier, J.G. and Lacey, R.M.C., "Heat Transfer to High Pressure Superheated Steam in an Annulus," International Developments in Heat Transfer, Part II, No. 40, p. 361.

For interest, it is noted that the coefficient and the exponent on the Reynolds number show a large deviation from the values of the basic equation (4). There is also the addition of the L/De correction term.

Collier and Lacey then made other correlations of dimensionless parameters using only the high pressure steam results and arriving at the following equations:

$$N_{Nu} = 0.0357\ (N_{Re})^{0.8}(N_{Pr})^{1/3}(L/De)^{-0.1} \tag{11}$$

or

$$N_{Nu} = 0.0208\ (N_{Re})^{0.8}(N_{Pr})^{1/3}(1\ 8.97De/L')$$

$$\text{where: } L' = L+12De \tag{12}$$

The properties are evaluated at the film temperature.

The author pointed out there is very little difference between the two equations mentioned above. This time the only difference from the basic equation (4) is in the coefficient and the addition of the correction term for the entrance effect. Notice also that the coefficient is very close to that of the basic equation (4).

Collier and Lacey also showed that the results of Heinemann and McAdams, <u>et al.</u> correlations are close to collinear despite the fact of the difference in the Reynolds number and geometry. The results of Collier and Lacey closely substantiate the work of McAdams, <u>et al.</u> and Heinemann.

Collier and Lacey further showed that at lower Reynolds numbers the results deviated from Colburn's equation for tubes but came into closer agreement at higher Reynolds number.

Neusen, Kangas, and Shar (13) presented a paper at the fifth National Heat Transfer Conference in August 1962, titled "Heat Transfer to Superheated Steam in a Thin Annulus."

This paper was the result of experimental work conducted to determine whether or not the classical Nusselt number and friction factor correlations could be used for the annular flow passages of the Pathfinder Atomic Power Plant which would use an integral nuclear superheater.

The equivalent diameter was 0.1046 inches at room temperature and 0.1056 inches at 1000° F. The temperature range was approximately 731° F. while the pressure variation was held to within 520-615 PSIA. Therefore, the pressure range of this paper was not as great as with previous papers. The big difference between this work and previously presented papers was that both the inner and outer tubes were heated so as to simulate conditions within the fuel core of the reactor as closely as possible. There was a long unheated entrance section used in the experiment, therefore giving enough time for the velocity profile to develop so that there would be no discernible effect of L/De on the heat transfer film coefficient. As the gap between the inner and outer walls of the annulus was small and the inner diameter large, Neusen, *et al.* felt that this annulus should approach the case of parallel plates with equal film coefficients. The experimental results showed that this assumption was correct.

There were no correlations developed in this paper for the Nusselt number, as done in the earlier papers. Instead, the authors used the correlation proposed by Heinemann for $L/De > 60$. The experimental results supported Heinemann's correlation within $\pm 15\%$.

It can be noted from the above reviewed literature that in all cases the exponent on the Prandtl number was assumed to be constant at either 0.4 or one-third, the latter being preferred.

The coefficient and the exponent on the Reynolds number were then determined by the experimental data obtained in each experiment.

In both cases where the exponent on the Prandtl number was assumed to be 0.4, the correlations for the coefficient and the exponent on the Reynolds number agreed within acceptable limits with equations (3) of McAdams.

In all cases where the exponent on the Prandtl number was assumed to be one-third, the coefficient does not agree with that recommended by equation (4). Only Collier and Lacey were able to approach the recommended coefficient by manipulation of the L/De correction term. The exponent on the Reynolds number was always higher for this same case except for the third and fourth correlation of Collier and Lacey, when the exponent was equal to that recommended by McAdams in equation (4).

III. DERIVATION OF EQUATIONS

Introduction

It is obvious from the review of literature that more work and study is necessary on heat transfer to superheated steam. Although some of the results obtained by the experimenters in this field agree with each other within the acceptable limits of experimental accuracy, there remains a great deal of work yet to be done.

There are several equations that should be derived to give a better understanding of the problem that faces an investigator in this particular area of heat transfer.

Heat Transfer Equation

The first equation that is necessary is one that will give an accurate value for the amount of heat transferred to the superheated steam as it flows through the tube.

Figure 1 shows the tube through which passes the steam. The wavy arrows are used to represent heat input per unit length to the tube as a function of its length. The segment Δx represents a small element of the tube.

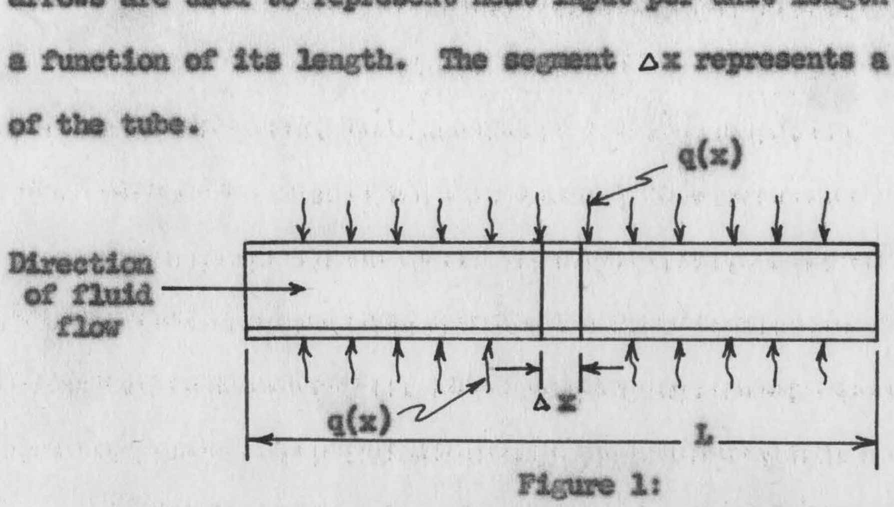


Figure 1:

SKETCH OF A TUBE SHOWING HEAT INPUT NOTATION

Figure 2 shows an enlargement of the element Δx of the tube. This sketch shows the positive direction of heat flow into and out of this element.

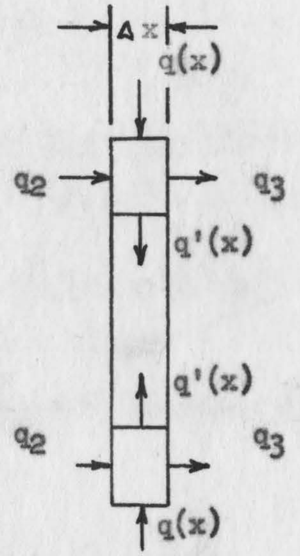


Figure 2.

ENLARGED VIEW OF ELEMENT Δ X FROM FIGURE 1

The term $q'(x)$ is the actual value of heat that is added to the fluid per unit length as it flows through element Δx.

By summing the heat flow into and out of the tube element in Figure 2, the following result is obtained:

$$q(x)\Delta x + q_2 = q'(x)\Delta x + q_3 \qquad (13)$$

Equation (13) can now be solved for $q'(x)\Delta x$ yielding the following equation:

$$q'(x)\Delta x = q(x)\Delta x + q_2 - q_3 \qquad (14)$$

The quantity q_2 of equation (14) can be written as:

$$q_2 = - kA \left(\frac{dt}{dx}\right)_x \tag{15}$$

The quantity q_3 of equation (14) can be written as:

$$q_3 = - kA \left(\frac{dt}{dx}\right)_{x+\Delta x} \tag{16}$$

Equations (15) and (16) for q_2 and q_3 respectively are now substituted into equation (14) with the following result:

$$q'(x)\Delta x = q(x)\Delta x - kA \left(\frac{dt}{dx}\right)_x + kA \left(\frac{dt}{dx}\right)_{x+\Delta x} \tag{17}$$

Collection of like terms and dividing through by Δx yields the following:

$$q'(x) = q(x) + \frac{kA}{\Delta x}\left[\left(\frac{dt}{dx}\right)_x \quad x - \left(\frac{dt}{dx}\right)_x\right] \tag{18}$$

The $\left(\frac{dt}{dx}\right)_{x+\Delta x}$ term of equation (18) should be evaluated so as to simplify equation (18). The Mean Value Theorem is one means by which the evaluation can be performed. The statement of this theorem is the following:

$$f\,(x+\Delta x) = f\,(x) + \left[\frac{d}{dx} \quad \left|f(x)\right|\right]_M \cdot \Delta x \tag{19}$$

By letting:

$$f\,(x+\Delta x) = \left(\frac{dt}{dx}\right)_{x+\Delta x}$$

and

$$f\,(x) = \left(\frac{dt}{dx}\right)_x$$

the following is obtained:

$$\left(\frac{dt}{dx}\right)_{x+\Delta x} = \left(\frac{dt}{dx}\right)_{x} + \left[\frac{d}{dx}\left(\frac{dt}{dx}\right)\right]_{M} \cdot \Delta x \qquad (20)$$

which is also equal to:

$$\left(\frac{dt}{dx}\right)_{x+\Delta x} = \left(\frac{dt}{dx}\right)_{x} + \left(\frac{d^2t}{dx^2}\right)_{M} \cdot \Delta x \qquad (21)$$

Substituting equation (21) into equation (18) yields:

$$q'(x) = q(x) + \frac{kA}{\Delta x}\left[\left(\frac{dt}{dx}\right)_{x} + \left(\frac{d^2t}{dx^2}\right)_{M} \cdot \Delta x - \left(\frac{dt}{dx}\right)_{x}\right] \qquad (22)$$

which is also equal to:

$$q'(x) = q(x) + kA\left(\frac{d^2t}{dx^2}\right)_{M} \qquad (23)$$

By taking the limit of equation (23) as $\Delta x \rightarrow 0$, M approaches x and the following results:

$$q'(x) = q(x) + kA\left(\frac{d^2t}{dx^2}\right)_{x} \qquad (24)$$

Equation (24) now gives a relation that will enable an investigator to calculate the heat, as a function of the tube length, that is actually transferred to the fluid from a heat source outside the tube wall, if the wall temperature distribution is known.

Film Coefficient Equations

Another equation that is necessary is one that will give the film coefficient from measured experimental data. There are several film coefficient equations and these equations can be developed in the following manner:

The heat that is added to a fluid flowing in a tube of length x can be obtained from the following expression:

$$Q(x) = 2\pi r_i \int_{x_1}^{x} h(x) \left[t_s(x) - t_f(x) \right] dx \tag{25}$$

The derivative of equation (25) with respect to tube length x yields an equation which gives heat input to the fluid as a function of tube length:

$$\frac{dQ}{dx} = 2\pi r_i\, h(x) \left[t_s(x) - t_f(x) \right] \tag{26}$$

As the term $q'(x)$ has been previously defined as the heat input to the fluid per unit of tube length, the following holds:

$$q'(x) = 2\pi r_i\, h\, (t_s - t_f) \tag{27}$$

As the radius of the tube normally is constant throughout its length, the quantity $2\pi r_i$ can be replaced by the quantity:

$$C_1 = 2\pi r_i \tag{28}$$

Substituting equation (28) into equation (27) yields the following:

$$q'(x) = C_1\, h\, (t_s - t_f) \tag{29}$$

First Equation

From equation (29) several equations for the film coefficient can be obtained. The first is obtained by dividing both sides of equation (29) by $C_1\ (t_s - t_f)$, which yields the following:

$$h = \frac{q'(x)}{C_1\ (t_s - t_f)} \tag{30}$$

This equation is one that is commonly found in the literature with the exception that $q'(x)$ is normally heat flux and the term C_1 is not included. Equation (30) requires measuring only three variables: the surface temperature, the fluid temperature, and the heat input to the fluid at the point x where the film coefficient is to be determined.

Second Equation

The second equation is obtained by the following substitution. We note that

$$t_f(x) = t_{f_1} + \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\ C_p} \tag{31}$$

It is assumed that the specific heat, C_p, is constant over the temperature change occurring in the fluid as it flows through the tube. Substitution of equation (31) into equation (30) yields the following result, which is the second equation for the film coefficient:

$$h = \frac{q'(x)}{C_1\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\ C_p}\right)} \tag{32}$$

If this second equation (32) is used instead of the first equation (30) to determine the value of the film coefficient, one more variable must be measured, which is the mass flow. The fluid temperature need only be measured at the inlet when using equation (32), and not throughout the tube length, as would be the case when using equation (30).

Third Equation

The third equation can be obtained in the following manner:

An expression for the incremental heat transferred to the fluid as it moves through an element dx of the tube is:

$$\frac{dQ}{dx} = \dot{m}\, C_p \, \frac{dt_f}{dx} \qquad (33)$$

Since the term $q'(x)$ has been previously defined as the heat input to the fluid per unit of tube length, the following is true:

$$q'(x) = \dot{m}\, C_p \, \frac{dt_f}{dx} \qquad (34)$$

By substituting equation (34) into equation (30) the third and final equation for the film coefficient is obtained:

$$h = \frac{\dot{m}\, C_p}{C_1} \cdot \frac{dt_f/dx}{(t_s - t_f)} \qquad (35)$$

When using the equation (35) it is not necessary to measure the heat input to the fluid but instead its mass flow rate must be measured. The fluid temperature must again be measured at points along the tube axis, as with equation (30).

Any one of the three equations, (30), (32), or (35) can be used to determine the film coefficient by measurement of the necessary quantities. Which equation of this group will give the most accurate results can be determined by making an error analysis of each of these three equations.

IV. ERROR ANALYSIS OF THE THREE EQUATIONS DEVELOPED FOR THE FILM COEFFICIENT

Introduction

Before any of the three equations developed for the film coefficient are used to determine a value for the film coefficient, an error analysis should be made on each of these three equations. This error analysis can be helpful during the design of the test section to be used to measure the film coefficient. The analysis can help in deciding where to place thermocouples, materials to be used in the construction, heater design, and the general geometry of the test section. The analysis will also help to indicate the degree of accuracy required for each measurement. The analysis should further show which of the three equations derived in Chapter III will give the most accurate value of the film coefficient.

Thus, it can be seen that the error analysis is a most necessary and important part of the design of the test section and the running of the experiment.

The total error that can result when using equations (30), (32), or (35) to determine the film coefficient is the sum of errors in measuring each of the quantities in the equations (30), (32), and (35). One method to estimate the value of these measurement errors is to take the differential of each measured quantity in the equations and then divide through by the original equation. This method will result in the relative error in the film coefficient. As the measurement error of each quantity can be either positive or negative, the absolute value of each error quantity should be taken to give the maximum error that can possibly exist.

First Error Equation

The first equation that was obtained for the film coefficient was:

$$h = \frac{q'(x)}{C_1\,(t_s - t_f)} \tag{36}$$

An error analysis of this equation can be made in the following manner:

The error that can be expected in film coefficient from use of equation (36) is:

$$dh = \frac{dq'(x)}{C_1\,(t_s - t_f)} - \frac{q'(x)\,dC_1}{C_1^2\,(t_s - t_f)} - \frac{q'(x)d\,(t_s - t_f)}{C_1\,(t_s - t_f)^2} \tag{37}$$

The letter "d" denotes the differential of the quantity which follows it, and in the limit is equal to the error in that quantity.

The relative error that can be expected in the film coefficient from use of equation (36) is obtained upon dividing equation (37) by equation (36), which yields the following:

$$\frac{dh}{h} = \frac{dq'(x)}{q'(x)} - \frac{dC_1}{C_1} - \frac{dt_s}{(t_s - t_f)} + \frac{dt_f}{(t_s - t_f)} \tag{38}$$

Each of the error quantities, dq', dC_1, dt_s, and dt_f in equation (38) can have one or more error terms associated with it as more than one measured variable may be necessary to determine the value of the quantity. To determine the actual value of the error in the film coefficient, each of the error terms in equation (38) must be evaluated further so that all variables are taken into consideration.

The evaluation of $dq'(x)/q'(x)$ in equation (38) can be performed by using the following method:

The quantity $q'(x)$ has previously been defined as

$$q'(x) = q - kA\frac{d^2t_s}{dx^2} \quad 2/ \tag{39}$$

The quantity q in equation (39) is obtained as follows:

$$q = 3.413\ VI - L_e \tag{40}$$

By substituting equation (40) into equation (39) the following is the amount of heat absorbed by the fluid per foot of tube length:

$$q'(x) = 3.413\ VI - kA\frac{d^2t_s}{dx^2} - L_e \tag{41}$$

The errors expected in q' can be found by performing the following operation on equation (41):

$$dq'(x) = 3.413\ IdV \quad 3.413\ VdI - A\frac{d^2t_s}{dx^2}dk - k\frac{d^2t_s}{dx^2}dA$$

$$- kAd\left(\frac{d^2t_s}{dx^2}\right) - dL_e \tag{42}$$

2/ See equation (24), page 25.

