An Experimental Investigation of the Air-Side Convective Heat Transfer Coefficient on Wire and Tube Refrigerator Condenser Coils

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ABSTRACT

This thesis presents the results of an experimental investigation of the convective airside heat transfer from wire and tube condensers. The first law of thermodynamics is applied to the "refrigerant", water in this investigation, flowing through the tubes in order to determine the total heat loss from the condenser. The test section is 910 mm (36 in) wide by 300 mm (12 in) tall; thus the coil is tested in an essentially infinite stream. During the course of the experiments, the influence of the free stream air velocity ranging from 0.15 m/s to 2.0 m/s (0.49 ft/s to 6.56 ft/s) is established. The angle of attack, α , was varied from - 40 degrees to 40 degrees with the air flow always normal to the tubes ($\psi = \pi/2$) and varied from -20 degrees to 20 degrees with the air flow normal to the wires ($\psi = 0$). A method for calculating view factors and the radiation heat transfer for wire and tube condensers is derived. The effect of the length of the coil is measured at 0 and -5° angle of attack. In addition, the influence of the fin efficiency on the heat transfer is investigated and accounted for in the definition of the heat transfer coefficient. The heat transfer data in the inertia dominated regime (Richardson number less than 0.0013) are correlated assuming $Nu_{coil} = f(Re, \alpha, \psi) \cdot g(S_w^*)$ with the Reynolds number based on the wire diameter. The range of Reynolds numbers covered is $15.7 < \text{Re}_w < 207.5$. The ranges of coil geometric parameters (nondimensionlized by dividing by the wire diameter) covered in this study are: 3.022 < nondimensional tube diameter < 5.134, 18.84 < nondimensional tube spacing < 5.134, 18.84 < 1.03440.94, 2.819 < nondimensional wire spacing < 4.427, 53.80 < nondimensional tube length < 143.6, and 207.2 < nondimensional wire length < 500.2. The function is represented by $f_1(\alpha) \cdot \operatorname{Re}^{f_2(\alpha)}$ for $\psi = 0$ and $f_3(\alpha) \cdot \operatorname{Re}^{f_4(\alpha)}$ for $\psi = \pi/2$. Approximately 1700 tests were performed in this investigation using seven different coils. The final correlation is capable of predicting the data with 2σ equal to 16.7% for Ri < 0.0013. A limited natural convection study is also presented.

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NOMENCLATURE

- A area, m²
- cp constant pressure specific heat, J/kg K
- D diameter, m
- g acceleration of gravity, 9.81 m/s^2
- h heat transfer coefficient, W/m^2 K
- k thermal conductivity, W/m K
- L length, m
- N number
- q heat flow rate, W
- q_{max} $hA_{fin}\Delta T_{max}$
- S centerline-to-centerline spacing, m
- T temperature, K
- V veloicity, m/s

Dimensionless Groups

- Gr Grashof Number, $g\beta(T_h-T_c)L^3/v^2$
- m fin parameter, $[hS_t^2/kD_w]^{1/2}$
- Nu Nusselt number, hL/k
- Ra Rayleigh number, Gr.Pr
- Re Reynolds number, VD/v
- Pr Prandtl number, $\mu c_p/k$

Greek Symbols

- α angle of attack, deg
- β volume coefficient of expansion, K⁻¹
- δ thickness, m
- ε emissivity
- η fin efficiency, q/q_{max}
- μ dynamic viscosity, kg/m-s
- ρ density [kg/m³]
- σ Stefan Boltzman's constant, 5.67x10⁻⁸, W/m²-K⁴
- v kinematic viscosity, m²/s

Subscripts

- a air
- e effective
- f based on film temperature
- i internal
- p paint
- r refrigerant (water in this investigation)
- rad radiation
- s steel or surrounding
- t tube
- w wire

Superscripts

* dimensionless quantity

1. INTRODUCTION

1.1 Motivation

Refrigerator condensers reject heat. One of the largest resistances to the heat flow from the condenser is the air side resistance, accounting for as much as 95% of the resistance when the refrigerant is in the two phase region (Admiraal and Bullard, 1993). By determining influential factors in the air side resistance, condenser coils can be designed to operate more efficiently. This will result in smaller, less expensive condensers.

In addition, the heat transfer coefficient for a single wire in cross flow of the same size used in a refrigerator condenser is approximately 6 times that of a typical condenser coil operating in a horizontal position, the position used in most refrigerators. This demonstrates the unrealized heat dissipation potential of a wire and tube condenser (Note: the condensers tested ranged from 60 to 81% wires by surface area.)

Seven wire and tube condensers from 4 manufacturers were tested at velocities ranging from 0.15 to 2 m/s (.5 to 6.6 ft/s) at numerous angles in a uniform air flow. The tube spacing varied from 25 to 51 mm (1 to 2") and the wire spacing varied from 4.6 to 6.8 mm/wire (0.17 to 0.27 inches/wire). All tube diameters tested were 4.8 mm (3/16") with the exception of one which was 6.4 mm (1/4").

1.2 Project Goals

This project has three main goals:

- (i) to design and construct an experimental facility tailored to test wire and tube refrigerator condenser coils,
- (ii) to experimentally evaluate the performance of a variety of wire and tube condenser designs and configurations,
- (iii) to investigate key variables in order to determine their effect on condenser performance.

2. LITERATURE REVIEW

No published studies of forced flow over refrigerator condenser coils were found in the literature. Studies of free convection over condenser coils have been conducted.

Witzell, Fontaine and Papanek investigated the effect of wire spacing on the heat transfer characteristics of a horizontal wire and tube condenser coil in free convection (1959). They defined an overall heat transfer coefficient:

$$h_{tot} = \frac{Q_{total}}{A_{tot}\Theta_t}$$
(2.1)

For 2.3 mm (0.0915" or 13 gauge) wires, the heat transfer was found to reach a maximum at a particular wire spacing and then decreased as the number of wires per unit length increased. They attributed the decrease in heat transfer to boundary layer interference. Using

$$N_{Nu} = c[N_{Gr}]^{a} \left[1 - \frac{1}{S_{w}^{*}} \right]^{b}$$
(2.2)

they were able to collapse they data and account for the interfering boundary layers. As will be shown, our experiments with forced convection required a geometric factor similar to that used by Witzell et al. to correlate the data.

The characteristic length used by Witzell et al. is

$$D_{c} = \left[\frac{A_{t} + A_{w}}{\frac{A_{t}}{D_{t}^{1/4}} + \frac{\eta A_{w}}{D_{w}^{1/4}}}\right]^{4}$$
(2.3)

In free convection the characteristic length of both the tubes and the wires is the diameter. In forced convection over a horizontal coil, only the element aligned perpendicular to the air flow has a characteristic length equal to its diameter. The other element has flow along its axis with no evident characteristic length. For our studies the characteristic length is chosen to be the diameter of the wire as most of the heat transfer from a well designed condenser coil should come from the wires, the extended surface. In general, our studies showed that better heat transfer is obtained when the flow is perpendicular to the wires as opposed to perpendicular to the tubes.

A radiation study of condenser coils was also done by Collicott, Fontaine and Witzell (1963). In this study, the coil was placed in a vacuum chamber and the heat loss due to radiation was measured. The "view factor" from the coil to its surroundings was then calculated.

$$q_{rad} = F_e \varepsilon_E \left(T_s^4 - T_a^4 \right) \tag{2.4}$$

Because the wire on the condenser coil is not isothermal, the "view factor" calculated in this manner is a function of variables other than just geometry and therefore not a true view factor.

$$F_e = F_e(\eta, D_w, D_t, S_w, S_t)$$
(2.5)

$$\eta = \eta (h_{rad}, h_c, k_s, D_w, S_t)$$
(2.6)

In calculating the fin efficiency with radiation present, an effective heat transfer coefficient,

$$h_e = h_{rad} + h_c \tag{2.7}$$

must be used. However, in a vacuum h_c is no longer present. Therefore, when this view factor is applied to a coil with convection present, the radiation contribution will be over predicted. When η is close to one, this approximation is valid. In our studies, η ranged from 0.57 to 0.95.

Another study on the heat transfer characteristics of wire and tube condensers in free convection was done by Cyphers, Cess, and Somers (1959). They defined an overall heat transfer coefficient identical to Eq. (2.1). In addition, by examining the characteristic equations, they were able to modify the free convection results for a horizontal cylinder to predict yawed cylinders. This was accomplished by the addition of the cosine of the yaw angle. This method breaks down near 90° so the correlation for a vertical cylinder was used for this point.

3. EXPERIMENTAL FACILITY AND PROCEDURE

3.1 Wind Tunnel

An induced flow wind tunnel was designed to measure the effects of air velocity over the condenser coil. The wind tunnel that was constructed produces a uniform air flow from 0.15 to 2 m/s (0.5 to 6.6 ft/s). The wind tunnel test section has a 0.3 by 0.91 m (1 by 3 ft) cross section, and is 0.76 m (30") long. The airflow is induced by a Dayton backward inclined centrifugal fan powered by a Dayton 3/4 hp variable speed DC motor.

The airflow is conditioned by a 150 mm (6") honeycomb flow straightener and five nylon window screens before it enters the test section. See Figure 3.1. This flow conditioning section is made of grade A/C plywood with the A or smooth side on the inside of the tunnel. Foam insulation board is used to recess the screen frames. The foam is lightweight and easily cut to hide the screen frames. Many of the ideas for the wind tunnel design were obtained from Kutscher's Thesis (1992).



Figure 3.1 Schematic Diagram of Wind Tunnel

The test section is made of 13 mm (1/2") Plexiglas, supported by an aluminum frame. Coils are supported in the test section by four pieces of 6.3 mm (1/4") threaded rod. The coil sits on a plastic nut at the top of the threaded rod and is secured by a disposable plastic tie. The nuts minimize the amount of heat conducted from the condenser coil because of the low conductivity of the plastic. The losses are estimated to

be less than 0.1 W (.34 Btu/hr). The threaded rod allows the coil to be mounted at any height in the wind tunnel and at various angles.

After the test section, there is an 2.44 m (8') converging, square to round, galvanized sheet metal section that draws the flow down from the 0.91 by 0.3 m (3' by 1') cross section to the 0.254 m (10") circular fan inlet. This section is connect to the fan via a 0.2 m (8") long flexible duct section. The fan outlet connects to a commercially available duct that exhausts into the room.

Because the wind tunnel is located in a small room, there are several screens strategically placed in the room to dissipate eddies. This helps to achieve uniform conditions at the entrance of the wind tunnel.

These room modifications in combination with the contraction, flow straighteners and screens yield a 2.5% flow uniformity across the test section and the flow remains steady to within 2.5%. The turbulence at 2 m/s (6.6 ft/s) is below 1%. These measurements were made with a TSI IFA 100 hot wire anemometer.