The relative error in $q'(x)$ can be found by dividing equation (42) by $q'(x)$ and by multiplying and dividing each term on the right-hand side of equation (42) by the variable which is in error. This results in the following:

$$\frac{dq'(x)}{q'(x)} = \frac{3.413\ VI}{q'(x)}\left(\frac{dV}{V}\right) + \frac{3.413\ VI}{q'(x)}\left(\frac{dI}{I}\right) - \frac{kA}{q'(x)}\cdot\frac{d^2t_s}{dx^2}\left(\frac{dk}{k}\right)$$

$$- \frac{kA}{q'(x)}\cdot\frac{d^2t_s}{dx^2}\left(\frac{dA}{A}\right) - \frac{kA}{q'(x)}\cdot\frac{d^2t_s}{dx^2}\left(\frac{d\left(\frac{d^2t}{dx^2}\right)}{\frac{d^2t}{dx^2}}\right) - \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right) \qquad (43)$$

Collecting like terms in equation (43) results in the following:

$$\frac{dq'(x)}{q'(x)} = \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] - \frac{kA}{q'(x)}\cdot\frac{d^2t_s}{dx^2}\left[\frac{dk}{k} + \frac{dA}{A} + \frac{d\left(\frac{d^2t_s}{dx^2}\right)}{\frac{d^2t_s}{dx^2}}\right]$$

$$- \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right) \qquad (44)$$

None of the relative error terms in equation (44) need further evaluation except for the term $d\left(\frac{d^2t_s}{dx^2}\right)\Big/\frac{dt_s}{dx}$. The evaluation of this term can be made using the following approximation:

$$\frac{d^2t_s}{dx^2} = \frac{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}}{(\Delta x)^2} \qquad (45)$$

To find the expected errors in equation (45), the following operation is performed:

$$d\left(\frac{d^2t_s}{dx^2}\right) = \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{(\Delta x)^2}$$

$$-\left[t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}\right] \cdot \frac{2\Delta x d(\Delta x)}{(\Delta x)^4} \qquad (46)$$

The relative error in equation (46) is obtained by dividing it by equation (45). The result is:

$$\frac{d\left(\frac{d^2t_s}{dx^2}\right)}{\frac{d^2t_s}{dx^2}} = \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x} \qquad (47)$$

Equation (47) may now be substituted into equation (44) giving the results below:

$$\frac{dq'(x)}{q'(x)} = \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] - \frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx^2}\left[\frac{dk}{k} + \frac{dA}{A}\right.$$

$$\left. + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x}\right] - \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right) \qquad (48)$$

The evaluation of the dC_1/C_1 term of equation (38) can be performed by the following method:

The term C_1 of equation (36) was previously defined as:

$$C_1 = 2\pi r_1 \qquad (49)$$ 3/

3/ See equation (28), page 26.

The only possible error that can exist in term C_1 is due to inaccuracy in measuring the inner radius of the tube. Therefore, it can be readily seen that:

$$\frac{dC_1}{C_1} = \frac{dr_i}{r_i} \tag{50}$$

Evaluation of the next term in equation (38), $dt_s/(t_s-t_f)$, can be done by the following method:

The quantity, t_s, is the temperature of the tube surface along the inner wall. To measure this temperature directly appears an almost impossible task without introducing a large error. Thus, the variable, t_s, is obtained by using the following formula:

$$t_s = t_{os} - \frac{q'(x) \ln (r_o/r_i)}{2\pi k} \tag{51}$$

The error that can be expected when equation (51) is used to find the variable t_s is:

$$dt_s = dt_{os} - \frac{dq'(x) \ln (r_o/r_i)}{2\pi k} + \frac{q'(x) \ln (r_o/r_i)\, dk}{2\pi k^2}$$

$$- \frac{q'(x) d\left(\ln (r_o/r_i)\right)}{2\pi k} \tag{52}$$

By multiplying and dividing the last three terms of equation (52) by the variables that are in error in each of the terms and collecting like terms, the following result is obtained:

$$dt_s = dt_{os} + \frac{q'(x) \ln (r_o/r_i)}{2\pi k}\left[\frac{dk}{k} - \frac{dq'(x)}{q'(x)} - \frac{d(\ln (r_o/r_i)\ )}{\ln (r_o/r_i)}\right] \tag{53}$$

The relative error in the $dq'(x)/q'(x)$ term has been previously evaluated and is presented by equation (48). The error associated with the last term in equation (53) can be neglected without undue error resulting because of its omission. Thus, by substituting equation (48) into equation (53) the following is the result for the expected error in the dt_s term in equation (38):

$$dt_s = dt_{os} + \frac{q'(x) \ln (r_o/r_i)}{2\pi k}\left\{\frac{dk}{k} - \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right]\right.$$

$$+ \frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx^2}\left[\frac{dk}{k} + \frac{dA}{A} + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}}\right.$$

$$\left.\left. - \frac{2d(\Delta x)}{\Delta x}\right] + \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right)\right\} \tag{54}$$

Evaluation of the dt_f term of equation (38) need not be carried further as the variable, t_f, can be determined directly from a thermocouple reading and no intermediate equation is necessary to determine its final value.

All the error terms in equation (38) have now been evaluated in equations (48), (50), and (54). By substituting these equations into equation (38), the following result is obtained:

$$\frac{dh}{h} = \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] - \frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx^2}\left[\frac{dk}{k} + \frac{dA}{A}\right.$$

$$\left. + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x}\right] - \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right)$$

$$- \frac{dr_i}{r_i} - \frac{dt_{os}}{t_s - t_f} - \frac{q'(x) \ln (r_o/r_i)}{2\pi k\ (t_s - t_f)}\left\{\frac{dk}{k} - \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right]\right.$$

$$+ \frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx^2}\left[\frac{dk}{k} + \frac{dA}{A} + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x}\right]$$

$$\left. + \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right)\right\} + \frac{dt_f}{t_s - t_f} \tag{55}$$

Combining like terms in equation (55) gives:

$$\frac{dh}{h} = \left[1 + \frac{q'(x) \ln (r_o/r_i)}{2\pi k\ (t_s - t_f)}\right]\left\{\frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] - \frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx^2}\left[\frac{dA}{A}\right.\right.$$

$$\left.\left. + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x}\right] - \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right)\right\} - \frac{dr_i}{r_i}$$

$$- \frac{dt_{os}}{t_s - t_f} + \frac{dt_f}{t_s - t_f} - \frac{dk}{k}\left\{\frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx^2} + \frac{q'(x) \ln (r_o/r_i)}{2\pi k\ (t_s - t_f)}\left[1 + \frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx^2}\right]\right\} \tag{56}$$

The absolute value of equation (56) will now be taken so that the maximum expected error can be determined when equation (36) is used to evaluate the film coefficient. It will be assumed further that the only existing error in the temperature error terms, e.g. dt_{os}, etc., will be that of thermocouple inaccuracy. Further, the term Δx is taken to be equal to the distance between thermocouples. Therefore, the results obtained when the absolute value of equation (56) is taken are:

$$\frac{|dh|}{h} \leqq \left[1 + \frac{q'(x)\ \ln (r_o/r_i)}{2\pi k\ (t_s - t_f)}\right]\left\{\frac{3.413\ VI}{q'(x)}\left[\frac{|dV|}{V} + \frac{|dI|}{I}\right] + \frac{kA}{q'(x)} \cdot \left|\frac{d^2 t_s}{dx^2}\right| \cdot \left[\frac{|dA|}{A} + \frac{4\,|dt_s|}{\left|t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2dt_{s_x}\right|} + \frac{2\,|d(\Delta x)|}{\Delta x}\right] + \frac{L_e}{q'(x)} \cdot \frac{|dL_e|}{L_e}\right\} + \frac{|dr_i|}{r_i}$$

$$+ \frac{|dt_{os}|}{(t_s - t_f)} + \frac{|dt_f|}{(t_s - t_f)} + \frac{|dk|}{k}\left\{\frac{kA}{q'(x)} \cdot \left|\frac{d^2 t_s}{dx^2}\right| + \frac{q'(x)\ \ln (r_o/r_i)}{2\pi k\ (t_s - t_f)}\left[1 + \frac{kA}{q'(x)} \cdot \left|\frac{d^2 t_s}{dx^2}\right|\right]\right\} \qquad (57)$$

Equation (57) can now be used to obtain the magnitude of the error estimate for equation (36) under assumed operating conditions. The term $\frac{d^2 t_s}{dx^2}$ in equation (57) is given by equation (45).

<u>Second Error Equation</u>

The error evaluation of the second equation developed for the film coefficient can now be undertaken. This equation is:

$$h = \frac{q'(x)}{C_1 \left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\ C_p}\right)} \qquad (58)$$

The error that can be expected in the film coefficient when equation (58) is used is:

$$dh = \frac{dq'(x)}{C_1\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)} - \frac{q'(x)dC_1}{C_1^2\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)}$$

$$- \frac{q'(x)dt_s}{C_1\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)^2} + \frac{q'(x)dt_{f_1}}{C_1\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)^2}$$

$$+ \frac{q'(x)d\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)}{C_1\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)^2} \qquad (59)$$

The relative error existing in the film coefficient from use of equation (58) can be found by dividing equation (59) by equation (58). This yields the following results:

$$\frac{dh}{h} = \frac{dq'(x)}{q'(x)} - \frac{dC_1}{C_1} - \frac{dt_s}{\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)}$$

$$+ \frac{dt_{f_1}}{\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)} + \frac{d\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)}{\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\,C_p}\right)} \qquad (60)$$

The $dq'(x)/q'(x)$, dC_1/C_1 and the dt_s terms of equation (60) have been previously evaluated in equations (48), (50), and (54) respectively; thus no further evaluation is necessary. The dt_{f_1} term of equation (60) need not be evaluated further. This variable can be determined directly from a thermocouple reading and does not need an intermediate equation to determine its value. The only term in equation (60) which needs further evaluation is the last term on the right-hand side, $d\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)$. The evaluation of this term can be made in the following manner:

The errors that can be expected from use of this term are:

$$d\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right) = \frac{d\left(\int_{x_1}^{x} q'(x)dx\right)}{\dot{m}\, C_p} - d\dot{m}\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right) - dC_p\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right) \qquad (61)$$

The right-hand side of the above equation can be multiplied and divided by the quantity $\int_{x_1}^{x} q'(x)dx$; this yields the following result:

$$d\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right) = \left[\frac{d\left(\int_{x_1}^{x} q'(x)dx\right)}{\int_{x_1}^{x} q'(x)dx}\right] \cdot \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p} - \left[\frac{d\dot{m}}{\dot{m}} + \frac{dC_p}{C_p}\right] \cdot \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p} \qquad (62)$$

The quantity $d\int_{x_1}^{x} q'(x)dx$ in equation (62) can be evaluated in the following manner:

$$d\int_{x_1}^{x} q'(x)dx = \int_{x_1}^{x} q'_a(x)dx - \int_{x_1}^{x} q'_m(x)dx \qquad (63)$$

It can be readily seen from equation (63) that the following is true:

$$d\left(\int_{x_1}^{x} q'(x)dx\right) = \int_{x_1}^{x} d(q'(x))dx \qquad (64)$$

Substituting equation (64) into equation (62) yields the following:

$$d\left(\frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right) = \left[\frac{\int_{x_1}^{x} d(q'(x))dx}{\int_{x_1}^{x} q'(x)dx}\right] \cdot \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}$$

$$- \left[\frac{d\dot{m}}{\dot{m}} + \frac{dC_p}{C_p}\right] \cdot \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p} \qquad (65)$$

All of the error terms in equation (60) have been fully evaluated. Each of the equations (48), (50), (54), and (65) for the individual error terms can now be substituted into equation (60), yielding the following:

$$\frac{dh}{h} = \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] - \frac{kA}{q'(x)}\frac{d^2t_s}{dx^2}\left[\frac{dk}{k} + \frac{dA}{A} + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}}\right.$$

$$\left. - \frac{2d(\Delta x)}{\Delta x}\right] - \frac{L_e}{q'(x)} \cdot \frac{dL_e}{L_e} - \frac{dr_i}{r_i} - \frac{dt_{os}}{\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)}$$

$$- \frac{q'(x)\ \ln\,(r_o/r_i)}{2\pi k\left(t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)} \cdot \left\{\frac{dk}{k} - \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] + \frac{kA}{q'(x)} \cdot \frac{d^2t_s}{dx}\left[\frac{dk}{k}\right.\right.$$

$$\left.\left. + \frac{dA}{A} + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x}\right] + \frac{L_e}{q'(x)}\left(\frac{dL_e}{L_e}\right)\right\}$$

$$+ \frac{dt_{f_1}}{\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)}$$

$$+ \frac{1}{\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)} \cdot \left\{ \frac{\int_{x_1}^{x} d(q'(x))dx}{\dot{m}\, C_p} - \left[\frac{d\dot{m}}{\dot{m}} + \frac{dC_p}{C_p}\right] \cdot \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p} \right\} \qquad (66)$$

The like terms of equation (66) are then combined together so that a more compact equation is arrived at. This operation yields the following result:

$$\frac{dh}{h} = \left[1 + \frac{q'(x)\ln(r_o/r_1)}{2\pi k\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)}\right] \left\{ \frac{3.413\, VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] - \frac{kA}{q'(x)} \cdot \frac{d^2 t_s}{dx^2}\left[\frac{dA}{A} \right.\right.$$

$$\left.\left. + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x}\right] - \frac{L_e}{q'(x)}\frac{dL_e}{L_e}\right\} - \frac{dr_1}{r_1} - \frac{dt_{os}}{\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)}$$

$$+ \frac{dt_{f_1}}{\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)} - \frac{dk}{k}\left\{\frac{kA}{q'(x)} \cdot \frac{d^2 t_s}{dx^2} + \frac{q'(x)\ln(r_o/r_1)}{2\pi k\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)}\left[\frac{kA}{q'(x)} \cdot \frac{d^2 t_s}{dx^2} + 1\right]\right\}$$

$$+ \frac{1}{\left(t_s - t_{f_1} - \dfrac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p}\right)} \cdot \left\{ \frac{\int_{x_1}^{x} d(q'(x))dx}{\dot{m}\, C_p} - \left[\frac{d\dot{m}}{\dot{m}} + \frac{dC_p}{C_p}\right] \cdot \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p} \right. \qquad (67)$$

The upper limit of the integral $\int_{x_1}^{x}$ will now be allowed to approach the value of x_2. This operation will cause the following to happen in equation (67):

$$\lim_{x \to x_2} \quad t_s - t_{f_1} - \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p} = t_s - t_{f_2} \tag{68}$$

$$\lim_{x \to x_2} \quad \frac{\int_{x_1}^{x} q'(x)dx}{\dot{m}\, C_p} = t_{f_2} - t_{f_1} \tag{69}$$

$$\lim_{x \to x_2} \quad \left| \int_{x_1}^{x} d(q'(x))dx \right| \leqq \left| q'(x) \right|_{max} (x_2 - x_1) \tag{70}$$

The absolute value of equation (67) will now be taken. This is done to determine the maximum expected error for the film coefficient when using equation (58). It is assumed that the only error existing in the temperatures, e.g. dt_{os}, etc., will be that of thermocouple inaccuracy and that the term Δx is the distance between thermocouples. When the absolute value is taken of equation (67), the terms found for the limits of the integrals can then be substituted in. The following result is obtained when the absolute value is taken of equation (67) and equations (68), (69), and (70) are substituted:

$$\frac{|dh|}{h} \leqq \left[1 + \frac{q'(x) \ln (r_o/r_i)}{2\pi k\, (t_s - t_{f_2})} \right] \left\{ \frac{3.413\; VI}{q'(x)} \left[\frac{|dV|}{V} + \frac{|dI|}{I} \right] + \frac{kA}{q'(x)} \cdot \left| \frac{d^2 t_s}{dx^2} \right| \cdot \left[\frac{|dA|}{A} \right. \right.$$

$$\left. \left. + \frac{4|dt_s|}{\left| t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x} \right|} + \frac{2|d(\Delta x)|}{\Delta x} \right] + \frac{L_e}{q'(x)} \cdot \frac{|dL_e|}{L_e} \right\} + \frac{|dr_i|}{r_i} + \frac{|dt_{os}|}{(t_s - t_{f_2})}$$

$$+\frac{|dt_{f_1}|}{(t_s-t_{f_2})}+\frac{|dk|}{k}\cdot\left\{\frac{kA}{q'(x)}\left|\frac{d^2t_s}{dx^2}\right|+\frac{q'(x)\ \ln\ (r_o/r_i)}{2\pi k\ (t_s-t_{f_2})}\cdot\left[1+\frac{kA}{q'(x)}\left|\frac{d^2t_s}{dx^2}\right|\right]\right\}$$

$$\frac{1}{(t_s-t_{f_2})}\cdot\left\{\frac{|dq'(x)_{max}|\ (x_2-x_1)}{\dot{m}\ C_p}+\left[\frac{|d\dot{m}|}{\dot{m}}+\frac{|dC_p|}{C_p}\right]\cdot(t_{f_2}-t_{f_1})\right\} \tag{71}$$

Equation (71) can now be used to determine the maximum expected error in the film coefficient from use of equation (58) to evaluate the film coefficient.