3.2 Hot Water Loop

Hot water is used as the refrigerant since its an excellent heat transfer medium, it's properties are well know, and it is inexpensive. The water is preheated in a domestic hot water heater and then flows through a constant temperature bath. There are two heat exchangers in the bath. The water flows through the heat exchangers and exits the bath at approximately the same temperature as the bath. The heat exchanger effectiveness is estimated to be 0.99. The temperature of the bath is controlled by an on/off controller which activates a 4000 Watt heater. The heater is turned on and off when the bath temperature deviates from the set temperature. The bath temperature is held at 322 ± 0.11 K (120 ± 0.2 °F) for all tests unless otherwise noted. The bath is stirred by two circulation pumps. After the water exists the bath it travels through insulated tubing to the condenser coil being tested. The thermocouples measuring the temperature of the water at the exit of the inlet mixing cup deviates less than 1μ V during a particular test. 1μ V corresponds to approximately 0.025 °C (0.045°F). For more detailed information on the water loop see Swofford, 1995.

A mixing cup instrumented with two calibrated type T thermocouples inserted 25 mm (1") into the flow is used to measure the water temperature immediately before the water enters the condenser coil, see Fig. 3.2. The same type of arrangement is used as the water exits the condenser coil. The four thermocouples used to measure the inlet and outlet temperatures were calibrated in a constant temperature bath. With these four

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calibrated thermocouples the error incurred in measuring a 3 K temperature change is about 0.83%.



Copper-Constantan, type T, thermocouples are used to measure all temperatures. The thermocouples used in the mixing cup are 1mm (.040") diameter, stainless steel sheathed, and grounded. All of the thermocouples are referenced to an ice point reference. The thermocouple emf's are measured with a Fluke digital voltmeter which has a resolution and accuracy of 1 μ V. The thermocouples used to measure the air and water temperatures are calibrated, and are accurate to within ± 0.05 K (0.09 °F). Therefore, the error in measuring a temperature difference could reach 0.1 K (0.18 °F).

An accurate determination of the mass flow rate of the water is also critical. The mass flow rate is adjusted by changing the supply pressure. This pressure is controlled using a pressure regulator. The mass flow rate is adjusted to obtain an appropriate temperature drop across the coil. If the mass flow rate is too high, the temperature drop across the coil will be too small, and the error in the temperature measurements becomes too high. If the mass flow rate is too low, then the water temperature drop across the coil is too large to simulate a condensing fluid. The water which passes through the coil during a test is collected and weighed. A stopwatch is used to measure the time over which the water is collected. The error in this measurement is lower than that of the temperature measurement, being less than $\pm 0.47\%$. As a rule, the water is collected for either 180 seconds, or until 2500 grams (5.5 lb_m) accumulates, whichever takes longer.

3.3 Experimental Procedure

The first step is to place a coil in the wind tunnel at the desired orientation. The air flow is started and adjusted until the desired velocity is achieved. Then the water mass flow rate is adjusted until the water temperature drop across the coil is between 3 and 5 K. The system is allowed to come to steady state, usually less than a minute. The water, after passing through the condenser coil, is directed into a container on an

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electronic scale; simultaneously, a stopwatch is started. While water is being collected, the operator records all relevant temperatures: inlet and outlet water temperatures, air temperatures, and test section surface temperatures. These temperatures are recorded three times during a test and averaged. The velocity of the air is also recorded. By now, the mass flow rate measurement should be close to completion. The velocity is incremented and the measurement procedure is repeated. Velocities typically used are 0.20, 0.25, 0.35, 0.5, 0.64, 0.75, 0.88, 1.0, 1.17, 1.34, 1.5, 1.67, 1.84, and 2.00 m/s (.66, .82, 1.2, 1.6, 2.1, 2.5, 2.89, 3.27, 3.9, 4.4, 4.92, 5.5, 6.04, and 6.6 ft/s). Typical angles used are horizontal, ± 5 , ± 10 , ± 15 , ± 20 , ± 30 , ± 40 degrees. These angles are limited by the cross section of the wind tunnel and the length of the condenser coil being tested. The angle of attack with flow perpendicular to the wires is limited to $\pm 20^{\circ}$.

4. DIMENSIONLESS ANALYSIS AND DATA REDUCTION

4.1 Dimensionless Analysis

The equations governing the air-side convective heat transfer from an **isothermal** wire-and-tube condenser, including the external geometrical aspects of this heat exchanger, show:

$$Nu_{w} = f_{w} \left(Re_{w}, Ri_{w}, Pr, \alpha, \psi, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*}, L_{w}^{*} \right)$$

$$(4.1)$$

and

$$Nu_{t} = f_{t} \left(Re_{t}, Ri_{t}, Pr, \alpha, \psi, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*}, L_{w}^{*} \right)$$

$$(4.2)$$

The Nusselt numbers in eqs. (4.1) and (4.2) are defined as

$$Nu_{w} \equiv \frac{h_{w}D_{w}}{k_{a}}$$
(4.3a)

where

$$h_{w} \equiv \frac{q_{w}}{A_{w} (T_{coil} - T_{a})}$$
(4.3b)

and

$$Nu_{t} \equiv \frac{h_{t}D_{t}}{k_{a}}$$
(4.4a)

where

$$h_{t} \equiv \frac{q_{t}}{A_{t} (T_{coil} - T_{a})}$$
(4.4b)

The angles α and ψ are defined as the angle of attack and the yaw, respectively. ψ is defined as being 0 for the case of flow perpendicular to the wires (consider $\theta < \pi/2$) and

 $\pi/2$ if the flow is perpendicular to the tubes. A single wire-and-tube matrix is being considered; it is assumed to be located in a uniform flow field that is essentially infinite in extent.

Air is the fluid of interest in this investigation; thus, the influence of the Prandtl number, need not be resolved. For the low velocities of interest, buoyant forces are known to be of importance in some situations. Hence, the Grashof number, or the Rayleigh number, $Ra \equiv Gr \cdot Pr$, or the Richardson number, $Ri \equiv Gr/Re^2$, or some other combination of these groups must be included.

The extent of the coil in the direction perpendicular to the velocity vector should have minor influences for the wire and tube lengths of interest. Thus, it would appear prudent to consider the following two cases separately: Case I, Flow perpendicular to Wires ($\psi = 0$) and Case II, Flow perpendicular to tubes ($\psi = \pi/2$). For brevity, only the relationships for Case 1 will be given. Equations (4.1) and (4.2) for Case I reduce to:

$$Nu_{w} = f_{w} \left(Re_{w}, Ri_{w}, \alpha, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*} \right)$$

$$(4.5)$$

and

$$Nu_{t} = f_{t} \left(Re_{t}, Ri_{t}, \alpha, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*} \right)$$

$$(4.6)$$

Even for the case of air flowing over an isothermal coil, the task at hand is overwhelming. Four functional relationships among eight dimensionless groups need to be established.

In an optimum wire-and-tube heat exchanger design, the wires are not isothermal surfaces; thus, the influences of the temperature gradients in the wires needs to be taken into account. To simplify the next step of the analysis, assume the tubes are isothermal surfaces, and the wire temperature at the wire/tube interface is equal to the surface temperature of the tubes. Assume further that the heat transfer coefficient averaged over the circumference of the wire does not vary along the wire.

The temperature distribution along the wire drastically influences the heat exchanged by the wire in many designs; hence, this influence must be accounted for in the dimensional analysis. In order to reduce the dependence of h_w on the temperature gradients in the wire, the area in the definition of h_w will be replaced by the effective wire area—the area times the fin efficiency η . That is:

$$h_{w} \equiv \frac{q_{w}}{A_{w}\eta(T_{t} - T_{a})}$$
(4.7)

where the fin efficiency of the wire follows from an analysis of this extended surface. It is:

$$\eta \equiv \frac{q_{w}}{q_{max}} = \frac{\tanh m}{m}$$
(4.8)

where

$$m^2 = \frac{h_w S_t^2}{k_w D_w}$$
(4.9)

and

$$q_{max} \equiv A_w h_w (T_t - T_a)$$
(4.10)

The fin parameter m, a dimensionless parameter, indicates the importance of the temperature gradients in the wires. m^2 is the ratio of the internal conductive resistance of the wire to the external convective resistance between the wire and the surrounding air.

The parameter, m, can be alternatively written in terms of S_t^* and Nu_w. Specifically,

$$m^{2} = \left(S_{t}^{*}\right)^{2} Nu_{w} \left(\frac{k_{a}}{k_{w}}\right)$$
(4.11)

If q_w were known, eqs. (4.7), (4.8), and (4.11) clearly show that a transcendental equation must be solved to determine h_w .

Refrigerator condensers are inexpensive heat exchangers because they are made out of steel wire and steel tubes, and the two elements are easily spot-welded together. Thus, for this application, (k_a/k_w) is a constant. Equation (4.11) shows that if (k_a/k_w) is a

constant, m is not an additional, independent variable; hence, eqs. (4.5) and (4.6) are still valid even for applications with highly non-isothermal wires.

Equations (4.3b) and (4.7) are both theoretically acceptable definitions for h_w . Although the use of Definition (4.7) requires the solution of a transcendental equation in order to determine h_w (given q_w , T_t and T_a), this definition removes the otherwise strong dependence of Nu_w on S_t^* . This is a significant accomplishment. Since the wire area accounts for approximately 2/3 of the total area in a typical wire-and-tube condenser, and since h_w is typically considerably larger than h_t , the tube spacing (or fin efficiency) strongly influences the air-side performance of such condensers. However, if Definition (4.7) is used, the influence of S_t^* on Nu_w becomes a secondary influence.

A fundamental problem in deducing correlations (4.5) and (4.6) is separating the rate of heat exchange with the wires from the total rate of heat transfer. The latter is the only quantity that can be easily measured. In addition, the tube and wire boundary layers interact extensively. For these reasons, let us consider looking at the condenser as a single surface.

4.2 Definition of Coil Heat Transfer Coefficient

In considering the wire-and-tube condenser as a single surface, two immediate questions arise. What definition should one use for the average heat transfer coefficient over the coil, h_{coil} , and what characteristic length should be used? Obvious choices for the characteristic length are D_w , D_t , and some weighted average of these two lengths, for example, an area weighted average. It should be noted that one of the areas cannot be defined in terms of the lengths being used since the transverse length of the coil has been discarded. Since the wires are hypothesized to be dominant, D_w will be used as the characteristic length.

Consider next the definition of the average heat transfer coefficient, h_{coil} . Commonly, the average heat transfer coefficient over an object is based on its total surface area; that is,

$$\dot{\mathbf{h}}_{\text{coil}} \equiv \frac{q}{\left(\mathbf{A}_{t} + \mathbf{A}_{w}\right)\left(\mathbf{T}_{t} - \mathbf{T}_{a}\right)}$$
(4.12)

where

$$Nu_{coil} = \frac{h_{coil}D_w}{k_a}$$
(4.13)

and

$$Nu'_{coil} = f\left(Re_w, Ri_w, \theta, S_w^*, S_t^*, D_t^*, L_t^*\right)$$
(4.14)

Unfortunately, definition (4.12) does not compensate for the fin efficiency of the wires; hence, Nu_{coil} would be a strong function of S_t^* in regimes where the fin efficiency is significantly less than unity.