Third Error Equation

An error analysis can now be made of equation (35) for the film coefficient. This is the third and final equation considered.

The third equation that was developed for the film coefficient is:

$$h = \frac{\dot{m}\ C_p}{C_1}\cdot\frac{dt_f/dx}{(t_s-t_f)} \tag{72}$$

The error that can be expected in the film coefficient from use of equation (72) is obtained in the following manner:

$$dh = \frac{C_p}{C_1}\cdot\frac{(dt_f/dx)}{(t_s-t_f)}\cdot d\dot{m} \quad \frac{\dot{m}}{C_1}\cdot\frac{(dt_f/dx)}{(t_s-t_f)}\cdot dC_p - \frac{\dot{m}\ C_p}{C_1^{\ 2}}\cdot\frac{(dt_f/dx)}{(t_s-t_f)}\cdot dC_1$$

$$\frac{\dot{m}\ C_p}{C_1}\cdot\frac{d(dt_s/dx)}{(t_s-t_f)} - \frac{\dot{m}\ C_p}{C_1}\cdot\frac{(dt_f/dx)}{(t_s-t_f)^2}\cdot d(t_s-t_f) \tag{73}$$

Again the letter "d" is used to denote an error in the term following it.

The relative error in film coefficient from use of equation (72) can be obtained by dividing equation (73) by equation (72). This results in the following:

$$\frac{dh}{h} = \frac{d\dot{m}}{\dot{m}} + \frac{dC_p}{C_p} - \frac{dC_1}{C_1} + \frac{d(dt_f/dx)}{(dt_f/dx)} - \frac{dt_s}{(t_s-t_f)} + \frac{dt_f}{(t_s-t_f)} \tag{74}$$

No further evaluations of the error terms $d\dot{m}/\dot{m}$ and dC_p/C_p of equation (74) are necessary as these terms are not determined by an additional equation but are obtained directly from various readings. The error terms dC_1/C_1 and dt_s have been previously evaluated under the first error equation development and they are given by equations (50) and (54) respectively. The evaluation of the dt_f term of equation (74) is the same as performed under the first error equation development on page 36 and does not need further clarification. Therefore, the only term in equation (74) which has not been previously evaluated is the dt_f/dx term. This term can be evaluated in the following manner:

It can be assumed that the term dt_f/dx is equal to the following expression:

$$dt_f/dx = \frac{t_{f_{x-\Delta x}} - t_{f_{x+\Delta x}}}{2\Delta x} \tag{75}$$

The error that may be expected in equation (75) can be obtained by performing an operation similar to the one performed on equation (72). This will result in the following:

$$d\left(\frac{dt_f}{dx}\right) = \frac{dt_{f_{x+\Delta x}} - dt_{f_{x-\Delta x}}}{2\,\Delta x} - \frac{\left(t_{f_{x+\Delta x}} - t_{f_{x-\Delta x}}\right)}{2(\Delta x)^2} \cdot d(\Delta x) \tag{76}$$

The relative error in equation (76) can be readily found by dividing by equation (75). The following is the result of this operation:

$$\frac{d(dt_f/dx)}{(dt_f/dx)} = \frac{\left(dt_{f_{x+\Delta x}} - dt_{f_{x-\Delta x}}\right)}{t_{f_{x+\Delta x}} - t_{f_{x-\Delta x}}} - \frac{d(\Delta x)}{\Delta x} \tag{77}$$

All the error terms of equation (74) have now been evaluated. The results of these evaluations will now be substituted in equation (74). This gives the following result:

$$\frac{dh}{h} = \frac{d\dot{m}}{\dot{m}} + \frac{dC_p}{C_p} - \frac{dr_i}{r_i} + \frac{dt_{f_{x+\Delta x}} - dt_{f_{x-\Delta x}}}{t_{f_{x+\Delta x}} - t_{f_{x-\Delta x}}} - \frac{d(\Delta x)}{\Delta x} - \frac{dt_{os}}{(t_s - t_f)}$$

$$- \frac{q'(x)\ln(r_o/r_i)}{2\pi k\,(t_s - t_f)} \cdot \left\{ \frac{dk}{k} - \frac{3.413\ VI}{q'(x)}\left[\frac{dV}{V} + \frac{dI}{I}\right] + \frac{kA}{q'(x)} \cdot \frac{d^2 t_s}{dx^2} \cdot \left[\frac{dk}{k} + \frac{dA}{A}\right.\right.$$

$$\left.\left. + \frac{dt_{s_{x+\Delta x}} + dt_{s_{x-\Delta x}} - 2dt_{s_x}}{t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}} - \frac{2d(\Delta x)}{\Delta x}\right] + \frac{L_e}{q'(x)} \cdot \frac{dL_e}{L_e} \right\} + \frac{dt_f}{(t_s - t_f)} \tag{78}$$

The absolute value of equation (78) will now be taken to determine the maximum expected error in the film coefficient when equation (72) is used for determining the film coefficient. It is assumed that all the temperature errors, e.g. dt_{os}, etc., will be due only to thermocouple inaccuracy and that the term Δx is the distance between the thermocouples.

Therefore the following is the result when the absolute value is taken of equation (78):

$$\frac{|dh|}{h} \leqq \frac{|d\dot{m}|}{\dot{m}} + \frac{|dC_p|}{C_p} + \frac{|dr_i|}{r_i} + \frac{2|dt_f|}{\left|t_{f_{x+\Delta x}} - t_{f_{x-\Delta x}}\right|} + \frac{|d(\Delta x)|}{\Delta x}$$

$$+ \frac{|dt_{os}|}{(t_s\ t_f)} + \frac{q'(x)\ \ln\,(r_o/r_i)}{2\pi k\ (t_s-t_f)} \cdot \Bigg\{ \frac{3.413\ VI}{q'(x)} \left[\frac{|dV|}{V} + \frac{|dI|}{I} \right]$$

$$+ \frac{|dk|}{k} \cdot \left[1 + \frac{kA}{q'(x)} \cdot \left| \frac{d^2t_s}{dx^2} \right| \right] + \frac{kA}{q'(x)} \cdot \left| \frac{d^2t_s}{dx^2} \right| \cdot \Bigg[\frac{|dA|}{A} + \frac{4\,|dt_s|}{\left|t_{s_{x+\Delta x}} + t_{s_{x-\Delta x}} - 2t_{s_x}\right|}$$

$$+ \frac{2\,|d(\Delta x)|}{\Delta x} \Bigg] + \frac{L_e}{q'(x)} \cdot \frac{|dL_e|}{L_e} \Bigg\} + \frac{|dt_f|}{(t_s-t_f)} \qquad (79)$$

Equation (79) can now be used to determine the maximum expected error in the film coefficient when using equation (72) to determine the film coefficient, under any assumed and actual operating conditions.

V. ERROR ANALYSIS INVESTIGATION RESULTS

Programming the Problem

The three equations (57), (71), and (79) developed to estimate the possible total error in the three equations (30), (32), and (35) respectively, are long and involved equations. It would not be good judgment to arbitrarily assume values for the different error quantities in the equations (57), (71), and (79) as some of the variables are directly and indirectly related to one another. This type of assumption could lead to erroneous results which would be of no value. The rather difficult task of solving these three equations (57), (71), and (79) using slide rule, pencil, and paper would involve many hours of time and assiduous effort before the trend of the three equations would become evident.

Thus, it was decided to programme the equations (57), (71), and (79) in Fortran II language for use in the IBM 1620 Data Processing System. The programme and subroutines used, together with sample data and answers can be found in the appendix. This programme was written to reduce the number of assumptions necessary to start the programme into operation. A large percentage of these assumptions are read into the programme so that control and versatility can be maintained.

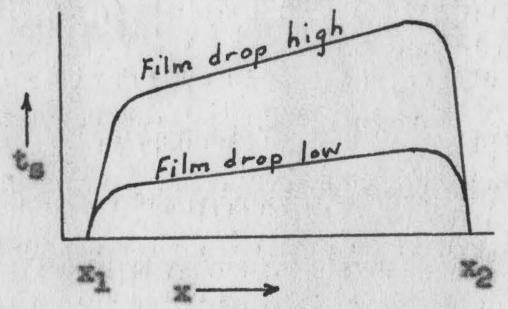
It was further decided to determine the maximum expected error for a variety of combinations of tube diameters and lengths, steam pressures, temperatures, and mass flows.

The inaccuracy of the thermocouples measuring the different temperatures was assumed to be $\pm 1^{\circ}$ F. It was concluded that an accuracy of this magnitude is possible with careful calibration of the temperature measuring equipment.

To calculate the amount of heat added to the fluid as it flows through a tube of set length and diameter and with pressure and temperature fixed at inlet, Heinemann's equation (8) was used to estimate the film coefficient. A temperature drop across the film and a fluid mass flow were also assumed. By multiplying the first two assumptions by the inside area of the tube, the amount of heat transferred to the fluid was obtained. The surface temperature of the tube was calculated next. With the surface temperature known, the current flow in the heater was then calculated. The voltage drop across the heater necessary to produce this heat input was then calculated by assuming a 1.5% end loss from the heaters.

The value of d^2ts/dx^2 in the error equation could not be determined without first running some experiments and measuring the temperature distribution along the tube. Therefore, it was assumed that this quantity d^2ts/dx^2 was some function of the film drop and an equation was used in the programme to obtain the value of this quantity.

The reason for the use of an arbitrary equation to obtain a value for the d^2ts/dx^2 term is that for a low film drop this value would not be as great as it would for a higher value of film drop.



The above figure illustrates the change in the slope of the surface temperature vs distance along the tube for constant heat input along the tube. It can be seen from these curves that the change in slope at the ends of the tube is greater at high film drop than at a lower value.

Curves of a similar nature are shown on page 53 of Heineman (11).

With all of the values for the quantities in the error equations now determined, the value of the expected error under the assumed conditions of operation was then obtained.

With the film temperature fixed at a certain value, the steam mass flow was then varied from a low value of Reynolds Number to a value of Reynolds Number that would produce either a pressure drop greater than 60 PSI or a heat input greater than 12.5 KW/FT. When either the value of the pressure drop or the heat input exceeded the above mentioned values, the programme was arranged so that a new value of film temperature would be produced. Then, when the film temperature drop exceeded a value of 160° F., the programme transferred control so that at the operator's command, a new value of pressure and temperature, or pressure, temperature, and tube length or pressure, temperature, tube length and diameter could be entered. When this new entry of data was made, the entire process of obtaining the values of expected error was repeated.

Results Obtained and Analysis of Results

After a sufficient number of different pressures, temperatures, tube lengths and tube diameters were run, the data were collected and analysed. The values of pressure, temperature, tube length and diameter were 200, 2200, and 4700 PSIA; 400, 900, and 1200° F.; 6, 12, and 18 inches; and 0.5, 1.0, and 1.5 inches respectively. The values used for the film temperature drop were 10, 20, 40, 80, and 160° F.

The results for the three equations (57), (71), and (79) showed the following trends. The error estimate values of equation (79) were several times larger than the error estimate values of the other two equations. The range of difference between the third equation, (79), and the other two equations was from twice as great to sometimes as large as 15 times. The error estimate values of equation (79) always increased as the mass flow increased, and at no point did these error estimate values fall below 10%. The above mentioned results held for the conditions tested.

The error estimate values of equation (57) were always less than the error estimate values of the second equation (71). As the film drop was increased, the error estimate value correspondingly decreased. The decrease was large with the first few film drop increases and then started to decrease in accuracy gained with additional film drop increase. This trend can be noted by observation of the curves on pages 52, 53 and 54.

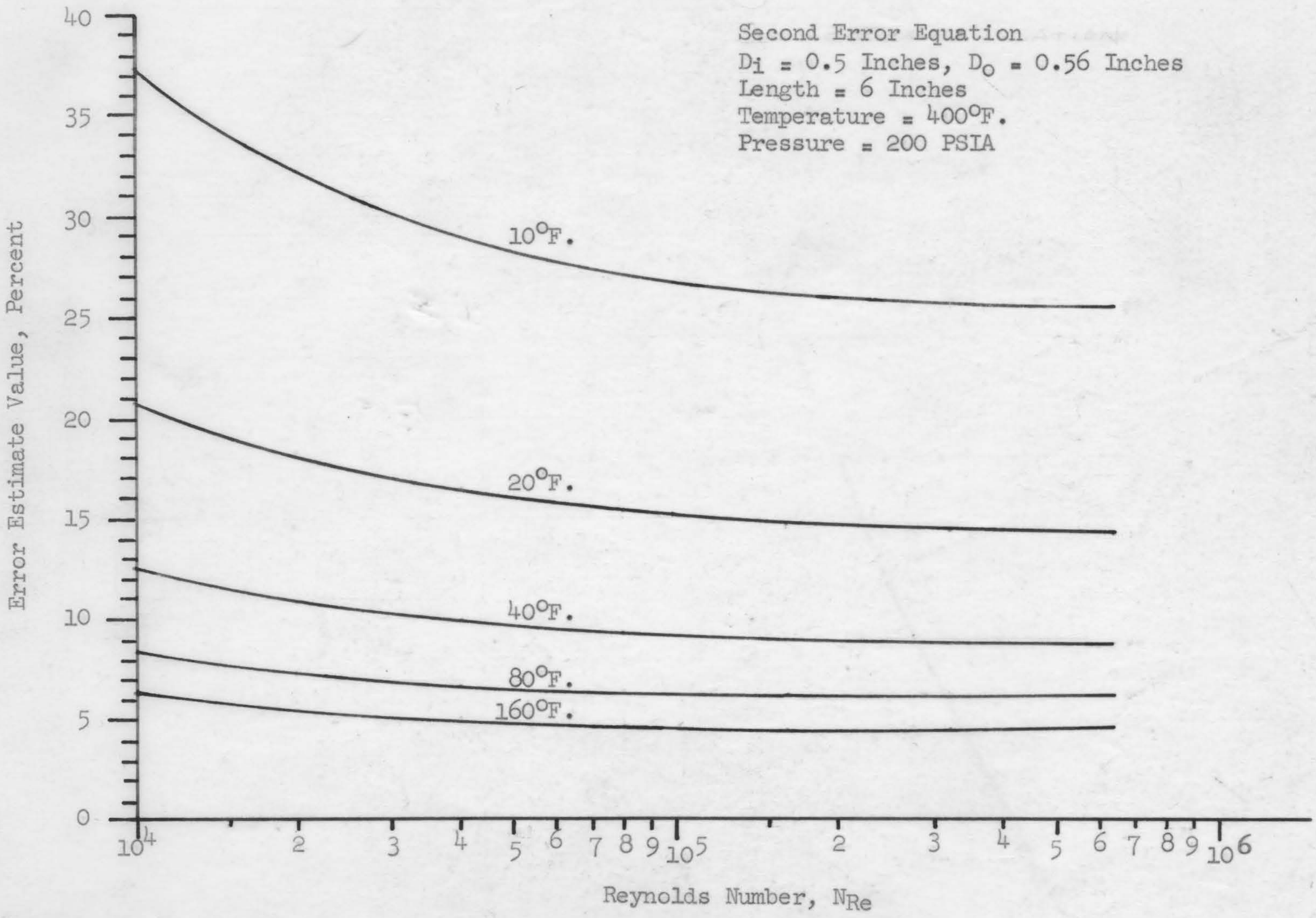


Figure No. 3 - Effect of Film Temperature Drop on the Error Estimate Value

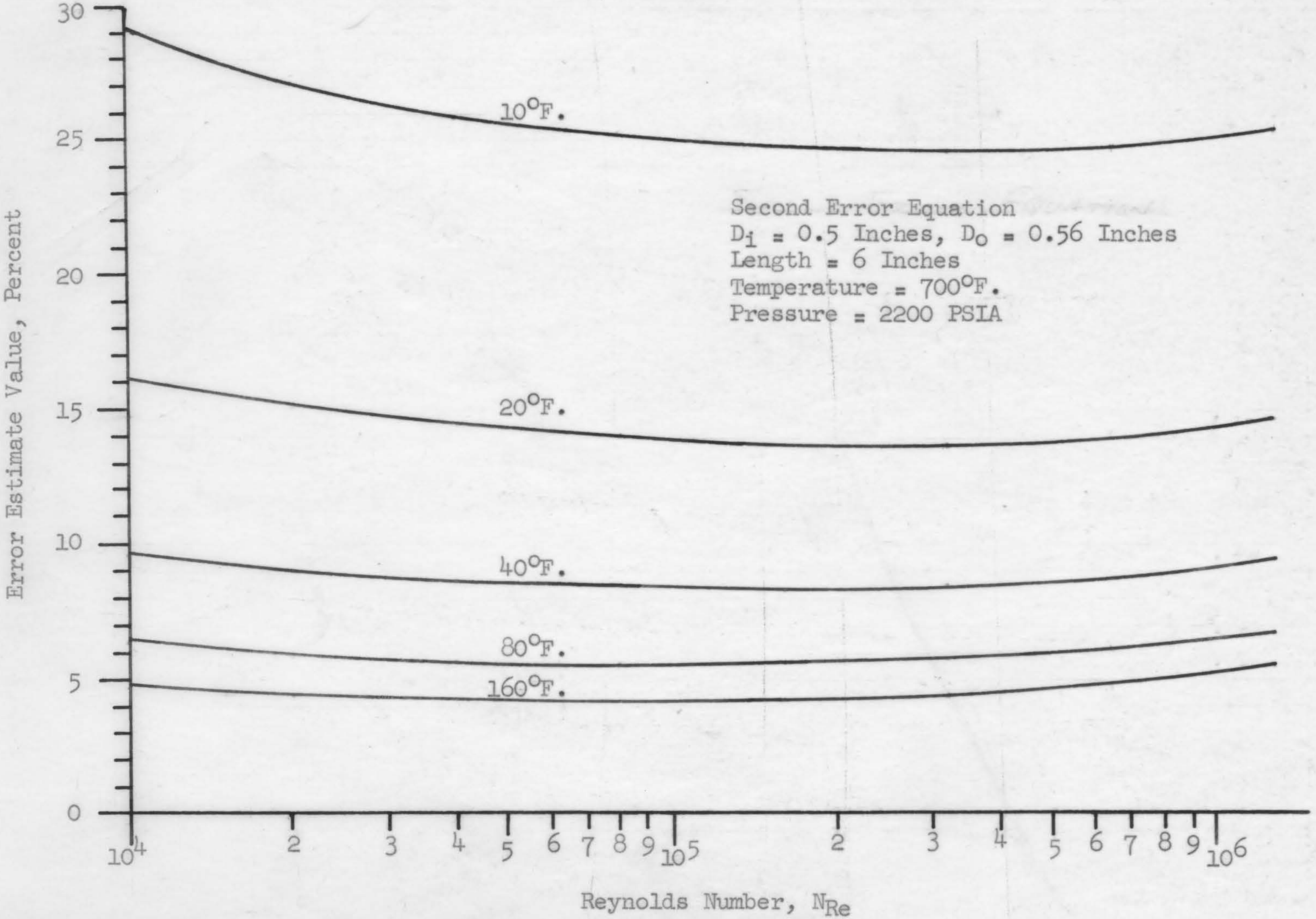


Figure No. 3 - Effect of Film Temperature Drop on the Error Estimate Value

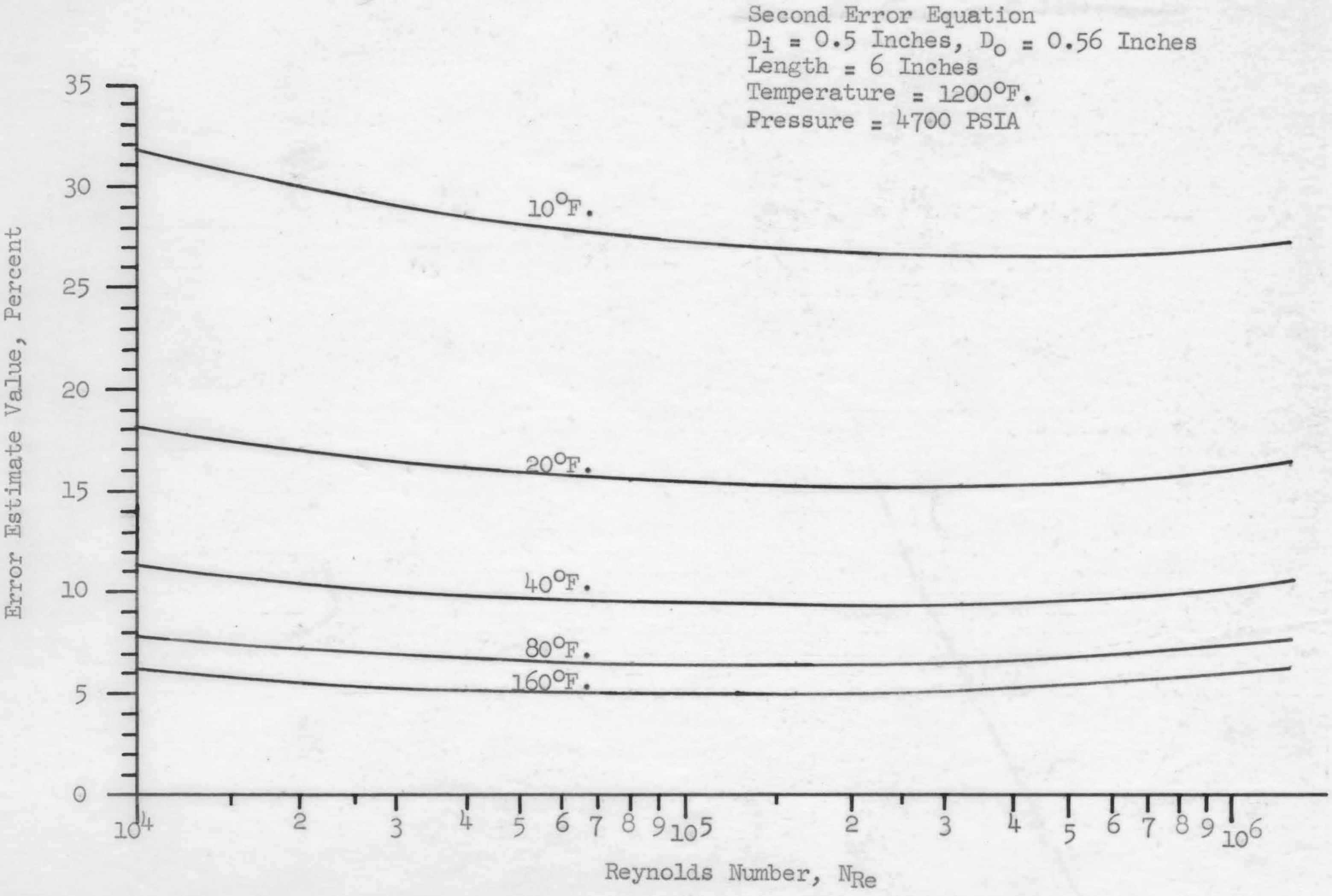


Figure No. 3 - Effect of Film Temperature Drop on the Error Estimate Value

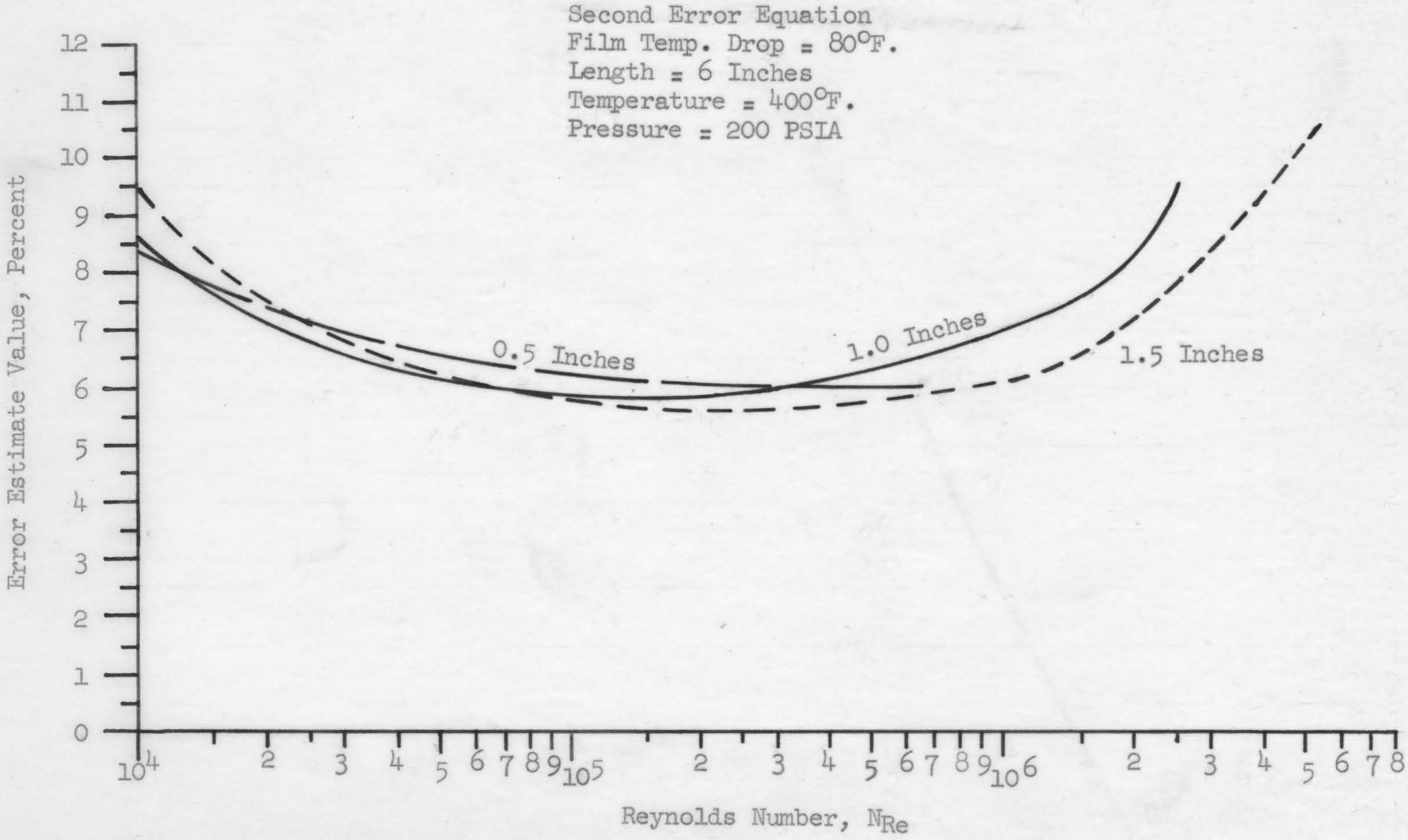


Figure No. 4 - Effect of Tube Diameter on the Error Estimate Value

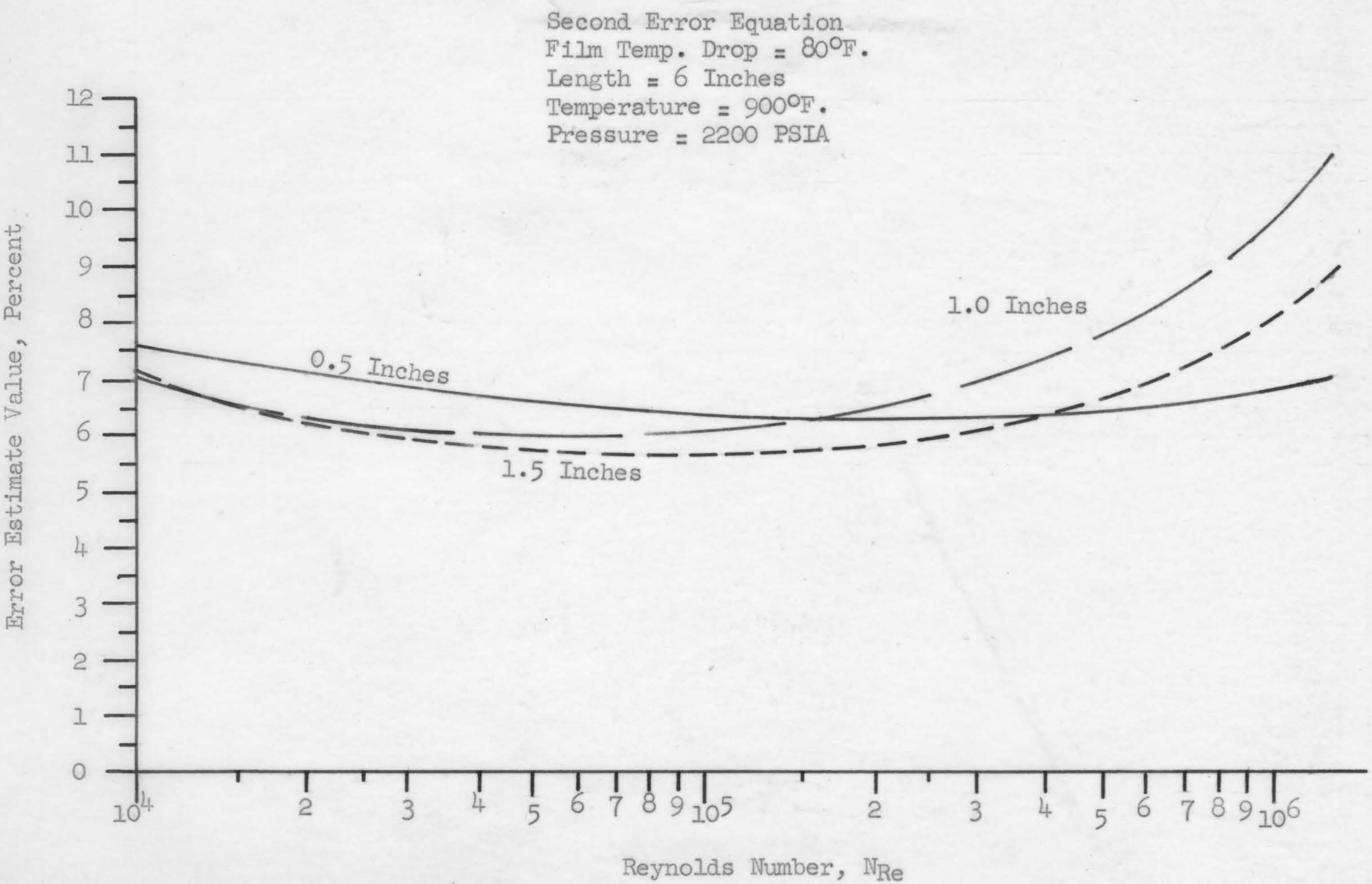


Figure No. 4 - Effect of Tube Diameter on the Error Estimate Value

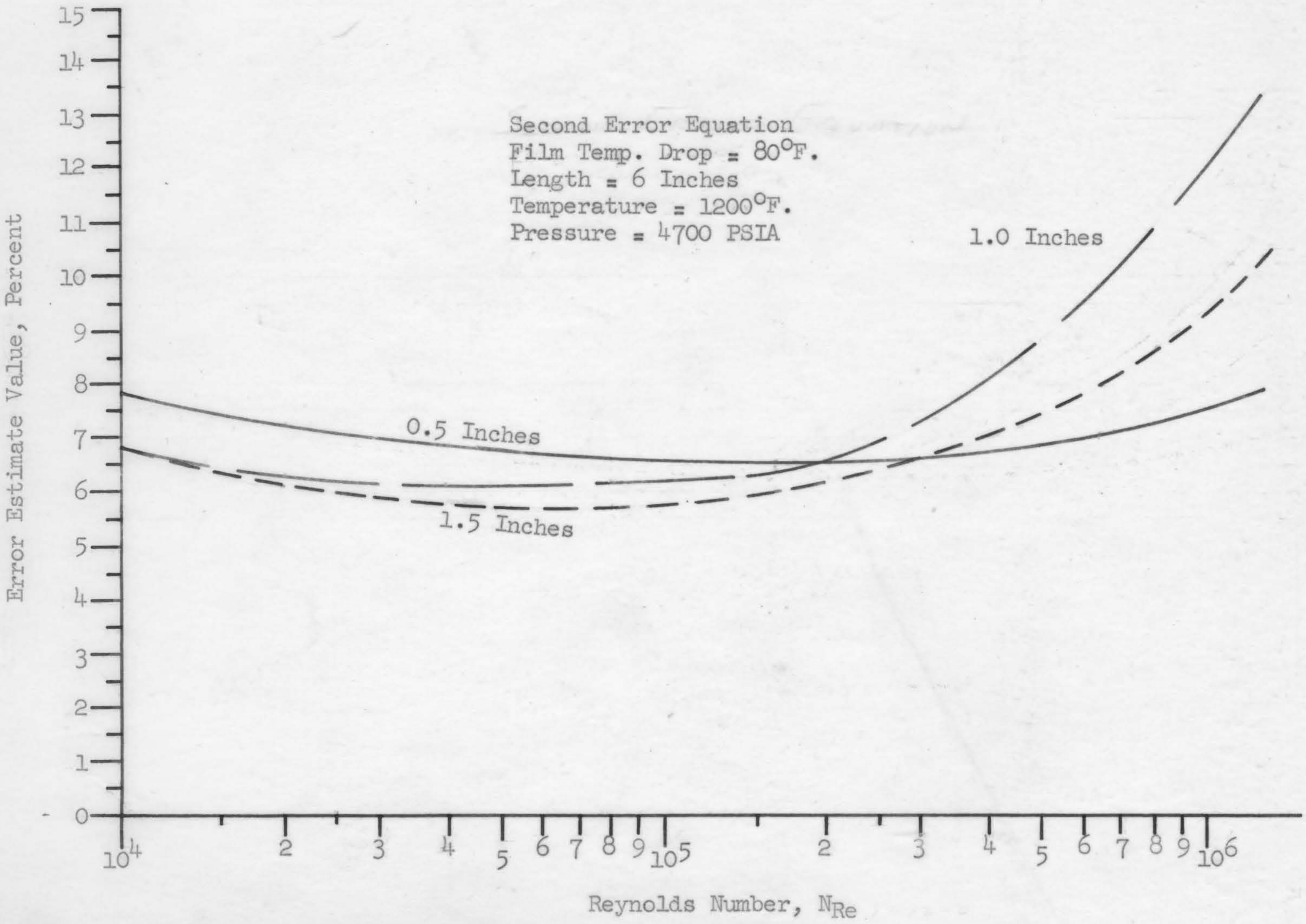


Figure No. 4 - Effect of Tube Diameter on the Error Estimate Value