A better choice for the definition of h_{coil} would appear to be:

$$h_{coil} \equiv \frac{q}{(A_t + A_w \eta)(T_t - T_a)}$$
(4.15)

Although one might think we are back to needing h_w so that the fin efficiency of the wires, η , can be calculated, it is more consistent with Eq. (4.15) if h_{coil} is used in calculating η . Note that Eq. (4.15) gives:

$$q = (h_{coil}A_t + h_{coil}A_w\eta)(T_t - T_a)$$
(4.16)

Definition (4.12) would appear to be appropriate if h_t were approximately equal to h_w and the wires were isothermal surfaces at T_t . Definition (4.15) accounts for the temperature gradients in the wires but still seems like it would only effectively collapse the data if h_t were approximately equal to h_w .

In an effort to find a better way of reducing the dependency of Nu on the geometrical parameters, consider the calculation of q if h_w and h_t were known.

$$q = (A_t h_t + \eta A_w h_w)(T_t - T_a)$$

$$(4.17)$$

Solving Eq. (4.17) for h_w gives:

$$h_{w} = \frac{q}{\left(A_{t}\frac{h_{t}}{h_{w}} + \eta A_{w}\right)\left(T_{t} - T_{a}\right)}$$
(4.18)

To reduce Eq. (4.18) to a useful definition, h_t needs to be eliminated. Is this possible?

The wire area accounts for approximately 2/3 of the total area in typical wire-andtube refrigerator condensers in use today. In addition, the convective heat transfer coefficients over the wires are generally expected to be much larger than those over the tubes. Thus, the second term in the denominator of Eq. (4.18) will be appreciably larger than the first term except for cases where the fin efficiency is low. Most current condenser designs appear to be operating at values of η greater than 0.6.

Providing a means of accurately estimating h_t , that is of general utility, appears unlikely; however, it may be possible to derive a viable estimate of h_t/h_w . Consider, for example, the two limits of natural convection from a single horizontal cylinder and pure forced convection with flow normal to a single cylinder. In the regimes of interest (10⁻² < Ra < 10²; 40 < Re < 4000), published correlations for both of these limits show that

$$h \propto D^{-n}$$
 (4.19)

where n is approximately equal to one half. Thus, if the same correlation were applicable to both surfaces, one obtains

$$\frac{\mathbf{h}_{t}}{\mathbf{h}_{w}} \cong \left(\mathbf{D}_{t}^{*}\right)^{-0.5} \tag{4.20}$$

If this approximation is used in Eq. (4.18), it becomes:

$$h_{w} = \frac{q}{\left(\frac{A_{t}}{\sqrt{D_{t}^{*}}} + \eta A_{w}\right) (T_{t} - T_{a})}$$
(4.21)

For the seven wire-and-tube condensers investigated to date,

$$\frac{\frac{A_t}{\sqrt{D_t^*}}(100\%)}{\frac{A_t}{\sqrt{D_t^*}} + A_w}$$

varies from 11.2% to 25.2%.

In some regimes, the approximation represented by Eq. (4.20) is expected to be very accurate, e.g., for cases with θ near $\pi/2$. In these regimes, h and η obtained using Eq. (4.21) are representative of the average heat transfer coefficient and the average fin efficiency of the wires in the coil. On the other hand, in regimes where Eq. (4.20) is a poor approximation, the values of h_w calculated from Eq. (4.21) will not be representative of the average heat transfer coefficient over the wires. It should be remembered, however, that no error has been made. Equation (4.21) is a definition. To avoid misinterpretations, h_w in Eq. (4.21) will be replaced by h_{coil}. Specifically, the following definition will be used:

(4.22)

$$h_{coil} \equiv \frac{q}{\left(\frac{A_{t}}{\sqrt{D_{t}^{*}}} + \eta A_{w}\right) (T_{t} - T_{a})}$$
(4.23)

also

$$Nu_{coil} = f(Re_w, Ri_w, \theta, S_w^*, S_t^*, D_t^*, L_t^*), \psi = 0$$

$$(4.24)$$

where

$$Nu_{coil} = \frac{h_{coil}D_{w}}{k_{a}}$$
(4.25)

and

$$\eta = \frac{\tanh m}{m} \text{ where } m^2 = \left(S_t^*\right) Nu_{\text{coil}}\left(\frac{k_a}{k_w}\right)$$
(4.26)

When correlation (4.24) becomes available, the heat transfer from the coil must be calculated from the following equation:

$$q = \left\{ Nu_{coil} \frac{k_a}{D_w} \right\} \left(\frac{A_t}{\sqrt{D_t^*}} + \eta A_w \right) (T_t - T_a)$$
(4.27)

where η is determined from Eq. (4.26).

4.3 Internal Resistance

By using a single phase refrigerant, (water) the internal resistance in our experiments can be easily removed to give a better estimation of the air side convective heat transfer. The model for the heat flow is shown below in Fig. 4.1.



Figure 4.1 Internal Resistance

Where R_r is

$$R_r = \frac{1}{h_r A_i}$$
(4.28)

and

$$h_{r} = \frac{Nuk_{w}}{D_{i}} = \frac{k_{w}}{D_{i}} \frac{\binom{f}{8}(Re_{D} - 1000)Pr}{1 + 12.7\binom{f}{8}^{1/2}(Pr^{2/3} - 1)} 0.5 < Pr < 2000 \text{ and } 2300 < Re_{D} < 5X10^{6} (4.29)$$

where

$$f = (0.79 \ln Re_D - 1.64)^{-2}$$
(4.30)

and properties for the Reynolds number are calculated at T_m (Gnielinski, 1976). The steel resistance is simply

$$R_{s} = \frac{\ln\left(\frac{D_{e}}{D_{i}}\right)}{2\pi Lk_{s}}$$
(4.31)

Te can then be calculated using

$$T_e = T_r - q(R_r + R_s)$$
 (4.32)

and a more accurate estimation of the convective and radiative heat transfer is obtained. T_r and q are measured in our experiments and R_r and R_s are easily calculated.

4.4 Radiation

With the assumption that the painted wire and tube surface is diffuse and gray, view factors can be calculated and the radiation contribution can be computed. The heat lost due to radiation is calculated for each tube pass. Each pass is broken up into four nodes, and a fifth node is the surroundings. The first three nodes are a primary tube pass and the two adjacent tube passes. The fourth node is the wires and the fifth node is the surroundings. The equations for the radiation heat transfer are given in eqs. (4.33), (4.34) and (4.35).

$$\mathbf{q}_{\text{out},i}^{"} = \varepsilon_{i} \mathbf{e}_{\mathbf{b}_{i}} + (1 - \varepsilon_{i}) \mathbf{q}_{\text{in},i}^{"}$$
(4.33)

$$q_{in,i}^{"} = \sum_{j=1}^{3} q_{out,j}^{"} F_{ij}$$
 (4.34)

$$q_i = q_{out,i} - q_{in,i}$$

$$(4.35)$$

 $q_{out,i}^{"}$ and $q_{in,i}^{"}$ are the radiosity and the irradiation for a particular surface respectively, and $q_{i}^{"}$ is the net radiative heat flux leaving the surface "i". ε_{i} is the emissivity of surface "i" and $e_{b_{i}}$ is the black body emission. F_{ij} is the view factor: the fraction of the diffuse energy leaving surface "i" that is intercepted by surface "j".

Calculating the radiative exchange requires knowledge of the surface temperatures for all five nodes. The surface temperature of a tube and the base temperature of the wires are approximated by the effective temperature at the center of the tube pass given be Eq. (4.32). The gradient in the wire is not treated exactly; rather the wire is assumed to be an isothermal surface at the average temperature that would result in the same convective heat exchange. This temperature follows from the definition of the fin efficiency as:

$$T_{avg_{w}} = T_{a} + \eta \bullet \left(T_{base_{w}} - T_{a} \right)$$
(4.36)

The wires are modeled as fins with an adiabatic tip located halfway between the tubes; hence, the length of all fins is equal to half of the tube spacing. The fin efficiency of the wires is calculated by using an estimated wire heat transfer coefficient. h_{coil} is calculated using Eq. (4.23) and this value is used to calculate the fin efficiency. Note that this coil heat transfer coefficient includes the loss due to radiation, as well it should since the temperature profile in the wire is effected by the amount of radiation loss.

The surface temperatures of the test section walls are measured with thermocouples mounted on the top and bottom of the inside of the test section. These thermocouples are in the center of the test section, the location receiving the highest radiative flux from the coil. Therefore, two thirds of the difference between the average of these test section temperatures and the ambient temperature is added to the ambient temperature as a representative value for the temperature of the surroundings. This is an estimate of the average surface temperature.

Given all surface temperatures, the emissivity and view factor are left to be determined. The emissivity of all painted surfaces on the coil is assumed to be 0.95. The emissivity of the Plexiglas test section is assumed to be 1.

Consider now, the determination of the view factors for the geometry shown in Fig. 4.2. The tubes are parallel to one another and orthonormal to the wires.



Figure 4.2 Wire and Tube Geometry of Interest

The condenser tubes and wires are approximated as infinite cylinders. Thus, the view factor from a single tube or wire to an adjacent tube or wire can be calculated (Howell, 1982), see Fig. 4.3 and eqs (4.37) and (4.38).





$$X = \frac{P}{d}$$
(4.37)

$$F_{12} = \frac{2}{\sqrt{X^2 - 1} + \sin^{-1}(\frac{1}{2}) - X}$$
(4.38)

$$\pi \begin{bmatrix} \pi \\ X \end{bmatrix} = F_{13} = F_{23} = F_{24} = \frac{1 - F_{12}}{2}$$
(4.39)

Eq. (4.39) gives an expression for the view factor from the half cylinder to the imaginary surfaces shown in Figure 4.3. Using reciprocity and summation, the view factors from the imaginary surfaces, 3 and 4, can be calculated; see Fig. 4.4 and eqs. (4.40) and (4.41).