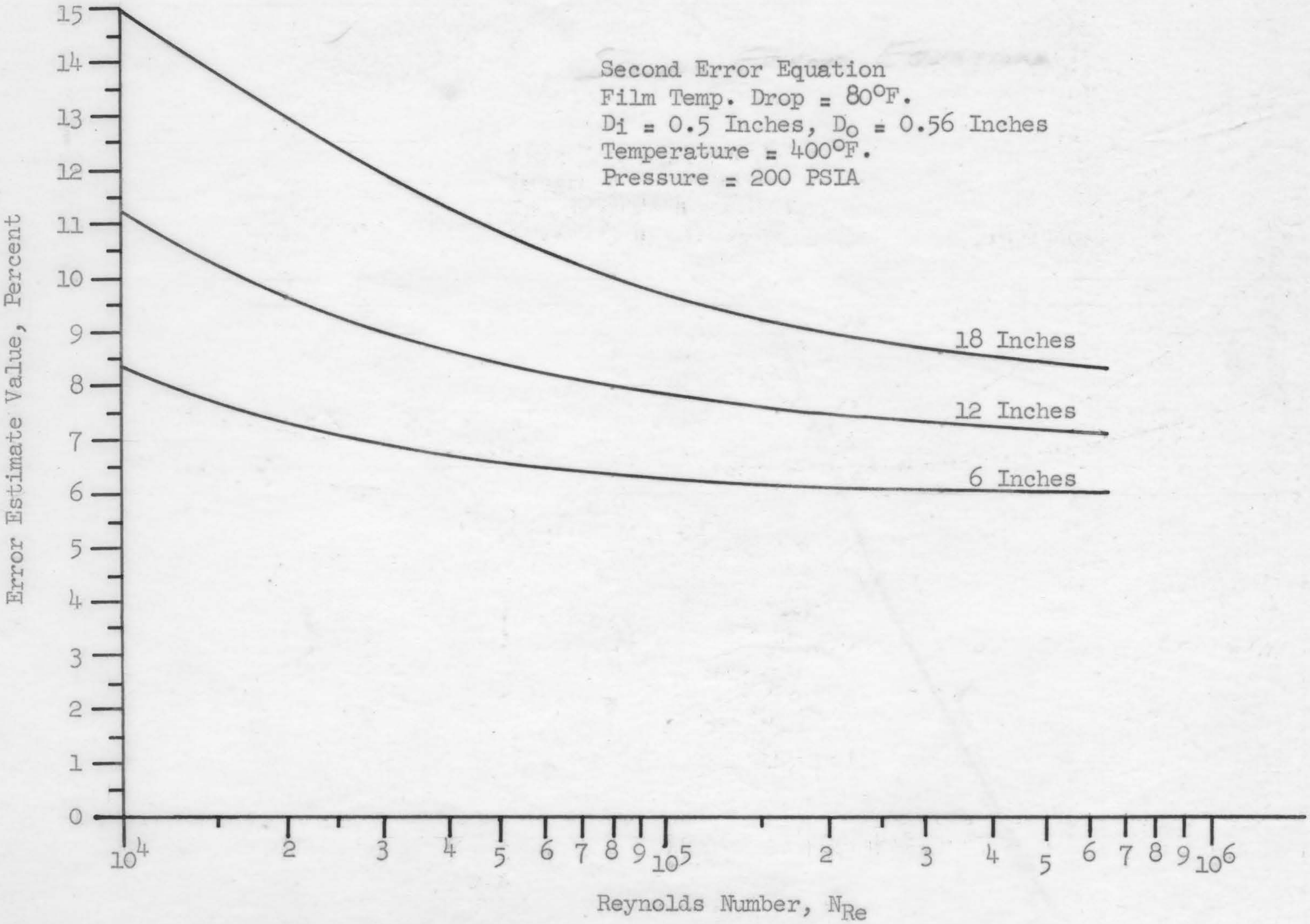


Figure No. 5 - Effect of Tube Length on the Error Estimate Value

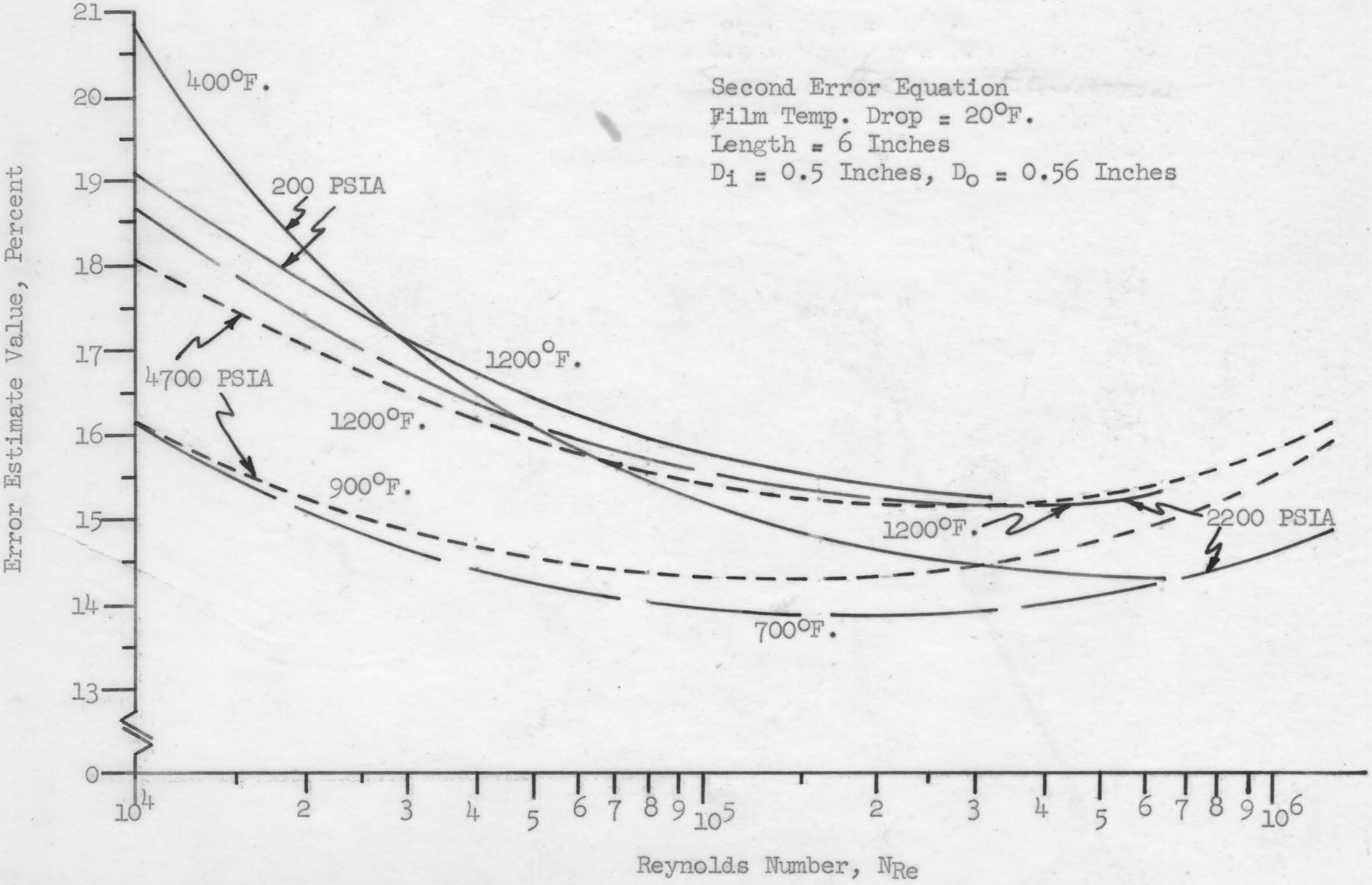


Figure No. 6 - Effect of Steam Pressure and Temperature on the Error Estimate Value

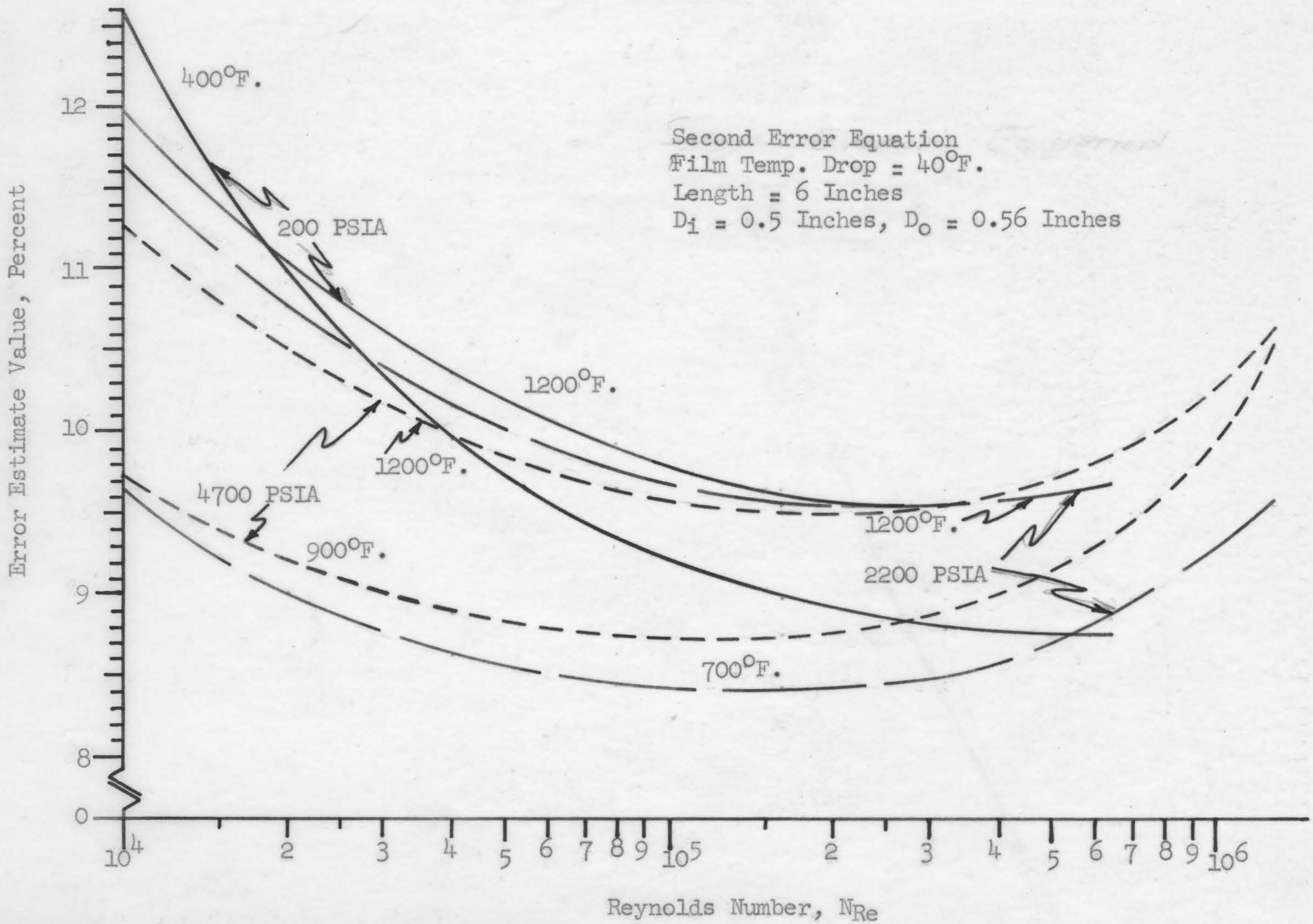


Figure No. 6 - Effect of Steam Pressure and Temperature on the Error Estimate Value

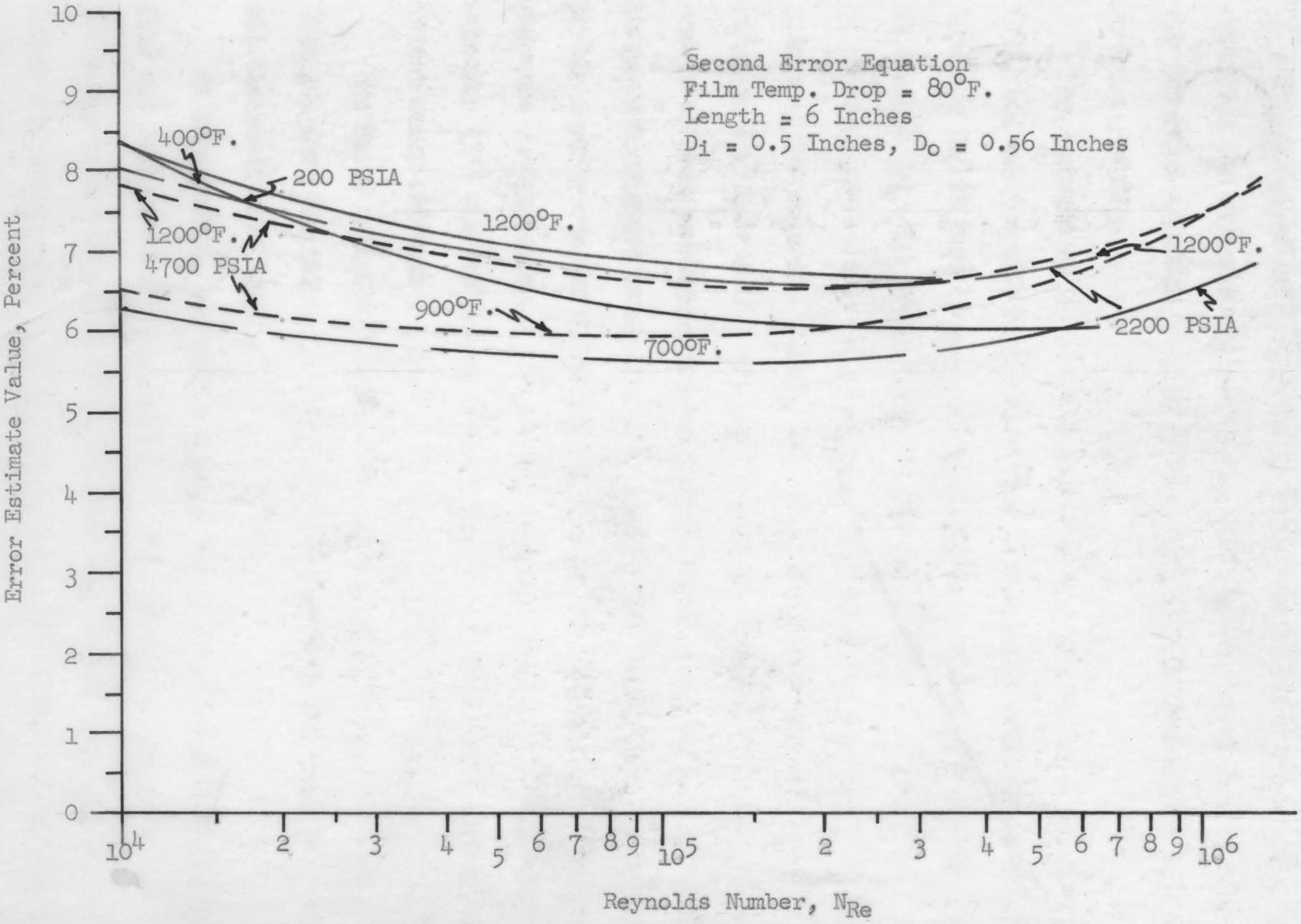


Figure No. 6 - Effect of Steam Pressure and Temperature on the Error Estimate Value

The effect of tube diameter on the error estimate can be seen by observing the curves on pages 55, 56, and 57. The conditions are true for the first equation (59), only with slightly different values of error estimate results.