Figure 4.4 View factors from Imaginary Surface

$$F_{31} = F_{32} = F_{41} = F_{42} = \frac{\pi d}{2P} F_{13}$$

$$F_{34} = F_{43} = 1 - 2 \bullet F_{31}$$
(4.40)
(4.41)

The view factor from the tubes to the imaginary surface, F_{t3} , see Fig. 4.3, is given by Eq. (4.39), where surface 1 is now a tube. The imaginary surface is shown again in Fig. 4.4, where surface 1 can be viewed as a wire. The view factor from the imaginary surface to the wires, F_{3w} , is given by Eq. (4.40). By multiplying the view factor from the tubes to the imaginary surface and the view factor from the imaginary surface to the wires, the view factor from the tubes to the wires is obtained:

$$\mathbf{F}_{\mathsf{tw}} = 4 \bullet \mathbf{F}_{\mathsf{t3}} \bullet \mathbf{F}_{\mathsf{3w}} \tag{4.42}$$

$$\mathbf{F}_{wt} = 2 \bullet \mathbf{F}_{w3} \bullet \mathbf{F}_{3t} \tag{4.43}$$

Similarly, the view factor from the wires to the tubes is obtained, see Eq. (4.43). The view factor from tube to tube is straightforward, use Eq. (4.38); however, the view factor from wire to wires is more complicated. Similar to a tube, any particular wire sees two adjacent wires; however, a wire also sees wires located in the plane on the other side of

the tubes, (see Fig. 4.5). The wires in the opposite plane are partially blocked by the tubes. The total view factor from wire to wire is determined by adding the view factors from a particular wire, A to all of the surrounding wires.



Figure 4.5 Wire Geometry

The percentage of energy which leaves wire A and goes toward the tubes through imaginary surface C is given below in Eq. (4.44) where F_{AB} is computed from eqs. (4.37) and (4.38).

$$F_{AC} = \frac{1 - 2 \bullet F_{AB}}{2} \tag{4.44}$$

Once the energy passes surface C, some of the energy is intercepted by the tubes. The portion which gets through the tubes to surface D is given by Eq. (4.41). The tubes are not shown in Fig. 4.5, but they are orthogonal to the wires and run from parallel to surfaces C and D.

The view factor from A to E is computed using eqs. (4.37) and (4.38) for parallel circular half cylinders, and then divided by two to account for the entire cylinder, and then the view factor, \dot{F}_{AE} , is multiplied by the view factor from C to D, see eqs. (4.45).

$$\mathbf{F}_{\mathbf{A}\mathbf{E}} = \mathbf{F}_{\mathbf{A}\mathbf{E}} \bullet \mathbf{F}_{\mathbf{C}\mathbf{D}} \tag{4.45}$$

The view factor from A to F is computed the same way. Symmetry is utilized, the two wires labeled F look the same to wire A. The total view factor from wire A to the surrounding wires is given by Eq. (4.46).

$$F_{ww} = 2 \bullet F_{AB} + F_{AE} + 2 \bullet F_{AF} + 2 \bullet F_{AG} + 2 \bullet F_{AH}...$$
(4.46)

View factors from wire A to wires below the tubes are added to Eq. (4.46) until the bottom wires become blocked from the view of wire A. This concept is illustrated by the right triangle in Fig. 4.5; the hypotenuse is approaching wire B.

The view factors computed this way can be combined into a coil view factor and compared to those measured by Collicott et al. (1963). The comparison is good in the midrange; however, when D_t/S_t gets small, Collicott's view factor goes to zero because the fin efficiency is taken into account by his view factor and the fin efficiency goes to zero as the tube spacing goes to infinity.

The method for determining view factors outlined above is restricted to the cases where the wires are far enough apart so that the wires labeled E, F, G, and H do not block each others view to wire A. When this happens, the wire to wire view factor will be over predicted.

A FORTRAN program was created to read the experimental data and output the convective heat transfer coefficient after removing the radiative heat transfer which is calculated using the above assumptions and approximations and can be found in Appendix F.

5. **RESULTS**

5.1 Wireless Coil

To qualify our experimental setup, an unpainted, 10 pass, serpentine coil without wires was tested in cross flow from 0 to 90°. This is Coil 7, and the dimensions of all coils studied are given in Appendix A. At 90°, the results from this coil should agree with published correlations for a cylinder in cross flow. The radiation component of the heat transfer is removed in a manner similar to that described in Section 4.4 of Hoke. Since the unpainted surface is copper, and the emissivity varies from 0.07 to 0.87 (Brewster 1992) depending on the oxidation of the surface, the emissivity of the coil was determined by measuring the free convection heat transfer coefficient when the coil is horizontal and then comparing it to a correlation for a horizontal cylinder in free convection, Eq. (5.1) (Churchill and Chu, 1975). Our coil appeared oxidized so the emissivity was expected to be closer to 0.87.

$$\overline{N}u_{D} = \left\{ 0.60 + \frac{0.387 Ra_{D}^{\frac{1}{6}}}{\left[1 + \left(0.559 / Pr\right)^{\frac{9}{16}}\right]} \right\}^{2} \qquad 10^{-5} < Ra_{D} < 10^{12} \qquad (5.1)$$

The natural convection test was conducted with $T_{coil} = 318$ K and $T_a = 295$ K. The emissivity determined in this manner is 0.84 ± 0.05 .

A large number of correlations for cylinders in cross flow have been published. Two correlations, Hilpert's (1933) and Zhukauskas' (1972), are compared to our experimental measurements taken at a 90° angle of attack in Fig. 5.1. Our data fall between the two correlations.

There are two different coil orientations which were tested: air flow perpendicular to the wires, defined as $\Psi = 0$ and air flow perpendicular to the tubes, $\Psi = \pi/2$. Within these two orientations, the coil is rotated about the wire axis or tube axis respectively to achieve a given angle of attack. Hence, one element is always perpendicular to the air flow in our tests. For the wireless coil, $\Psi = 0$ is the orientation where the wires, if they had been welded to the serpentine, would be perpendicular to the air flow.

Fig. 5.2 shows how the heat transfer coefficient varies with the angle of attack for $\Psi = \pi/2$ at selected velocities. Notice that at the higher velocities, the heat transfer
coefficient hits a maximum at about 20° . The interaction between the flow and the tubes causes this maximum. This interaction is a function of velocity since the maximum does not occur for velocities below 1.0 m/s (3.3 ft/s). The tubes stop seeing each others shadow above approximately 40° , and the heat transfer coefficient becomes independent of the angle of attack.

This wireless coil was also tested in the $\Psi = 0$ orientation. The wind tunnel test section height, 0.30 m (12"), limits the angle of attack to 20°. The measured heat transfer coefficient for the horizontal coil in "parallel" flow is shown in Fig. 5.3 along with the free convection heat transfer coefficient computed from Eq. (5.1) with an average coil temperature of 318 K and an ambient temperature of 295 K. There is a substantial decrease in heat transfer coefficient once the velocity is increased from the free convection point. The forced flow results in a heat transfer coefficient that exceeds the natural convection limit only above 0.7 m/s (2.3 ft/s).



Figure 5.1 Cylinder Correlations verses Tube Measurements



Figure 5.2 h verses Angle of Attack for a Wireless Coil

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5.2 Effect of Condenser Coil Length on h

The average heat transfer coefficient with flow over a flat plate decreases with increasing characteristic length. Similarly, the heat transfer coefficient along a condenser coil in the horizontal and -5° orientation with flow perpendicular to the tubes, $\Psi = \pi/2$ depends on the length of the coil in the direction of the air flow. To determine this effect, Coil 8 was tested and then several tube passes were cut off to shorten the coil. This process was continued until only two tube passes remained. Figure 5.4 shows a comparison between the heat transfer coefficient of a flat plate and that of Coil 8 (see Appendix A for dimensions of Coil 8) tested at an air velocity of 2m/s (6.6 ft/s). Each point represents the measurement of the average heat transfer coefficient over the coil of the indicated length.

Both curves show a similar dependence on the characteristic length parallel to the flow. The flow over the flat plate is assumed to be laminar since the Reynolds number based on the length of the plate for the longest plate calculated is less than 7.2×10^4 which is much less than 5×10^5 , the transition to turbulence. The equation used to calculate the heat transfer coefficient for the flat plate is given by

$$\overline{h}_{x} = \frac{k_{a}}{x} 0.664 \operatorname{Re}_{x}^{\frac{1}{2}} \operatorname{Pr}^{\frac{1}{3}} \qquad 0.6 < \operatorname{Pr} < 50 \qquad (5.2)$$

where all properties are evaluated at the film temperature (Incropera and DeWitt, 1990).

A dimensionless parameter, L_w^* can be defined as the length of the condenser coil along the wires divided by the condenser coil wire diameter, 1.58 mm (0.062"). For a horizontal coil the effect of L_w^* was measured for a Reynolds number from 20 to 201, where the Reynolds number is based on the wire diameter, D_w . Note that for Coil 8, the Reynolds number is approximately 100 times the air velocity in m/s. At the lower Reynolds numbers, in the mixed convection regime the effect of the length of the coil is not as evident as it is at the higher Reynolds numbers where inertia forces are dominant.



Figure 5.4



Figure 5.5

At positive angles of attack, the length of the coil does not influence the average heat transfer coefficient since the boundary layer is blown through the coil and does not interact with the wires or tubes downstream. For negative angles -10° and above, the length of the coil does not effect the heat transfer; however, at -5° there is a dependence on the length of the condenser coil. Comparing figs. 5.5 and 5.6, the dependence on the length of the coil is smaller for a coil at -5° than it is for a horizontal coil, but it is still significant. There is approximately a 25% decrease in the average Nusselt number for a coil oriented at -5° as L_w^* is increased from 60 to 350 at a Reynolds number of 201. For a horizontal coil there is approximately a 38% decrease.



Figure 5.6 Total Heat Transfer Coefficient as a Function of L^{*}_w for Coil 8 at an Angle of Attack of Negative 5°

5.3 Heat Transfer from a Typical Coil

Examining a typical coil, comparisons can be made between the two orientations, $\Psi = 0$ and $\pi/2$. Specifically, the 25 mm (1") pitch Frigidaire coil, Coil 3, is examined in detail here. This coil is cut to be square so that the effect of the length of the coil as described in Section 5.2 of Hoke will not effect the comparison between the two orientations. Note that figs. 5.5 and 5.6 show that there is little effect of the length of the coil after approximately L_w^* of 250. After the internal resistance and radiation

contribution have been removed, the convective heat transfer coefficient can be determined. Figure 5.7 shows that there is almost no difference between the two orientations at zero angle of attack.



Figure 5.7 Comparison of Nu_{coil} for $\Psi = 0$ verses $\Psi = \pi/2$

In the horizontal orientation, the element which is perpendicular to the flow should perform significantly better than the parallel element. In addition, correlations for cylinders in cross flow show that the smaller diameter wire should have a higher heat transfer coefficient than the larger diameter tube. Combining this with the greater area of the wires, 60% of the surface area for this coil, it would seem that flow perpendicular to the wires would be the best orientation. However, for a horizontal coil, the two orientations give essentially identical results.

When angled in either direction the performance of the condenser coil increases over that of a horizontal coil. An exception to this is when the coil is oriented at -5°. At low velocities, in the mixed convection regime, the performance of the condenser can be lower than when the coil is in the horizontal position. This is shown in Fig 5.8 at the very low Reynolds numbers. There is no question that the -5° coil in either orientation, $\Psi = 0$ or $\pi/2$, outperforms the horizontal coil at higher Reynolds numbers. In addition, the orientation where the wires are perpendicular to the flow begins to show a slight advantage over the orientation where the tubes are perpendicular to the flow. Figure 5.9 shows that at a Reynolds number of about 170 and a 20° angle of attack, there is at least a 10% advantage for $\Psi = 0$ over $\Psi = \pi/2$.