The increase in tube length had no effect on the first equation (59), but has the effect of increasing the estimate error value with an increase in the tube diameter for the second equation (71). This trend is evident from the curves found on page 58.

The effect of steam pressure and temperature on the error estimate values of the second equation (71) can be noted by studying the curves on pages 59, 60, and 61. The only conclusion that can be made from these curves is that the error estimate values are less at the lower temperatures with constant pressure. This is due most likely to the decrease of the density and increase of the viscosity of superheated steam with increase in temperature. The effect of steam pressure and temperature on equation (59) was the same as for equation (71) only with slightly different error estimate values.

The error estimate value of both equations (59) and (71) were less than 10% when the film drop was 80 or 160° F. This was true for nearly all the conditions tested.

At some points, the estimate error value for the second equation (71) was twice that of equation (59). This condition was prevalent at the lower values of pressure and temperature, longer tube lengths and larger diameters. At the other test points, the error estimate values of the two equations were closer, and at the higher values of film drop the error estimate values were almost identical.

Conclusions

The results of the error analysis showed the following to be true:

1. The accuracies of the equations to determine the value of the film coefficient were in this order:

a) the first equation was most accurate;

b) the second equation;

c) the third equation.

2. The first and second equations are almost equally accurate and should give almost identical results.

3. The third equation has a large error associated with it, and henceforth will be discarded.

4. The value of the film coefficient should only be determined from experimental data when the film temperature drop is of such a value that the expected error will be 10%.

Recommendations

Although equation (32) has higher error estimate values than equation (30), the temperature of fluid at points throughout the test section must be measured to insure the accuracy predicted by equation (59). To measure the fluid temperature in this manner would require sophisticated instrumentation, resulting in high cost and construction difficulties. This measurement would also disrupt the flow pattern within the test section and add additional error not herein accounted for. Alternatively, the temperature profile of the fluid could be assumed to follow some pattern along the length of the test section, thus eliminating the extensive instrumentation. Either way, additional error would be introduced.

The metal to be used for the test section tube should have a high thermal conductivity to insure a minimum of temperature drop across the tube wall and resistance to heat flow.

The instrumentation should be of good quality and have high accuracy with a minimum of expense. The equipment should be carefully calibrated with special attention given to the thermocouples and their related equipment. The thermocouple inaccuracy contributes most to the expected error and therefore should receive extreme care during calibration.

VI. EQUIPMENT LAYOUT

It is suggested that the test section and its related equipment be arranged in the manner shown in Figure 7. This arrangement can be changed at the discretion of the experimenter.

One unique change that can be noted in the assembly of equipment used by other investigators in this field is the use of a steam pump (1) to circulate the steam and to compensate for pressure loss in the system.

The normal method of obtaining the superheated steam is to generate it in a steam generator of some type. This type of system uses a boiler feed pump for circulation and pressure make-up, and a fossil fuel unit or an electrical unit for steam generation. By use of a steam pump the problem of fuel storage and flue gas is eliminated for a fossil fuel unit and the problem of high KW input is eliminated for an electrical unit.

Positive displacement and centrifugal steam pumps have been designed, built, and used by the Germans on the Loeffler Boiler (16). The temperatures and pressures under which these pumps were used were not as high as desired in this experiment, but they could readily be designed with the improvements made in gland packings and metals since these pumps were first used.

The upper part of the loop (1) should be of 2 inch diameter pipe, so as to reduce the pressure loss in this section.

The test section (8) of the loop will be made of three different size pipe with inner diameters of approximately 1/2, 1, and 1-1/2 inches.

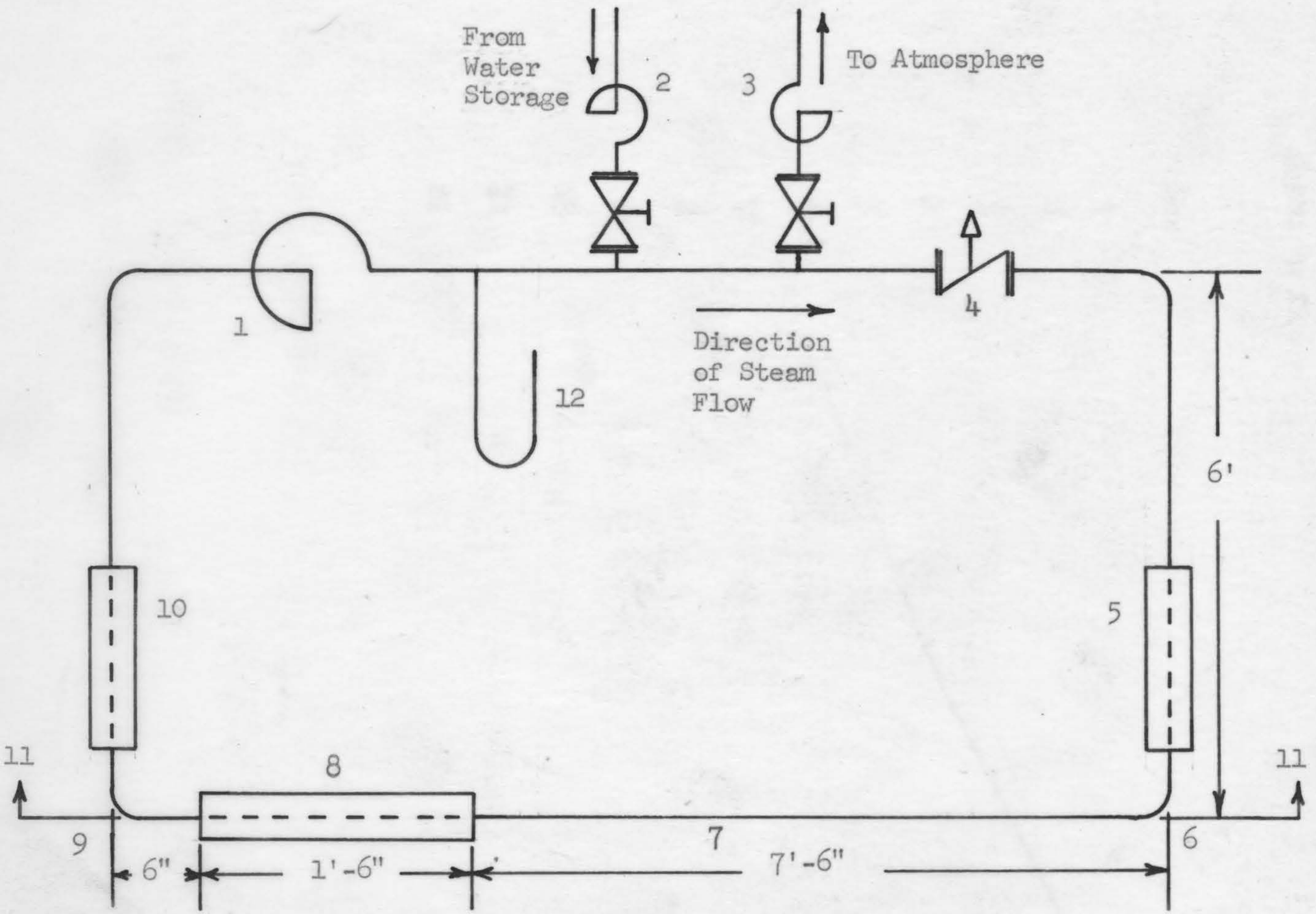


Figure No. 7 - Tentative Equipment Layout

Table I. Listing of equipment for the tentative equipment layout shown in figure 7.

No.	Description
1	Steam Pump
2	Charging Pump
3	Vacuum Pump
4	Safety Valve
5	Heating Section
6	Reducing Elbow
7	Calming Section
8	Test Section
9	Reducing Elbow
10	Cooling Section
11	Upper Part of Test Section
12	Flowmeter

The long entrance section (7) into the test section is used to insure that the velocity profile will be fully developed when the steam reaches the test section.

The test section (8) and the entrance section (7) will be made in the three diameter sizes previously mentioned above. These three sizes can be easily attached and detached for the upper part of the system, to enable the film coefficient to be determined for tubes of various diameters.

The heating (5) and cooling sections (10) in the loop will be used to insure that the steam entering the test section is at the same temperature throughout a test run.

The vacuum pump (3) will be used to evacuate the system before charging with distilled water.

The charging pump (2) will be used to charge the system with the distilled water after the system has been evacuated. This pump will also be used to make-up any losses occurring due to leakage from the system.

All of the piping in the system will be wrapped with resistance heaters. These heaters will be used to evaporate the distilled water after the initial charging. All the piping will also be covered with insulation to reduce the heat loss from the system, and to keep the experiment room at a comfortable working temperature.

The voltmeter and ammeters will be used to measure voltage drop and current flow, respectively, within the test section heaters. A wattmeter will also be provided as a check on the voltmeters and ammeters.

The potentiometers will be used to determine temperatures in the test section at the various necessary points.

The flowmeter (12) will be used to measure and determine the amount of steam circulating through the system.

The safety valve (4) is provided to ensure that if the pressure within the system goes above a predetermined allowable pressure the system will be evacuated before an accident occurs.

All of the distances and pipe lengths shown in Figure 3 are approximate and can be changed at the discretion of the equipment designer.

All the pipe joints shall be of the flange type for ease of assembly and disassembly and should be designed following the ASME Code for high pressure - high temperature steam.

VII. TEST SECTION DESIGN

Introduction

The test section will be the heart of the experiment. It must be designed so that an accurate value of film coefficient can be obtained. It should also be designed so that minimum of expense will be necessary and that construction and instrumentation can be readily performed and also for interchangeability.

Design of the Components and Instrumentation

The Figure 8 is the tentative layout of the test section. It is designed so that a minimum of heat loss from the heaters will occur. The tube through which the steam flows is encased in a pressure jacket at the same pressure as the steam within the tube. Thus the only stress within the tube wall will be that of thermal stress. This pressure jacket will allow the tube test section wall thickness to be very thin. The thin wall thickness will help in making heat losses from the ends of the tube very small and will produce a small temperature drop across the tube wall, both of which are desirable.

The individual heaters (2) of the test section shall be approximately one inch in length. There will be 12 heaters, as the tube which heats the steam will be approximately a foot in length. The use of several heaters will permit the surface temperature profile and the heat flux along the tube to be varied to suit the desires of the experimenter.

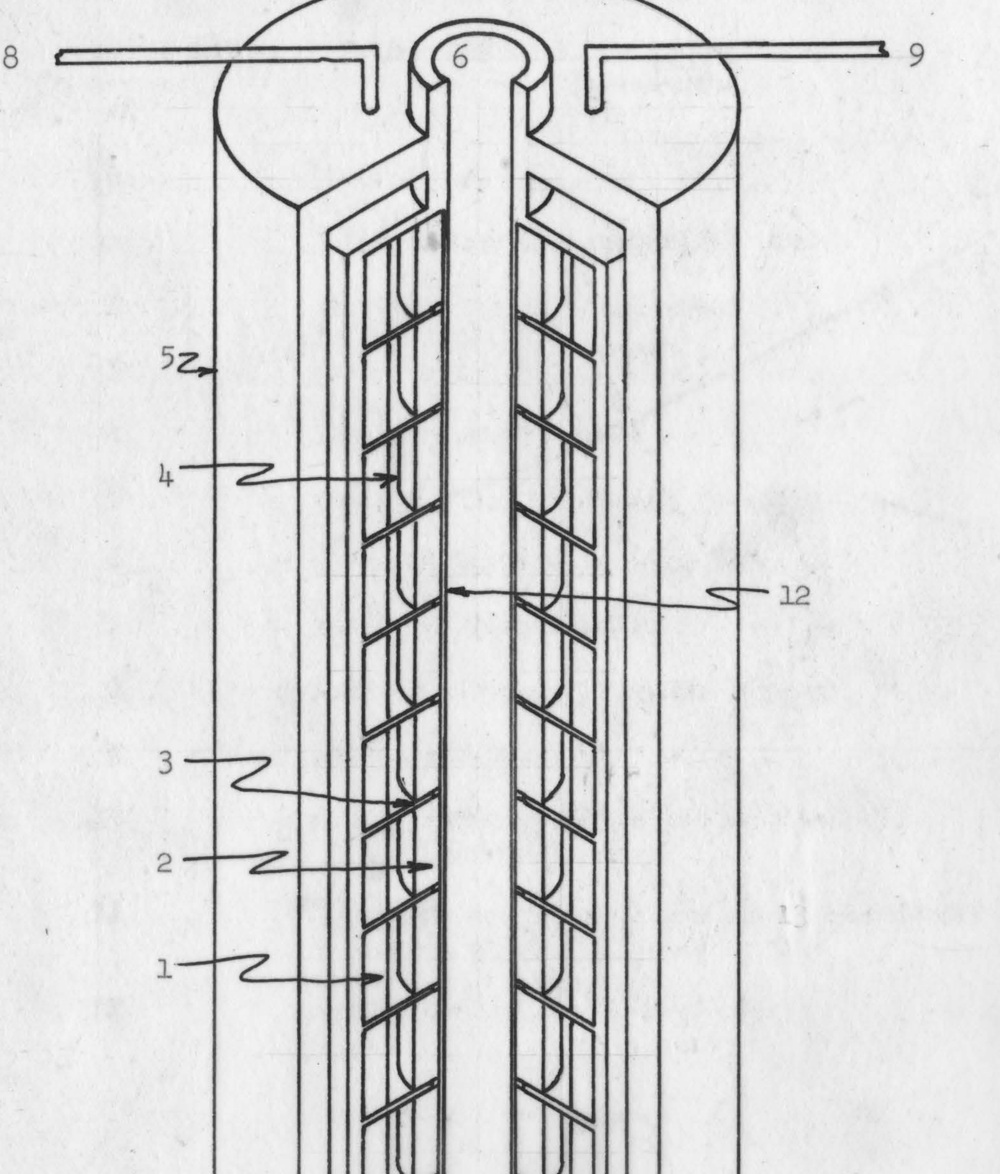


Figure No. 8 - Tentative Test Section Layout

Table II. Listing of components for the tentative test section design shown in figure 8.