Figure 5.9 Orientation Comparison, $\alpha = 20^{\circ}$

Identical tests were performed for selected angles of attack. As was indicated, higher angles of attack lead to higher heat transfer coefficients. Figure 5.10 shows this effect for angles from 0 to 20° . Notice the largest jump occurs when the angle of attack is increased from 5 to 10° .



Figure 5.10 Effect of the Angle of Attack and Velocity on h

5.4 Effect of Fin Efficiency

In Section 4.1 of Hoke it was shown that the heat transfer coefficient has a dependence on eight different dimensionless groups. Of course, there are certain variables that have a greater influence on the heat transfer coefficient than others. Our goal is to derive an empirical correlation to predict the influence of all significant variables. Unfortunately, some of the variables need more investigation. Our correlation concentrates on the variables shown in Eq (5.3).

$$Nu_{coil} = Nu_{coil} \left(S_t^*, \alpha, \Psi, Re_w, S_w^* \right)$$
(5.3)

The fin efficiency of the wires is one of the variables that plays a major role in determining how much heat is removed from a condenser coil. It was shown in Section

4.1 of Hoke that the fin efficiency is dependent on S_t^* and Nu_w , and is therefore, not an independent variable.

The tube spacing ranged from 25 to 51 mm (1 to 2"), a fin length from 13 to 25 mm (0.5 to 1"), half of the tube spacing. When correlating heat transfer data from the different coils, an important dependence to remove is that of the fin efficiency. By multiplying the area of the wire by the efficiency of the wire, η , in the definition of h_{coil}, the dependence on η is removed.

The fin efficiency between a 51 mm (2") pitch and 25 mm (1") pitch can vary by as much as 34% as shown in Fig 5.11. Using a simple definition for the heat transfer coefficient, Eq. (4.12), the 25 and 51 mm tube pitch coils' heat transfer coefficients diverge from each other by as much as 24% at the higher velocities, see Fig. 5.12. By using the definition for the heat transfer coefficient developed in Section 4.2 of Hoke, the difference in fin efficiency between different tube pitch coils is accounted for and there is less than a 7% difference in the heat transfer coefficient at 2 m/s (6.6 ft/s), see Fig. 5.13.



Figure 5.11 Fin Efficiency verses Velocity; $\Psi = \pi/2$, 2 m/s (6.6 ft/s), $\alpha = 40^{\circ}$



Figure 5.12 Effect of Definition of the Heat Transfer Coefficient



Figure 5.13 h_{coil} verses Velocity for 25 and 51 mm Tube Pitch

5.5 Angle of Attack and Air Velocity Dependence

As shown in the graphs in Section 5.3 of Hoke, the heat transfer coefficient has a strong dependence on the angle of attack of the coil as well as the velocity of the air stream. The Reynolds number for our correlation is based solely on the diameter of the wire, D_w . The constants C and n in our case, are functions of the angle of attack that need to be determined. The equation used to corrolate our data is given be Eq. (5.4).

$$Nu_{coil} = C Re^{n} g(S_{w}^{*})$$
(5.4a)

where

$$C = C(\alpha, \Psi) \tag{5.4b}$$

$$n = n(\alpha, \Psi) \tag{5.4c}$$

and $g(S_w^*)$ is a function to be determined.

There are two sets of C and n, one for $\Psi = \pi/2$ and one for $\Psi = 0$. These functions are continuous but not necessarily symmetric about zero angle of attack; however, they should have the same asymtote when the entire coil is perpendicular to the flow, 90° angle of attack. Although data have not been taken above 40° for most of the coils, the constants C and n should approach the same value at \pm 90° for both orientations ($\Psi = 0$ and $\pi/2$). For the seven condenser coils, only one coil could be rotated to an angle of attack of 90°; the balance were limited to either 40 or 20° depending on their length.

Two coils with similar wire diameters and wire spacing were used to determine the constants, C and n, in Eq. (5.4) for each angle measured. First a curve fit for n verses angle of attack was determined. Using this curve fit, C values were determined. A curve fit was then applied to the C's. The results are:

Flow Perpendicular to the Wires, $\Psi = 0$:

$$C = 0.274 - 0.247 \cos(abs(\alpha) - 4.87) \exp(-0.00234(\alpha + 0.902)^2)$$
(5.5)

$$n = 0.585 + 0.249 \cos(abs(\alpha) + 20.0) \exp(-0.00441(\alpha + 1.66)^2)$$
(5.6)

Flow Perpendicular to the Tubes, $\Psi = \pi/2$:

$$C = 0.263 - 0.235 \cos(\alpha) \exp(-0.00289\alpha^2)$$
(5.7)
n = 0.55 + 0.269 cos(\alpha) exp(-0.00597\alpha^2) (5.8)

Figures 5.14 and 5.15 show C and n plotted versus angle. Figure 5.15 shows that the constants are approaching asymptotic values at large angles of attack.



Figure 5.14 C and n vs. Angle of Attack

Figure 5.16 shows how well the correlation without the function, $g(S_w^*)$ predicts the experimental data of all 7 wire and tube condenser coils. The correlation does not predict the heat transfer coefficient well below a Reynolds number of 50. There are several more dimensionless groups which have not been accounted for in the correlation.



Figure 5.15 C and n vs. Angle of Attack



Figure 5.16 Correlation Accounting for Angle of Attack and Velocity

5.6 Influence of Wire Spacing, S_w^*

A limited investigation of the effects of the wire spacing was accomplished. Additional studies of the effect of the wire spacing are planned. The limited number of test taken show that if the wire spacing is too close, the effectiveness of the wires decreases. After removing the angle dependence and velocity dependence the data is plotted verses S_w^* . Figure 5.17 shows the dependence of the data on S_w^* . Only data below a Richardsons number of 4.86 X 10⁻³ is plotted here to ensure that inertia forces are dominant. All properties are evaluated at the film temperature.

$$Ri_{w} = \frac{Gr_{w}}{Re_{w}^{2}} = \frac{\frac{g\beta}{v^{2}}(T_{coil} - T_{a})D_{w}^{3}}{Re_{w}^{2}}$$
(5.9)

By curve fitting the data a correction for the different wire spacings is obtained.



Figure 5.17 Wire Spacing Dependence

The wire spacing has a decreasing influence as the wire spacing increases. This is expected; hence a decaying exponential is used to correlate the data.

$$g(S_{w}^{*}) = 0.985(1 - 100\exp(-2.32S_{w}^{*}))$$
(5.10)

and the combined correlation is:

$$Nu_{coil} = C \operatorname{Re}_{w}^{n} 0.985 \left(1 - 100 \exp\left(-2.32S_{w}^{*}\right) \right)$$
(5.11)

Figure 5.18 shows the improvement of the correlation by including the effects of the wire spacing. For all the data as shown if Fig. 5.18 the average absolute value error is 8.6% with a standard deviation of 13.7%. Looking closer at the deviation in the range of Reynolds numbers of 50 and above, the correlation has only 15 points which lie outside \pm 20%. In addition, the average absolute value error is 6.7% with a standard deviation of 8.34%. Therefore, assuming a gaussian distribution, 95% of the data above a Reynolds number of 50 lie within \pm 16.7% of the correlation.



Figure 5.18 Difference Between the Correlation and Experimental Data

6. CONCLUSIONS

The following conclusions are drawn from this investigation:

- (1) The convective heat transfer from wire and tube condensers increases with increasing air velocities or angle of attack in the forced convection regime.
- (2) In the horizontal position, flow perpendicular to the tubes has essentially the same heat transfer coefficient as that for flow perpendicular to the wires.
- (3) Air flow perpendicular to the wires results in higher h_{coil} 's than flow perpendicular to the tubes at all angles of attack greater than 5°.
- (4) The length of the coil in the direction of air flow has an influence on the heat transfer coefficient for angles of attack of -5 and 0°; however, above L^{*}_w of 250, there is little change in the average heat transfer coefficient with increasing L^{*}_w. The effect of L^{*}_w is greater on a horizontal coil than it is on a coil at an angle of attack of -5°.
- (5) The spacing of the tubes significantly effects the fin efficiency of the wires, and is therefore a significant design parameter. The fin efficiency effects the amount of heat rejected by a condenser coil, but the fin efficiency does not effect h_{coil} because η is accounted for in the definition of h_{coil} .
- (6) The heat transfer coefficient can be accurately predicted for a condenser coil in a uniform air flow within the measured parameters. 95% of the data above a Reynolds number of 50, 1195 points, lie within ± 16.7% of the correlation developed.

1. INTRODUCTION

The refrigerator condenser is the main heat rejecting component in the refrigerating system. The condenser can be located on the rear of the refrigerator cabinet and cooled by natural convection, or it can be located below the refrigerator cabinet and cooled by a fan driven forced flow.

The condensers typically used for household refrigerators consist of steel tubing that is bent into a planar serpentine. Two parallel rows of steel wires are spot welded to the tubing, on both sides of the tubing, perpendicular to the rows of tubes. The wires enhance the heat transfer by adding extra surface area for the convection and radiation heat loss to the surroundings.

Admiraal and Bullard (1993) showed that the air side resistance for a refrigerator condenser is greater than 95% of the total resistance for the two-phase region and greater than 62% for the superheated and subcooled regions. Since a large fraction of the condenser is in the two-phase region, a large air-side resistance can significantly degrade the thermal performance of the condenser.

This investigation focuses on determining the factors that influence the convective heat transfer coefficient for typical refrigerator wire and tube condensers. The objective is to determine a correlation to estimate the heat transfer in future condenser designs. The factors investigated in this study include:

free stream air velocity, V diameter of the wires, D_w diameter of the tubes, D_t spacing of the wires, S_w spacing of the tubes, S_t orientation of the coil (flow always normal to either the wires or the tubes), ψ angle of attack of the coil, α temperature level of the coil

2. LITERATURE REVIEW

Presently, there does not exist any literature on forced or mixed convection heat transfer for a wire and tube heat exchanger. The only studies found in the literature were for wire and tube heat exchangers cooled by natural convection and radiation. These studies resulted in several MS theses and technical papers.

A study by Rudy (1956) dealt with determining an optimum wire diameter and wire pitch to maximize the heat transfer for a horizontal wire and tube heat exchanger while maintaining a constant tube diameter and tube pitch. The data indicated that in natural convection the air-side conductance, which is the product of the air-side heat transfer coefficient and the overall outside surface area, increased with larger diameter wires given a constant wire pitch. An increase in this conductance was also observed when the wire pitch was decreased. Several tests were performed on a vertical coil with horizontal wires. The average heat rate for the vertical test was 68.3% of the heat rate for the same coil in a horizontal position. This study included a discussion about the radiative heat transfer, but the radiation heat transfer was not removed from the total heat transfer.