No.	Description
1	Guard heater (12 individual ones)
2	Heater (12 individual ones)
3	Compartment Separator
4	Pressure Jacket Space
5	Outer Shell on Pressure Jacket
6	Entrance to Test Section
7	Exit from Test Section
8	Electrical Leads to Guard Heaters
9	Electrical Leads to Heaters
10	Thermocouple Leads to the Differential Thermocouples
11	Thermocouple Leads to the Tube Temperature Measuring Thermocouples
12	Inner Surface of Heating Tube

The heater wire will be made of Ni-Chrome V wire and encased in a porcelain ceramic coat. Four holes, 90° apart, and half way between the heater ends, will be left in the ceramic coat for the thermocouples that measure the tube metal temperature to pass through. Four thermocouples to measure the outside surface temperature of heaters will be in the middle of the heater, with each one off-set 45° from the thermocouples used to determine metal temperature. The heaters will be designed so that a maximum output of one kilowatt can be obtained with a maximum inner surface tube metal temperature of 1400° F. The inner diameter of the heaters will be made in such a way that the heaters can be slid over the heating tube during assembly.

The individual guard heaters (1) are to be of approximately one inch in length. They, too, will be Ni-Chrome V wire encased in a ceramic coat. Thermocouples will be installed in the guard heater opposite those used to determine heater surface temperature.

The thermocouples used to measure the surface temperature of the heaters and guard heaters will be connected to form a differential thermocouple. This differential thermocouple will be used to control the guard heaters so that the surface temperature of the guard heater and the heater will remain equal when the experiments are being performed.

Metal separators (3) will be used to divide the heaters into their individual compartments. These metal walls will be welded to the inner shell covering the guard heaters. Their main purpose is to keep the heat loss from the heaters by radiation at a minimum. Small holes will be drilled in these separators to allow the pressurized fluid to flow freely between compartments, thus equalizing the pressure throughout the pressure jacket.

The distance from the heater to guard heater should be kept small to minimize on heat loss due to radiation. This distance can be on the order of 0.2 inches. This should allow sufficient room to run the thermocouple and electrical leads through. The shorter the distance is, the smaller the overall diameter of the test section, thus reducing the wall thickness of the outer pressure shell jacket.

The thickness of the heating tube will only depend on thermal stresses as the sum of the external and internal pressure on this tube is zero because of the use of the pressure jacket. Thus, the wall thickness of this tube can be made fairly small.

The test section and pressure jacket should be of all welded construction and conform to the ASME Code for pressure vessels.

The entire test section will be covered with insulation to help reduce heat loss and to keep working conditions around the test section comfortable.

Material Selection

All the metal parts of the test section except for the heating tube should be made of a high-temperature, high-strength stainless steel. The manufacturers of stainless steel products should be consulted as to which type of stainless steel would be correct to use.

The heating tube of the test section should be made of a metal that will be able to withstand the high-temperatures imposed above it, and it should be a metal with a high thermal conductivity so that the temperature drop across the tube wall is small.

Several metals were investigated to determine which of them would best fit the experimental conditions. With all factors taken into account, it was found that Molybdenum would be the best metal to use. The thermal conductivity is high, ranging from 80 BTU/HR-FT-F^{o} @ 100^{o} F. to 55 BTU/HR-FT-^{o}F @ 2000^{o} F. It has high strength characteristics at high temperatures and is not readily attacked by high-temperature, high-pressure steam. Its coefficient linear expansion is half that of stainless steel, and it can be formed into the length and diameters desirable.

The heater wires should be made of Ni-Chrome V wire which is the standard resistance wire for heaters.

The thermocouples should be made of Chromuel-Aumel wire which will operate in the range of temperatures desired and has the high accuracy necessary for this experiment. By careful calibration the accuracy of the thermocouples can be increased.

The heater wires should be encased with porcelain. This material offers good electrical insulating qualities and can withstand the high temperatures at which it will be operating.

The electrical lead wires should be of a quality to withstand the load and temperature at which they will be expected to exist.

<u>Heat Loss Accounting</u>

The test section was designed with the thought in mind of keeping the heat losses from the heaters at the lowest possible value. To accomplish this objective, the tube wall thickness is to be made as thin as possible. With no other stress in this wall other than thermal stress, the tube wall can be made thin. The thin wall will help in reducing the heat loss at the ends due to conduction within the tube. The thin wall also reduces the amount of resistance of the wall to heat flowing through it.

To reduce the radiation loss from the heater, the guard heaters are placed opposite each heater and are to be designed to operate at the same surface temperature as the heater. The guard heaters are also to be placed as close as possible to the heaters, allowing for clearance, so that radiation losses to the ends of each heater can be kept to a minimum. Several calculations were made assuming the ends to be black, reradiating walls at zero degrees Rankine. The other conditions assumed were that the heater surface temperatures ranged from 400-1200° F., the length of the heaters was one inch, and that the distance between the main heater and guard heater was approximately one-fourth of an inch. The results showed that even at these conditions the heat lost by radiation would be negligible.

VIII. SAFETY DEVICES

The following are some safety devices that should be included in the equipment to insure safety to life and limb and to prevent damage to the equipment.

A safety valve should be used somewhere in the system, as shown in Figure 7, to be certain that the maximum allowable working pressure is never exceeded. This could cause untold damage to the equipment, and result in personal injury or death.

Another safety device that should be used is one that will never allow the kilowatt capacity of the heaters to be exceeded. The failure to use this safety device could cause burnout of the heater wires and result in extensive damage and loss of time in replacing the heater. Another device that should be included is one that will prevent the heaters from operating at a temperature greater than the design point.

IX. EXPERIMENTAL PROCEDURE

Introduction

The following is the recommended procedure to be used when experiments are conducted to determine the value of superheated steam heat transfer film coefficient using the equipment so designated in this thesis and the equation (32) for the film coefficient developed in this thesis.

Start-Up

The system should first be evacuated by the vacuum pump to the lowest possible pressure to insure that most of the air has been removed. The system should then be filled by the charging pump with the correct amount of distilled water at the proper pressure so that when the system is heated the water will evaporate to steam at the proper pressure and temperature for the test run.

The system should then be heated up slowly to insure even expansion throughout and so that no hotspots develop in the system. Care should be taken to see that the steam pump is isolated from the rest of the system at this time to be sure no damage occurs to the pump.

Running of the Experiment

With the system fully charged and the steam at the desired pressure and temperature, operation of the steam pump can begin. The controls on the pump should then be set for the desired mass flow rate and so that the pressure of the steam at the test section will be held constant. The heaters in the test section can now be set for the desired amount of heat to be added to the steam as it flows through the test. Care should be taken at this point to be sure the film drop temperature remains at the value necessary for an accuracy of $\pm 10\%$ or less. The system should be allowed to reach steady-state before recording of data is begun.

To maintain a constant temperature at the test section inlet, the heating or cooling section of the test loop can be used.

When steady-state has been reached, recording of the needed data can begin. After the data has been recorded, or enough has been taken, the experimenter can change any one of the following three variables to obtain a new test run: inlet pressure, inlet temperature, or mass flow rate.

The first variable change can be made by adding to or reducing the amount of fluid in the system.

The value of the second variable can be changed by adding more heat or by removing heat.

The last variable can be changed by varying the speed of the steam pump.

When the experiments that are to be conducted are finished, the steam in the system should be exhausted to the atmosphere and the system allowed to cool slowly to reduce the hazard of thermal shock somewhere within the system.

Limitations of the Experiment

There are several items which should be checked during the running of the experiment. One of these items is the amount of fluid flow. As the flow increases, so does the pressure drop. A differential pressure gauge should be placed so that it can measure the pressure increase across the steam pump. The steam pump should be designed to handle a pressure drop of 60 PSI. When the differential pressure gauge shows a value of 60 PSI the run in progress should be completed and a new one started under correct operating conditions. At no time should the differential pressure gauge read higher than 60 PSI.

X. RECOMMENDATIONS

The error analysis investigation results have indicated that the value of the heat transfer film coefficient of superheated steam can be determined experimentally with an error of less than 10%. This is within the acceptable limits of experimental accuracy.

It is therefore feasible that a test section can be designed and built which will have the accuracy predicted in this thesis.

As the expense of such a project will be large, it is suggested that a proposal be submitted to one of the educational Foundations or an industrial firm that would be interested in a project of this nature, to solicit funds to fully design and build the equipment necessary to measure the heat transfer film coefficient of superheated steam.

It is further proposed that another Master's Thesis continue on from where this Thesis stops, and actually design the equipment necessary in the experiment.

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XIV. APPENDIX

The following is a listing of the notations used in the programme's input, output, and column heading symbols. A listing of the programme and its subroutines follow with an example of sample results at the end.

Notation

Input Statements

SYMBOL	DESCRIPTION
O	Thermal Conductivity of tube metal
DX	Distance between the thermocouples measuring surface temperature
DC	Error in determining the tube metal thermal conductivity
DRI	Error in determining the inner radius of the tube
DDX	Error in measuring distance between the thermocouples measuring surface temperature
DCP	Error in determining the specific heat of the steam
RV	Relative error of the voltmeter
RAMP	Relative error of the ammeter
RM	Relative error in measuring mass flow rate
DTS	Thermocouple inaccuracy in measuring surface temperature
DTF	Thermocouple inaccuracy in measuring the fluid temperature
DTF1	Thermocouple inaccuracy in measuring the inlet fluid temperature

SYMBOL	DESCRIPTION
DI	Inside diameter of the tube
DO	Outside diameter of the tube
B	Tube length
P	Pressure of the steam at inlet to the tube
T	Temperature of the steam at inlet to the tube

Output Statements

SYMBOL	DESCRIPTION
FD	Assumed film temperature drop
XT	Temperature of the steam at exit from the tube
ST	Surface temperature of the tube. Assumed to be that of heater wire also
SW	Mass flow rate of steam
RB	Reynolds number of the steam
WATT	Kilowatt input to the heater per foot of length including losses
HF	Heat flux
H	Heat transfer film coefficient of the steam obtained from Heineman's equation (8)
HL	Length of the heater wire
TN	Number of turns per inch of the wire around the tube
HAA	Expected error for the first equation for the film coefficient

SYMBOL	DESCRIPTION
HBB	Expected error for the second equation for the film coefficient
HCC	Expected error for the third equation for the film coefficient

Table Headings

SYMBOL	DESCRIPTION
C	Thermal Conductivity of the tube metal
DX	Distance between the thermocouples measuring surface temperature
DC	Error in determining the tube metal thermal conductivity
DRI	Error in determining the inner radius of the tube
DA	Error in measuring tube area normal to the tube axis
DDX	Error in measuring distance between the thermocouples measuring surface temperature
DCP	Error in determining the specific heat of the steam
RV	Relative error of the voltmeter
RAMP	Relative error of the ammeter
RM	Relative error in measuring mass flow rate
ET	Temperature of the steam at exit from the tube
ST	Surface temperature of the tube. Assumed to be that of heater wire also.
WS	Mass flow rate of steam

SYMBOL	DESCRIPTION
RE	Reynolds number of the steam
KW	Kilowatt input to the heater per foot of length including losses
HF	Heat flux
H	Heat transfer film coefficient of the steam obtained from Heineman's equation (8)
HL	Length of the heater wire
TN	Number of turns per inch of the wire around the tube

MAINLINE

```
DIMENSION TC(61),PC(61),CPP(61),CYU(61),VY(61),ETH(61),VU(61)
DIMENSION H(12),SW(12),WATT(12),HF(12),HL(12),TN(12),XT(12),ST(12)
DIMENSION RB(12),RF(12)
DIMENSION HAA(12),HBB(12),HCC(12)
COMMON HAA,HBB,HCC
PI=3.14159265358979323846
CZ=35.54*144.E-10/8.
CX=0.01059*CZ
CY=.8694350*CZ
CA=35.*144.E-10/.125
CB=2.1238011*CA
CC=0.01542*CA
CD=23.1*144.E-10
CE=1.4532533*CD
CF=0.013189*CD
CG=22.*144.E-10/3.375
CH=0.91660515*CG
CI=0.0117*CG
```

```
C     READ THERMAL CONDUCTIVITY OF TUBE METAL AND DISTANCE BETWEEN
C     THERMOCOUPLES.
C     READ ERROR IN THE TERMS OF THERMAL CONDUCTIVITY, INSIDE RADIUS,
C     AREA OF THE TUBE NORMAL TO THE AXIS, DISTANCE BETWEEN THERMOCOUPLES,
C     SPECIFIC HEAT, VOLTAGE READINGS, CURRENT READINGS, AND MASS FLOW
C     RATE.
      READ103,O,DX,DC,DRI,DA,DDX,DCP,RV,RAMP,RM
  103 FORMAT(F6.2,1X,F6.3,1X,F6.3,1X,F6.4,1X,F6.4,1X,F6.4,1X,F6.4,1X,F7.
     14,1X,F7.4,1X,F7.4)
      VR=RV+RAMP
      PO=1./(2.*PI*O)
      RDX=DDX/DX
      RK=DC/O
C     PUNCHING OF THE INFORMATION READ IN ABOVE.
      PUNCH104
  104 FORMAT(63H C     DX     DC     DRI    DA     DDX    DCP    RV     RAMP
     1  RM  )
      PUNCH105,O,DX,DC,DRI,DA,DDX,DCP,RV,RAMP,RM
```

```
105 FORMAT(F6.2,2F6.3,4F6.4,3F7.4/)
    K1=3
C   READ THE ASSUMED THERMOCOUPLE INACCURACY.
    READ106,DTS,DTF,DTF1
106 FORMAT(3F8.4)
C   LOADING OF THE STORAGE TABLES
    DO101 K=1,61
101 READ 102,PC(K),TC(K),ETH(K),CYU(K),CPP(K),VY(K)
102 FORMAT (3F8.2,F7.4,2F12.8)
    DO 113 I=1,61
113 READ114,VU(I)
114 FORMAT(F12.8)
    DO107 K=1,11
107 READ108,RB(K),RF(K)
108 FORMAT(F10.0,F12.2)
C   READ THE TUBE INNER AND OUTER DIAMETER.
  1 READ2,DI,DO
  2 FORMAT(F6.1,1X,F6.3)
```

```
      DODIL=LOGF(DO/DI)
      YX=PI*DI/12.
      Z=PI*(DO*DO-DI*DI)/4.
      W=O*Z
      PID=PI*DI/48.
      HA=12.*0.0133/DI
      RRI=DRI*2./DI
      RA=DA/Z
C     READ THE TUBE LENGTH.
    3 READ4,B
    4 FORMAT (F6.0)
      XX=12./(DO*PI*B)
      XY=144./(PI*DI*B)
      UY=1./XY
      TL=B/12.
C     PUNCH THE TUBE LENGTH, INSIDE DIAMETER, AND OUTSIDE DIAMETER.
      PUNCH5,B,DI,DO
    5 FORMAT(12HTUBE LENGTH=F4.0,19HINCHES, INSIDE DIA=F5.1,20HINCHES, O
```

```
     1UTSIDE DIA=F6.3,7HINCHES.)
      K2=1
C     READ THE PRESSURE AND TEMPERATURE AT INLET.
    9 READ 10,P,T
   10 FORMAT(F8.1,F8.1)
C     PUNCH THE PRESSURE AND TEMPERATURE AT INLET.
  109 PUNCH 110,P,T
  110 FORMAT(21HPRESSURE AT ENTRANCE=F6.0,25H TEMPERATURE AT ENTRANCE=F6
     1.0/)
      K3=2
      KT=0
      PP=P/14.696
      TT=T
C     STORAGE TABLE LOOK-UP
      DO131 I=1,61
      IF(P-PC(I))131,151,131
  151 IF(T-TC(I))131,161,131
  161 ETHI=ETH(I)
```

```
      CP=1./CYU(I)
      CPR=CPP(I)
      VX=VY(I)
      VIS=VU(I)
  131 CONTINUE
      HB=HA*CPR
      RCP=DCP*CP
      C5=CX*VX
      C4=CY*VX
      IF(DI-1.)6,7,8
    6 C1=CB*VX
      C2=CC*VX
      GO TO 11
    7 C1=CE*VX
      C2=CF*VX
      GO TO 11
    8 C1=CH*VX
      C2=CI*VX
```

```
   11 FD=10.
C     CALCULATION OF THE FILM COEFFICIENT AND MASS FLOW FOR THE GIVEN
C     CONDITIONS.
      DO36 I=1,11
      H(I)=HB*RF(I)
   36 SW(I)=RB(I)*PID*VIS
C     BEGINNING OF THE CALCULATIONS FOR THE HEAT INPUT AND EXPECTED ERROR
C     RESULTING FROM THE GIVEN CONDITIONS.
   29 PUNCH13,FD
   13 FORMAT(18H THE FILM DROP IS F6.0/)
      K4=2
      GO TO 32
   30 PUNCH31,FD
   31 FORMAT(18H THE FILM DROP IS F6.0,56H
     1                              -/)
      K4=2
   32 NR=1
      PUNCH14
```

```
14 FORMAT(74H   ET    ST    WS    RE    KW    HF    H
  1    HL    TN   )
   DF=1./FD
15 RE=RB(NR)
   Q=H(NR)*FD*YX
   WS=SW(NR)
   QI=H(NR)*FD*UY
   DE=QI/SW(NR)
   ETHX=ETHI+DE
   SUMT=0.4*FD*ETHX/ETHI
   CALL ETHP(PP,TT,ETHX,TX)
   TCFTS=TX-T
   XT(NR)=TX
   TF=(TX+T)*.5
   TS=TF+FD
   ST(NR)=TS
   CALL RES(TS,RC)
   CALL CUR(TS,CU)
```

```
      BC=CU*CU*RC*3.228E-3
      CALL ERROR(DX,CU,Q,O,Z,DTF1,FD,DTF,DTS,DODIL,PO,TL,TCFTS,VR,DF,W,D
     1C,DA,DDX,RA,RDX,RK,NR,WS,CP,SUMT,RM,RCP,V,RRI)
      WATT(NR)=V*CU*1.E-3
      HF(NR)=WATT(NR)*3413.*XY
      HL(NR)=WATT(NR)/BC
      TN(NR)=HL(NR)*XX
      CALL PRCHK(DI,RE,C1,C2,C4,C5,DPT)
      IF(DPT-60.)16,18,18
   16 IF(WATT(NR)-12.5)17,18,18
   17 NR=NR+1
      GO TO 15
C     PUNCH THE RESULTS OBTAINED IN THE PROGRAMME.
   18 DO19 N=1,NR
   19 PUNCH20,XT(N),ST(N),SW(N),RB(N),WATT(N),HF(N),H(N),HL(N),TN(N)
   20 FORMAT(2F8.2,F7.0,F10.0,F8.4,F8.0,F9.2,2F8.2)
      PUNCH21
   21 FORMAT(1H )
```

```
   PUNCH22
22 FORMAT(46H FIRST EQUATION-SECOND EQUATION-THIRD EQUATION)
   PUNCH23
23 FORMAT(46H PERCENT  ERROR PERCENT   ERROR PERCENT  ERROR/)
   DO24 J=1,NR
24 PUNCH25,HAA(J),HBB(J),HCC(J)
25 FORMAT(4X,F9.3,7X,F9.3,6X,F9.3)
   PUNCH26
26 FORMAT(1H /)
   K5=6
   FD=2.*FD
   IF(FD-160.)12,12,27
12 KT=K1+K2+K3+K4+K5+2*NR+KT + 1
   K1=0
   K2=0
   K3=0
   K4=0
   K5=0
```

```
   IF(KT-31)29,29,33
33 KT=0
   GO TO 30
27 PAUSE
   IF(SENSE SWITCH 2)3,28
28 IF(SENSE SWITCH 3)1,9
   END
```