The second study performed concurrently with Rudy's was completed by Howard (1956). The goal of this project was to determine the effect of tube spacing on the natural convection heat transfer from a horizontal wire and tube heat exchanger. It was determined that the heat transfer increases with an increasing number of tube passes (decreased tube pitch). This study did not account for the increased outside area associated with a different number of tube passes. It is difficult to determine from his plot of the heat transfer versus the number of tube passes if the heat transfer coefficient increases or decreases with tube spacing.

Carley (1956) completed the third thesis relating to the previous two studies. The goal of this investigation was to determine the effect of tube diameter on the natural convection heat transfer from a horizontal coil. The data suggests that increasing the diameter of the tube increases the heat transfer but decreases the heat transfer coefficient. An optimum tube diameter was not found.

Witzell and Fontaine (1957a) compiled information from the three previous sources into a technical article on parameters that influence the heat transfer for wire and tube heat exchangers. They plotted the Nusselt number of the data versus the Grashof number for each of the runs and developed a general correlation. In order to nondimensionalize the heat transfer coefficient, they defined the characteristic length as:

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$$L_{char} \equiv \frac{A_t D_t + A_w D_w}{A_t + A_w}$$
(2.1)

Witzell and Fontaine (1957b) used their previously developed correlation, Nu = f(Gr), to determine a design method for wire and tube condensers. The design calculations place the following limits on the coils:

- 1. Heat exchangers must be horizontal.
- 2. Outside dimensions of the exchanger should be 0.610 x 0.914 m (24 x 36 in) with 0.914 m (36 in) wires.
- 3. The tube diameter lies between 4.763 and 15.87 mm (0.1875 and 0.625 in); wire diameter between 0.8839 and 2.324 mm (20 and 13 gage); tube centerline spacing between 25.4 and 101.6 mm (1 and 4 in); and wire centerline spacing between 4.23 and 25.4 mm (0.167 and 1.00 in).

Papanek (1958) performed tests for the angular dependence of the heat transfer coefficient ranging from horizontal to vertical with a condenser with $D_t = 6.35 \text{ mm} (0.25)$ in) and $D_w = 2.324$ mm (13 gage). The rotation of the coils oriented the tubes at the desired angle while maintaining horizontal wires. Condensers with 0, 39.37, 157.48, and 236.22 wires per meter (0, 1, 4, and 6 wires per inch) were studied to determine the effects of the wire spacing. These tests were done with natural convection, and the radiation heat transfer was estimated and removed before correlating the data. Papanek determined that bare tubes performed best in the horizontal position, and the performance decreased slightly when rotated. The heat transfer coefficient for the vertical coil was found to be 91% of the heat transfer coefficient for the horizontal coil. The heat transfer coefficient for the coil with 39.37 wires per meter (1 wire per inch) has the same angular dependence as the coil with no wires. The largest percent decrease in heat transfer coefficient, when the coil was rotated from a horizontal to a vertical position, occurred when the wire density was 157.48 wires per meter (4 wires per inch). In this case, the heat transfer coefficient for the vertical coil decreased to 40% of heat transfer coefficient of the horizontal coil.

A Nusselt number versus Grashof number plot was given using the entire group of horizontal and vertical tests. The characteristic length employed was the same as that used by Witzell and Fontaine (1957a). The Nusselt number for the tests with horizontal coils was larger than the Nusselt number for the tests with vertical coils . The Nusselt number correlation for the vertical coil has a larger power on the Grashof number; therefore, the Nusselt number for the vertical coil increases faster with increasing Grashof number compared to the Nusselt number for the horizontal coil.

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Papanek's data for the heat transfer coefficient versus angular position was used to create a new graph showing the heat transfer coefficient versus the number of wires per inch for various angular positions (Witzell, Fontaine, and Papanek, 1959). This graph more clearly shows the benefit of placing the coil at small angles relative to horizontal in order to increase the heat transfer coefficient for a coil cooled by natural convection. This graph also gives an envelope of possible values for the heat transfer coefficient with the maximum value occurring for a horizontally positioned coil and the minimum value occurring for a vertical coil. The equation for the characteristic length was changed after Papanek's thesis publication to include the general correlation for natural convection from cylinders and the wire fin efficiency. The characteristic length was redefined as:

$$L_{char} \equiv \left(\frac{A_t + A_w}{\frac{A_t}{D_t^{1/4}} + \frac{\eta A_w}{D_w^{1/4}}}\right)^4$$
(2.2)

Cyphers, Cess, and Somers (1959) performed an investigation to determine the effect of coil angle between horizontal and vertical, both in an unconfined space and between parallel confining walls. This study tested a coil through a range of angles while maintaining horizontal tubes and a range of angles with horizontal wires. The results indicate that the average heat transfer coefficient for the vertical coil with horizontal tubes is $\approx 80\%$ of the horizontal heat transfer coefficient. In the case with horizontal wires, the heat transfer coefficient remained essentially unchanged when the coil was rotated from horizontal until 45 degrees was reached. The heat transfer coefficient then decreased until the coil reached a vertical position and the heat transfer coefficient dropped to 75% of the horizontal coil's coefficient.

The effect of the confining plates changes the results of the angular test. During a set of tests varying the angle of a coil with horizontal tubes, the vertical plates were placed at the edge of the coil so that a chimney effect would be produced. This dramatically reduces the heat transfer coefficient at higher angles when the plates come closer together. At less than 60 degrees from horizontal, the effect of the confining walls is negligible compared to the case with no walls. For a plate spacing greater than 101.6 mm (4 in), the heat transfer coefficient for a vertical coil is smaller than the heat transfer coefficient for a coil rotated until the coil edges touch the plates.

Collicott et al. (1963) experimentally determined a radiation heat loss; hence, they were able to reduce the overall heat loss to a natural convection heat transfer coefficient.

This study used an evacuated chamber to reduce all but radiation transfer from the coil. By testing a number of heat exchangers, they generated a graph showing the effective configuration factor for the coil versus the ratio of tube diameter to tube pitch for various ratios of wire diameter to wire pitch. The effective configuration factor, defined as:

$$F_{e} = \frac{q_{r}}{\varepsilon \sigma A_{total} \left(T_{coil}^{4} - T_{s}^{4} \right)}$$
(2.3)

was then used to estimate the radiation contribution to the heat loss in subsequent natural convection tests. This effective configuration factor is dependent on the geometry of the coil and the fin efficiency of the wires. In tests including natural convection, the effective configuration factor will be overestimated because the fin efficiency of the wires is now lower.

Collicott et al. (1963) defined an efficiency for a wire and tube condenser coil as the ratio of the coil's Nusselt number to a single tube's Nusselt number. This produced a graph that shows a linear increase in the coil efficiency with an increasing tube diameter to tube pitch, D_t/S_t , ratio for the range: 0.04 to 0.12. The effectiveness approaches an asymptotic value of 1.0 as D_t/S_t approaches infinity.

Collicott et al. (1963) also performed natural convection tests at various angles with Rayleigh numbers ranging from 67 to 133. At angles below 50 degrees, the effectiveness for all of the Rayleigh numbers lie on the same line. However, as the coil approaches a vertical position, the effectiveness of the coil decreases with a higher decrease corresponding to a lower Rayleigh number.

3. DESIGN OF EXPERIMENTAL FACILITY

The preliminary work in this project consisted of the design of a facility to accurately measure the ability of the wire and tube heat exchangers to transfer heat. This facility needs to be versatile to accommodate unforeseen new condenser designs and accurate to be able to obtain reproducible results. The facility consists of three major units each containing many separate parts: the constant temperature water loop, the low speed wind tunnel, and the data acquisition system.

3.1 The Constant Temperature Water System

Since the air-side of the condensers is to be evaluated, the temperature of the refrigerant flowing inside the tubes must be controlled and measured accurately. Figure 3.1 is a diagram of the system supplying hot water that serves as the refrigerant, the working fluid flowing through the condenser.



Figure 3.1 Schematic of Constant Temperature Water Loop

The water, from the main water supply to the building, enters the loop at a temperature of approximately 17°C (63°F) and is then preheated by a domestic hot water heater. The

water exits the hot water heater at $49 \pm 6^{\circ}$ C ($120 \pm 10^{\circ}$ F) and can be tempered by the valve connected to the cold water inlet of the hot water heater.

Since the temperature of water exiting a domestic hot water heater cannot be precisely controlled, an isothermal bath is used to supply a stream at the desired temperature which does not fluctuate with time. The isothermal bath consists of two plate-fin aluminum evaporator coils immersed in forty-two gallons of propylene glycol (SierraTM antifreeze). The propylene glycol has excellent thermal properties and the corrosion resistance needed to maintain a highly stable bath. The temperature of the bath is monitored with a 610 mm (24 in) long stainless steel thermocouple probe connected to a Partlow controller. The controller uses an ON/OFF controlling scheme with a 0.06°C (0.1°F) hysteresis. The wiring diagram, Fig. 3.2, shows that the controller output of 4.88 volts when ON will activate a solid state relay, thus connecting the 4 kW (13600 Btu/hr) bath heater to the 240 V single phase circuit. Two 15 W (1/50 hp) immersion pumps are located in the propylene glycol to stir the bath in order to reduce temperature stratification.



Figure 3.2 Electrical Schematic of the Constant Temperature Bath

The water flowing from the domestic hot water heater will pass through the two evaporators and exit the bath. The overall heat transfer coefficient and the capacity rate of the water stream are such that the effectiveness of this heat exchanger is 0.99; hence, the water will exit this bath at the set point temperature. Water is an ideal fluid to use because its thermal and transport properties are well known and the inside heat transfer coefficient of the condensers can be evaluated accurately. The inside resistance due to convection with water as a working fluid will be less than 3% of the overall resistance in most of the experimental cases. Even a slight error in the prediction of the water side resistance due to bends, etc., will not have a significant impact on the accuracy of the experimentally determined air-side convection coefficient.

3.2 The Wind Tunnel

The wind tunnel as seen in Fig. 3.3, is capable of free stream velocities from 0.15 m/s to 2.00 m/s (0.49 ft/s to 6.56 ft/s). The air is induced through the wind tunnel by a backwards inclined centrifugal fan powered by a 250 W (1/3 hp) motor with a DC controller. The air travels through a converging inlet section and passes through an aluminum honeycomb section to reduce swirling flows produced by ambient instabilities. The air then passes through four screens which are designed to reduce the turbulence and obtain uniform flow in the test section. Next the air passes through the test section and the fan. A more detailed description of the wind tunnel can be found in the thesis by Hoke (1995).