SUBROUTINE ETHP

```
C     SUBROUTINE TO CALCULATE THE TEMPERATURE OF THE STEAM LEAVING THE
C     TEST SECTION.
      SUBROUTINE ETHP(PP,TT,ETHX,TX)
      A=1.89
      X=273.16
      B=2641.62
      C=10.
      CC=LOGF(C)
      D=80870.
      F=1.6246E5
      E=82.546
      H=1.2697E5
      G=0.21828
      UU=.23888888
      R=4.55504
      SS=-1.48847
      U=0.43
      QX=.101295
```

```
      HH=2502.36
      W=698.65
      AN=47.8365
      AM=7.5566E-4
      AL=1.4720
      AJ=3.635E-4
      AK=6.768E-8
      ADA=64./13.
      AY=5./9.
    9 T=AY*(TT-32.)
      TU=1./(X+T)
      ABC=1./TU
      AC=TU*TU
      V=D*AC
      ALPHA=B*C**V
      BETA=D*CC*AC
      EMU1=PP*PP*.5
      BZERO=A-TU*ALPHA
```

```
  QQ=BZERO*BZERO*BZERO*BZERO
  XX=QQ*QQ
  RR=QQ*XX
  DELTA=E-F*TU
  GAMMA=ALPHA*(1.+2.*BETA)
  R1=BZERO*BZERO*AC*(3.*DELTA-F*TU)
  R2=DELTA*TU*AC*2.*BZERO*GAMMA
  H1=R1-R2
4 G1=H1*EMU1
  ETA=G-H*AC
  AX=TU*PP
  EMU2=AX*AX*AX*AX*.25
  R3=QQ*ABC*(4.*ETA-2.*H*AC)
  R4=ETA*4.*(BZERO*BZERO*BZERO)*GAMMA
  H2=R3-R4
5 G2=H2*EMU2
  EMU3=EMU2*EMU2*EMU2*AX*ADA
  BD=1000.*TU
```

```
      BDD=BD*BD*BD*BD*BD*BD
      BDB=BDD*BDD*BDD*BDD
      Q1=AK*BDB
      Q2=AJ
      ROE=Q2-Q1
      R5=(-1.*BZERO*RR*ABC)*(13.*ROE-24.*Q1)
      R6=ROE*13.*RR*GAMMA
      H3=R5+R6
    6 G3=H3*EMU3
      S1=AL*ABC
      S2=.5*AM*ABC*ABC
      S3=AN*LOG(TU)
    7 E1=A-2.*TU*ALPHA*(1.+BETA)
      E2=PP*E1
      E3=(G1+G2+G3+E2)*QX
      ETHA=(E3+S1+S2-S3+W+HH)*U
      ET=ETHX/ETHA
      IF(ET-1.)1,8,2
```

```
1 ETHD=ETHA-ETHX
  IF(ETHD-0.10)8,8,3
3 TT=TT*ET
  GO TO 9
2 ETHD=ETHX-ETHA
  IF(ETHD-0.10)8,8,3
8 TX=TT
  RETURN
  END
```

SUBROUTINE ERROR

```
C     SUBROUTINE TO DETERMINE THE EXPECTED ERROR FROM USE OF THE THREE
C     FILM COEFFICIENT EQUATIONS UNDER THE IMPOSED OPERATING CONDITIONS.
      SUBROUTINE ERROR(DX,CU,Q,O,Z,DIF1,FD,DTF,DTS,DODIL,PO,TL,TCFTS,VR,
     1DF,W,DC,DA,DDX,RA,RDX,RK,NR,WS,CP,SUMT,RM,RCP,V,RRI)
      DIMENSION HAA(12),HBB(12),HCC(12)
      COMMON HAA,HBB,HCC
      S=1./Q
      OSZ=W
      REL=0.5
      SUM=SUMT/(DX*DX)
    4 AMP=CU
      V=(Q+O*Z*SUM)/(3.361805*AMP)
      EL=0.051195*V*AMP
      DEL=REL*EL
      FD1=FD-TCFTS
      DF1=1./FD1
      RTS1=DTS*DF1
      RTF1=DTF1*DF1
```

```
RTF=DTF*DF
RTS=DTS*DF
AA=Q*DODIL*PO*DF
AAA=AA*FD*DF1
QA=3.413*V*AMP*S
DQ=3.413*V*AMP*VR+DC*Z*SUM+O*DA*SUM+4.*DTS*OSZ/(DX*DX)+OSZ*SUMT*2.
1*DDX/(DX*DX*DX)+DEL
QB=OSZ*SUM*S
QC=1.+QB
B=1.+AA
BB=1.+AAA
G=OSZ*SUM*RA*S+4.*DTS*OSZ*S/(DX*DX)+OSZ*SUM*RDX*S+REL*EL*S
D=RK*(QB+AA*QC)
DD=RK*(QB+AAA*QC)
DDD=RK*QC
E=2.*DTF/TCFTS
F=B*(QA*VR+G)
FF=BB*(QA*VR+G)
```

```
FFF=AA*(QA*VR+G+DDD)
H1=F+RRI+RTS+RTF+D
H2=FF+RRI+RTF1+RTS1+DD+(DQ*TL*CP/WS+(RM+RCP)*TCFTS)*DF1
H3=RM+RCP+RRI+E+RDX+RTS+FFF+RTF
HAA(NR)=H1*100.
HBB(NR)=H2*100.
HCC(NR)=H3*100.
RETURN
END
```

SUBROUTINE PRCHK

```
C     SUBROUTINE TO CHECK IF THE PRESSURE DROP AROUND THE TEST LOOP
C     EXCEEDS 60 PSI.
      SUBROUTINE PRCHK(DI,RE,C1,C2,C4,C5,DPT)
      IF(DI-1.)1,2,3
    1 RN=.25*RE
      DPT=C1*RE**1.46690342+C2*RE*RE+C4*RN**1.59010742+C5*RN*RN
      GO TO 4
    2 RN=.5*RE
      DPT=C1*RE**1.52037690+C2*RE*RE+C4*RN**1.59010742+C5*RN*RN
      GO TO 4
    3 RN=.75*RE
      DPT=C1*RE**1.57910240+C2*RE*RE+C4*RN**1.59010742+C5*RN*RN
    4 RETURN
      END
```

SUBROUTINE RES

```
C     SUBROUTINE TO OBTAIN THE CHANGE IN THE RESISTANCE OF THE HEATER
C     WIRE DUE TO TEMPERATURE.
      SUBROUTINE RES(TS,RC)
      A=-.95046221E-16
      B= .53648085E-12
      C=-.10634308E-8
      D= .84401245E-6
      E=-.17871473E-3
      F= .10258839E 1
      RC=TS*(TS*(TS*(TS*(TS*A+B)+C)+D)+E)+F
      RETURN
      END
```

SUBROUTINE CUR

```
C     SUBROUTINE TO OBTAIN THE AMOUNT OF CURRENT NECESSARY TO PRODUCE THE
C     TEMPERATURE OF THE HEATER WIRE.
      SUBROUTINE CUR(TS,CU)
      A=-.46392348E-15
      B= .18376947E-11
      C=-.18966523E-8
      D= .23289488E-6
      E= .25849943E-2
      F= .43857533
      CU=TS*(TS*(TS*(TS*(TS*A+B)+C)+D)+E)+F
      RETURN
      END
```

C SAMPLE DATA FOR ONE RUN ONLY.

C	DX	DC	DRI	DA	DDX	DCP	RV	RAMP	RM
10.00	1.000	.100	.0010	.0010	.0010	.0500	.0050	.0050	.0050

TUBE LENGTH= 6.INCHES, INSIDE DIA= .5INCHES, OUTSIDE DIA= .560INCHES.
PRESSURE AT ENTRANCE= 200. TEMPERATURE AT ENTRANCE= 400.

THE FILM DROP IS 10.

ET	ST	WS	RE	KW	HF	H	HL	TN
401.10	410.55	13.	10000.	.0069	361.	16.25	.97	1.11
401.10	410.55	26.	20000.	.0119	621.	29.10	1.68	1.91
401.10	410.55	52.	40000.	.0208	1088.	52.09	2.95	3.35
401.02	410.51	104.	80000.	.0369	1924.	93.25	5.21	5.93
400.94	410.47	209.	160000.	.0655	3420.	166.92	9.27	10.54
400.85	410.42	418.	320000.	.1169	6098.	298.80	16.54	18.80
400.77	410.38	837.	640000.	.2088	10891.	534.87	29.55	33.59

FIRST EQUATION-SECOND EQUATION-THIRD EQUATION
PERCENT ERROR PERCENT ERROR PERCENT ERROR

32.072	37.252	209.082
27.734	32.190	209.091
25.321	29.406	209.106
23.992	27.596	223.195
23.282	26.484	240.983
22.946	25.799	262.325
22.864	25.415	287.281

THE FILM DROP IS 20.

ET	ST	WS	RE	KW	HF	H	HL	TN
402.40	421.20	13.	10000.	.0138	722.	16.25	1.89	2.15
402.40	421.20	26.	20000.	.0238	1243.	29.10	3.26	3.70
402.16	421.08	52.	40000.	.0417	2177.	52.09	5.71	6.49
401.94	420.97	104.	80000.	.0738	3848.	93.25	10.09	11.47
401.74	420.87	209.	160000.	.1311	6840.	166.92	17.95	20.40
401.59	420.79	418.	320000.	.2338	12196.	298.80	32.01	36.39
401.43	420.71	837	640000.	.4177	21782.	534.87	57.18	65.01

FIRST EQUATION-PERCENT ERROR	SECOND EQUATION-PERCENT ERROR	THIRD EQUATION PERCENT ERROR
17.360	20.849	102.044
15.094	18.188	102.052
13.838	16.449	110.987
13.155	15.402	121.482
12.807	14.767	133.475
12.672	14.432	144.543
12.703	14.283	158.044

THE FILM DROP IS 40.

ET	ST	WS	RE	KW	HF	H	HL	TN
404.95	442.47	13.	10000.	.0277	1444.	16.25	3.54	4.03
404.70	442.35	26.	20000.	.0477	2487.	29.10	6.10	6.94
404.22	442.11	52.	40000.	.0835	4355.	52.09	10.70	12.16
403.77	441.88	104.	80000.	.1476	7697.	93.25	18.93	21.52
403.38	441.69	209.	160000.	.2623	13681.	166.92	33.66	38.27
403.05	441.52	418.	320000.	.4677	24392.	298.80	60.05	68.26
402.73	441.36	837.	640000.	.8354	43565.	534.87	107.30	121.98

FIRST EQUATION-PERCENT ERROR	SECOND EQUATION-PERCENT ERROR	THIRD EQUATION PERCENT ERROR
10.004	12.543	54.112
8.774	10.974	56.258
8.097	9.966	61.153
7.737	9.354	66.741
7.570	8.985	73.036
7.535	8.799	79.459
7.623	8.753	87.115

THE FILM DROP IS 80.

ET	ST	WS	RE	KW	HF	H	HL	TN
410.12	485.06	13.	10000.	.0554	2890.	16.25	6.26	7.12
409.30	484.65	26.	20000.	.0954	4976.	29.10	10.80	12.28
408.32	484.16	52.	40000.	.1670	8711.	52.09	18.94	21.53
407.47	483.73	104.	80000.	.2952	15396.	93.25	33.51	38.10
406.68	483.34	209.	160000.	.5247	27363.	166.92	59.63	67.79
406.01	483.00	418.	320000.	.9355	48785.	298.80	106.42	120.98
405.38	482.69	837.	640000.	1.6708	87131.	534.87	190.24	216.27

FIRST EQUATION-PERCENT ERROR	SECOND EQUATION-PERCENT ERROR	THIRD EQUATION PERCENT ERROR
6.327	8.380	31.029
5.614	7.378	32.760
5.226	6.738	35.315
5.028	6.349	38.078
4.951	6.113	41.279
4.967	6.003	44.721
5.083	6.011	48.771

THE FILM DROP IS 160.

ET	ST	WS	RE	KW	HF	H	HL	TN
420.63	570.31	13.	10000.	.1108	5782.	16.25	10.04	11.41
418.69	569.34	26.	20000.	.1909	9955.	29.10	17.32	19.69
416.71	568.35	52.	40000.	.3341	17424.	52.09	30.39	34.55
414.93	567.46	104.	80000.	.5905	30794.	93.25	53.84	61.21
413.33	566.66	209.	160000.	1.0495	54728.	166.92	95.88	108.99
411.94	565.97	418.	320000.	1.8711	97572.	298.80	171.23	194.66
410.67	565.33	837.	640000.	3.3418	174265.	534.87	306.29	348.20

FIRST EQUATION-SECOND EQUATION-THIRD EQUATION
PERCENT ERROR PERCENT ERROR PERCENT ERROR

4.491	6.310	19.709
4.035	5.598	20.720
3.792	5.142	22.002
3.674	4.854	23.460
3.642	4.682	25.10[illegible]
3.683	4.610	26.940
3.813	4.643	29.084

ABSTRACT

After reviewing all available literature on heat transfer to superheated steam at high temperatures and pressures, it was concluded that further investigation of this problem would be of value.

The thesis was concerned with the derivation of three heat transfer film coefficient equations and their related error equations. The three equations thus derived were not used to determine the value of the heat transfer film coefficient. No experimentation was performed to obtain the necessary data required by the three equations for calculating the heat transfer film coefficient value.

Instead an error analysis was made of the film coefficient equations using the derived error equations. Prediction of the most accurate film coefficient equation was made based on results obtained from this analysis.

Recommendations for the test apparatus and arrangement, test section design, and experimental procedure were advanced based on the error analysis results.

No attempt was made in the thesis to develop an experimental heat transfer film coefficient equation similar to the equations found in the reviewed literature.