Flow conditioning section



Fan



3.3 The Data Acquisition System

Applying the first law of thermodynamics to the refrigerant-side of the condensers gives:

$$q = \dot{m}_r C_{p,r} \left(T_{r,out} - T_{r,in} \right)$$
(3.1)

This equation shows that the mass flowrate of the water needs to be measured as well as the inlet and outlet temperatures of the refrigerant. The inlet and outlet water temperatures are measured using mixing cups at the two ends of the coil to enable an accurate determination of the desired bulk water temperatures. A mixing cup, as seen in Fig. 3.4, consists of copper fittings connected to form a sudden expansion followed by a sudden contraction. Two type T thermocouple probes with 1.016 mm (0.040 in) diameter stainless steel sheaths are inserted approximately 25 mm (1 in) into the flow to measure the temperature of the water as it exits the mixing cup. The temperature of the refrigerant at each bend of the coil is also measured in some of the tests with type T thermocouples. Initially, the bead of the junction was inserted into the stream at the tube bend and secured in place with epoxy as seen in Fig. 3.5.a. The temperature profile for the coil was then plotted. As can be seen in Fig. 3.6, the accuracy of these measurements was unacceptable. It was determined that conduction along the thermocouple wire caused the error in the temperature measurements. The method that was employed to solve this problem consists of inserting the thermocouple bead into the flow 25 mm (1 in) to reduce the temperature gradient near the bead, thereby reducing the conduction errors (Fig. 3.5.b). The new temperature profile, Fig. 3.7, shows a nearly linear temperature drop through the coil if the temperature drop of the refrigerant is small.



Figure 3.4 Schematic of Mixing Cup for Water Temperature Measurement



Figure 3.5.a Schematic of Initial Thermocouple Mounting



Figure 3.5.b Schematic of Improved Thermocouple Mounting

All of the thermocouples used for this project came from the same spool of thermocouple wire. The mixing cup thermocouple probes and the air thermocouples were calibrated using a constant temperature bath and thermometers that were NBS calibrated to within ± 0.056 K ($\pm 0.1^{\circ}$ F). It was determined that all of the thermocouples made from the spool followed the same calibration curve. A thermocouple junction box was built to allow the user to connect and disconnect the coil thermocouples easily. Two thermocouple switches are used with the junction box to enable the operator to read the EMFs from forty-seven different thermocouples with only one reference junction. This reference thermocouple junction is kept at 0.0° C (32° F) by immersing the cold junction thermocouple in a Kay Instruments ICE POINT Reference.



Figure 3.6 Typical Temperature Profile with Initial Mounting Technique



Figure 3.7 Typical Temperature Profile with Improved Mounting Technique

The mass flowrate of the water is determined by weighing all of the water flowing through the coil during a test run and using an electronic timer to determine the elapsed time. A minimum of 3000 grams is weighed to determine the flowrate in order to reduce

the error in the flowrate measurement. For instance, a data set taken on 5/18/95 had an average mass flowrate of 0.013181 kg/s (0.02906 lb_m/s) over 11 runs with a standard deviation of 2.04 x 10^{-5} kg/s (4.49 x 10^{-5} lb_m/s).

The tests were conducted with velocities ranging from 0.20 m/s to 2.00 m/s (0.656 to 6.56 ft/s). The air velocity is measured with an IFA hot-wire anemometer. It was calibrated with a recently calibrated TSI anemometer that is accurate to within $\pm 0.6\%$ in the velocity range of interest.

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4. EXPERIMENTAL PROCEDURE

A digital appliance switch is used to turn on the bath controller one hour before tests are to be taken to expedite the heating of the bath. The specific coil to be tested is then inserted into the wind tunnel and attached to the four threaded rods used to fix the coil in the test section. The mixing cups are attached to the inlet and outlet of the coil, and the water flow is started. The angle of the coil is then adjusted to the desired angle using a PRO Smartlevel digital level accurate to within 0.1 degrees. The hot wire anemometer probe is inserted, and the lid of the wind tunnel replaced.

The temperature drop through the coil is kept between 3 and 5 K to approximate an isothermal coil while still having a large enough temperature drop to reduce measurement error. Since the temperature drop and mass flowrate are inversely related, the EMF between the inlet and outlet mixing cups is used to determine if the water flowrate is satisfactory. The EMF dependence on the thermocouple temperature is nearly linear in the range of interest. A 1 K difference results in an EMF of $\approx 40 \,\mu\text{V}$. The pressure regulator is adjusted until this EMF is around 120 μ V. As the heat transfer increases, this EMF will increase due to the reduced outlet temperature. When the potential difference across the inlet and outlet thermocouples reaches around 200 μ V, the flowrate is increased again to reduce the temperature drop.

After the mass flowrate is adjusted the outlet stream is collected in a container on a digital scale, and a timer is started. The operator then proceeds to enter in the EMF for the air, wall, and water thermocouples into a spreadsheet. The EMFs for all thermocouples are recorded three times with a one minute interval between scans. These three sets are then averaged in order to reduce the effects of small fluctuations. After all temperatures are recorded, the operator stops the flow of water into the container and simultaneously stops the timer. The time and water mass are entered into the spreadsheet to determine the flowrate.

4.1 Natural Convection Data Acquisition

Natural convection experiments were performed with a small coil rotated from horizontal to vertical with the tubes always perpendicular to the gravity vector and again with the wires always perpendicular to the gravity vector. The test was performed with the wind tunnel lid removed; thus, the center of rotation for the coil was 300 mm (12 in) above the wind tunnel floor. Side walls 810 mm (32 in) tall were built from foam board to form a 910 mm x 760 mm (36 in x 30 in) enclosure to reduce fluctuations due to room

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drafts. Six ambient thermocouples were placed below the heat exchanger to measure the ambient air temperature.

4.2 Forced Convection Data Acquisition

A typical forced convection test takes about three to five minutes for a single velocity with the entire range of velocities taking approximately two hours. First, the fan motor is adjusted until the IFA flow analyzer reads the correct voltage for the desired air velocity. The temperatures are recorded after a period of two minutes in order to ensure steady state is achieved. After the test is completed, the air speed is increased and another data point is taken.

5. DATA ANALYSIS AND REDUCTION

The wire and tube condenser has a very complex geometry so it is important to determine the geometric factors affecting the heat transfer. The following sections will discuss the importance of each parameter on the heat transfer coefficient, and the method that is used to incorporate that parameter into the data reduction scheme.

5.1 Governing Dimensionless Parameters

The equations governing the air-side convective heat transfer from an **isothermal** wire-and-tube condenser including the external geometrical aspects of this heat exchanger, show:

$$Nu_{w} = f_{w} \left(Re_{w}, Ri_{w}, Pr, \alpha, \psi, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*}, L_{w}^{*} \right)$$

$$(5.1)$$

and

$$Nu_{t} = f_{t} \left(Re_{t}, Ri_{t}, Pr, \alpha, \psi, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*}, L_{w}^{*} \right)$$
(5.2)

The Nusselt numbers in eqs. (5.1) and (5.2) are defined as

$$Nu_{w} \equiv \frac{h_{w}D_{w}}{k_{a}}$$
(5.3.a)

where

$$h_{w} \equiv \frac{q_{w}}{A_{w}(T_{coil} - T_{a})}$$
(5.3.b)

and

$$Nu_t \equiv \frac{h_t D_t}{k_a}$$
(5.4.a)

where

$$h_{t} \equiv \frac{q_{t}}{A_{t}(T_{coil} - T_{a})}$$
(5.4.b)

The angles α and ψ are defined as the angle of attack and the yaw, respectively. As in airfoil design, the angle of attack, α , for this study is considered to be a positive angle if the leading edge of the coil lies above the trailing edge (see Fig. 5.1). ψ is defined as being 0 for the case of flow perpendicular to the wires (consider $\alpha < \pi/2$) and $\pi/2$ if the flow is perpendicular to the tubes. A single-layer wire and tube condenser is considered in this investigation and is assumed to be located in a uniform flow field that is essentially infinite in extent.



Figure 5.1 Schematic of Angle of Attack

Air is the external fluid of interest in this investigation; thus, for the temperature range of interest, the influence of the Prandtl number need not be resolved. For the low velocities of interest, buoyant forces are known to be of importance in some situations. Hence, the Grashof number, or the Rayleigh number, $Ra \equiv Gr \cdot Pr$, or the Richardson number, $Ri \equiv Gr/Re^2$, or some other combination of these groups must be included.

The extent of the coil in the direction perpendicular to the velocity vector should have minor influences for the wire and tube lengths of interest. Thus, it would appear prudent to consider the following two cases separately: Case I, flow normal to the wires $(\psi = 0)$ and Case II, flow normal to the tubes $(\psi = \pi/2)$. For brevity, only the relationships for Case I will be given. Equations (5.1) and (5.2) for Case I reduce to:

$$Nu_{w} = f_{w} \left(Re_{w}, Ri_{w}, \alpha, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*} \right)$$

$$(5.5)$$

and

$$Nu_{t} = f_{t} \left(Re_{t}, Ri_{t}, \alpha, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*} \right)$$

$$(5.6)$$

Even for the case with air flowing over an isothermal coil, the task at hand is overwhelming. Four functional relationships among eight dimensionless groups need to be established.

In an actual wire and tube heat exchanger, the wires are not isothermal surfaces; thus, the influences of the temperature gradients in the wires need to be taken into account. To simplify the next step of the analysis, assume the tubes are isothermal surfaces, and the wire temperature at the wire/tube interface is equal to the surface temperature of the tubes. Assume further that the heat transfer coefficient averaged over the circumference of the wire does not vary along the wire.

The temperature distribution along the wire drastically influences the heat exchanged by the wire in many designs. In order to reduce the dependence of h_w on the temperature gradients in the wire, the area in the definition of h_w will be replaced by the effective wire area—the area times the fin efficiency η . That is:

$$h_{w} \equiv \frac{q_{w}}{A_{w}\eta(T_{t} - T_{a})}$$
(5.7)

where the fin efficiency of the wire follows from an analysis of this extended surface. The wire can be treated as a fin with an adiabatic plane at the midpoint between the two tubes. This makes the length of the fin equal to $\frac{S_{1/2}}{2}$ and the fin efficiency equal to

$$\eta \equiv \frac{q_{\rm w}}{q_{\rm max}} = \frac{\tanh m}{m} \tag{5.8}$$

where

$$m^2 = \frac{h_w S_t^2}{k_w D_w}$$
(5.9)

and

$$q_{max} \equiv A_w h_w (T_t - T_a)$$
(5.10)

The fin parameter m, a dimensionless parameter, indicates the importance of the temperature gradients in the wires. m^2 is the ratio of the internal conductive resistance of the wire to the external convective resistance between the wire and the surrounding air.

The parameter, m, can be alternately written in terms of S_t^* and Nu_w . Specifically,

$$m^{2} = \left(S_{t}^{*}\right)^{2} Nu_{w}\left(\frac{k_{a}}{k_{w}}\right)$$
(5.11)

If q_w were known, eqs. (5.7), (5.8), and (5.9) clearly show that a transcendental equation must be solved to determine h_w .

Refrigerator condensers are inexpensive heat exchangers because they are made out of steel wire and steel tubes, and the two elements are easily spot-welded together. Thus, for this application, (k_a/k_w) is a constant. Equation (5.11) shows that if (k_a/k_w) is a constant, m is not an additional, independent variable; hence, Eq. (5.5) is still valid even for applications with highly non-isothermal wires.

Equations (5.3.b) and (5.7) are both theoretically acceptable definitions for h_w . Although the use of Eq. (5.7) requires the solution of a transcendental equation in order to determine h_w (given q_w , T_t and T_a), this definition removes the otherwise strong dependence of Nu_w on S_t^* . Since the wire area accounts for approximately 2/3 of the total area in a typical wire-and-tube condenser, and since h_w is considerably larger than h_t , the tube spacing (or fin efficiency) strongly influences the air-side performance of such condensers. However, if Definition (5.7) is used, the influence of S_t^* on Nu_w becomes a secondary influence.

A fundamental problem in deducing correlations (5.5) and (5.6) is separating the rate of heat exchange with the wires from the total rate of heat transfer. The latter is the only quantity that can be easily measured. In addition, the tube and wire boundary layers interact extensively. For these reasons, let us consider looking at the condenser as a single surface.

In considering the wire-and-tube condenser as a single surface the definition for the average heat transfer coefficient over the coil, h_{coil} , and the characteristic length become important issues. Obvious choices for the characteristic length are D_w , D_t , or some weighted average of these two lengths, for example, an area weighted average. It should be noted that one of the areas cannot be defined in terms of the lengths being used since the transverse length of the coil has been discarded. Since the wires are hypothesized to be dominant, D_w will be used as the characteristic length. The Reynolds number is defined as:

$$Re_{w} = \frac{V_{a}D_{w}}{v_{f}}$$
(5.12)

and the Grashof number is:

$$Gr_{w} = \frac{g\beta_{f}(T_{t} - T_{a})D_{w}^{3}}{v_{f}^{2}}$$
(5.13)

In an effort to find a better way of reducing the dependency of Nu on the geometrical parameters, consider the calculation of q if h_w and h_t were known.

$$q = (A_t h_t + \eta A_w h_w)(T_t - T_a)$$
(5.14)

Solving Eq. (5.14) for h_w gives:

$$h_{w} = \frac{q}{\left(A_{t}\frac{h_{t}}{h_{w}} + \eta A_{w}\right)\left(T_{t} - T_{a}\right)}$$
(5.15)

To reduce Eq. (5.15) to a useful definition, h_t needs to be eliminated.

The wire area accounts for approximately 2/3 of the total area in typical wire-andtube refrigerator condensers in use today. In addition, the convective heat transfer coefficients over the wires are generally expected to be much larger than those over the tubes. Thus, the second term in the denominator of Eq. (5.15) will be appreciably larger than the first term except for cases where the fin efficiency is low. Most current condenser designs appear to be operating at values of η greater than 0.6.

Providing a means of accurately estimating h_t , that is of general utility, appears unlikely; however, it may be possible to derive a viable estimate of h_t/h_w . Consider, for example, the two limits of natural convection from a single horizontal cylinder and forced convection with flow normal to a single cylinder. In the regimes of interest ($10^{-2} < \text{Ra} < 10^2$; 40 < Re < 4000), published correlations for both of these limits show that

$$h \propto D^{-n}$$
 (5.16)

where n is approximately equal to one half. Thus, if the same correlation were applicable to both surfaces, one obtains

$$\frac{\mathbf{h}_{t}}{\mathbf{h}_{w}} \cong \left(\mathbf{D}_{t}^{*}\right)^{-0.5} \tag{5.17}$$

If this approximation is used in Eq. (5.15), it becomes:

$$h_{w} = \frac{q}{\left(\frac{A_{t}}{\sqrt{D_{t}^{*}}} + \eta A_{w}\right)} (T_{t} - T_{a})$$
(5.18)

For the seven wire-and-tube condensers investigated to date,

$$\frac{\frac{A_{t}}{\sqrt{D_{t}^{*}}}(100\%)}{\frac{A_{t}}{\sqrt{D_{t}^{*}}} + A_{w}}$$
(5.19)

varies from 11.2% to 25.2%.

In some regimes, the approximation represented by Eq. (5.17) is expected to be very accurate, e.g., for cases with α near $\pi/2$. In these regimes, h and η obtained using Eq. (5.18) are representative of the average heat transfer coefficient and the average fin efficiency of the wires in the coil. On the other hand, in regimes where Eq. (5.17) is a poor approximation, the values of h_w calculated from Eq. (5.18) will not be representative of the average heat transfer coefficient over the wires. It should be remembered, however, that no error has been made. Equation (5.18) is a definition. To avoid misinterpretations, h_w in Eq. (5.18) will be replaced by h_{coil}. Specifically, the following definition will be used:

$$h_{coil} \equiv \frac{q}{\left(\frac{A_{t}}{\sqrt{D_{t}^{*}}} + \eta A_{w}\right) (T_{t} - T_{a})}$$
(5.20)

also
$$Nu_{coil} = f(Re_{w}, Ri_{w}, \alpha, S_{w}^{*}, S_{t}^{*}, D_{t}^{*}, L_{t}^{*}), \psi = 0$$
(5.21)

where

$$Nu_{coil} = \frac{h_{coil}D_w}{k_a}$$
(5.22)

and

$$\eta = \frac{\tanh m}{m} \text{ where } m^2 = \left(S_t^*\right) Nu_{\text{coil}}\left(\frac{k_a}{k_w}\right)$$
(5.23)

When Correlation (5.21) becomes available, the heat transfer from the coil must be calculated from the following equation:

$$q = \left\{ Nu_{coil} \frac{k_a}{D_w} \right\} \left(\frac{A_t}{\sqrt{D_t^*}} + \eta A_w \right) (T_t - T_a)$$
(5.24)

where η is determined from Eq. (5.23).

5.2 Calculation of Heat Transfer Rate

A calorimetric study was performed on the wire and tube condensers in order to determine the heat loss. The three measurements needed for this are the water inlet and outlet temperatures and the mass flowrate. The heat loss is calculated from:

$$q = \dot{m}_r c_{p,r} \left(T_{r,in} - T_{r,out} \right)$$
(5.25)

The heat loss cannot be used to determine how well the coil performs because of ambient fluctuations between tests; therefore, this parameter cannot be used to compare tests. Both the bulk air temperature and the wall temperatures are fluctuating quantities. Also, the radiant contribution needs to be removed before different tests can be compared.

5.3 Calculation of Internal Resistance

The calculation of the outside convective heat transfer coefficient requires the removal of the other resistances. The resistance equations used for the data reduction are found in Table 5.1. The refrigerant-side heat transfer coefficient is determined using the Gnielinski correlation:

$$Nu_{\rm D} = \frac{(f/8)(Re_{\rm D} - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \qquad \left(0.5 < Pr < 2000, \ 2300 < Re_{\rm D} < 5x10^6\right) \quad (5.26)$$

where:

$$f = (0.79 \ln(Re_D - 1.64)^{-2}$$
(5.27)

and

$$\operatorname{Re}_{\mathrm{D}} = \frac{\operatorname{V}_{\mathrm{r}} \operatorname{D}_{\mathrm{t},\mathrm{i}}}{\operatorname{v}_{\mathrm{r}}}$$
(5.28)

The heat transfer coefficient can be calculated by the equation, $h_r = \frac{Nu_D k_r}{D_{t,i}}$, and used in the calculating the internal resistance with Eq. 5.32 found in Table 5.1.

5.4 Calculation of Radiation Contribution

Calculation of the convective heat transfer coefficient for the coil requires that the radiation heat loss be subtracted from the total heat loss. The radiant contribution of the total heat transfer can be calculated if the temperature of the coil's surface is known. The temperature gradients along the tube are considered a second order effect, thus, the tube surface temperature is assumed to be uniform in this study. The temperature gradients along the wire surface are first order effects; therefore, the average temperature of the wire must be determined.

Once the surface temperatures are calculated the radiation heat losses can be calculated using view factor calculations and measured ambient surface temperatures. The average surface temperature of the wire follows from the definition of η as:

$$T_{w,avg} = T_a + (T_{base} - T_a) \cdot \eta$$
(5.29)

The effective heat transfer coefficient over the wire includes the influences of the convective and radiative heat transfer from the coils as well as the wire paint resistance. The temperature gradients along the surface of the wire are therefore also affected by the radiative and paint resistances. In order to determine the average temperature of the wire, the effective fin efficiency of the wire must be used in Eq. 5.29. Equations (5.20), (5.22), and (5.23) are combined with h_{coil} replaced by $h_{w,e}$ to form the transcendental equation:

$$h_{w,e} \equiv \frac{q}{\left(\frac{A_t}{\sqrt{D_t^*}} + \frac{\tanh\sqrt{\frac{h_{w,e}S_t^2}{k_w D_w}}}{\sqrt{\frac{h_{w,e}S_t^2}{k_w D_w}}}A_w\right)} (T_t - T_a)$$
(5.30)

Every variable in this equation is either known from geometry or is measured experimentally except for $h_{coil,e}$. A Newton-Raphson routine was incorporated into the data reduction code to solve for the effective coil heat transfer coefficient. This coefficient is then used to calculate the effective wire efficiency and then used as previously explained to determine the average wire temperature. The radiative heat transfer can now be determined using the calculated view factor, the average surface temperature of the wire, and the surface temperatures of the tube and surroundings. A more complete description of the radiation calculation is given by Hoke (1995).

5.5 Calculation of Nu_{coil} using η_e

The reduction of the convective coil Nusselt number requires the use of the effective wire efficiency because the wire temperature dependence for the tests includes radiation. Therefore; Nu_{coil} is calculated from eqs. (5.20) and (5.22) using η_e instead of η . The heat loss used in these equations is the total heat loss minus the calculated radiation heat loss.

Resistance	Definition	Equation
Air Side	$R_{a,e} = \frac{1}{h_{coil,e} \left(\frac{A_t}{\sqrt{D_t^*}} + \eta_e A_w\right)}$	(5.31)
Tube Internal	$R_{r} = \frac{1}{h_{r}\pi D_{t,i} \left(\pi \frac{S_{t}}{2} (N_{t} - 1) + L_{t} N_{t}\right)}$	(5.32)
Tube Wall	$R_{t,wall} = \frac{ln\left(\frac{D_t}{D_i}\right)}{2\pi\left(\pi\frac{S_t}{2}(N_t - 1) + L_tN_t\right)k_s}$	(5.33)
Tube Paint	$R_{t,p} = \frac{\delta_{t,p}}{\left(\pi \frac{S_t}{2} (N_t - 1) + L_t N_t\right) D_t k_s}$	(5.34)

Table 5.1 Resistance Network Calculations

6. EXPERIMENTAL RESULTS AND DISCUSSION

6.1 Certification of Data Acquisition and Reduction

The heat loss measured in the tests includes the radiative heat transfer. Reducing the data to obtain the air side convection coefficients requires that the radiation and internal resistances are accounted for. The first sets of tests were taken to determine the effects of varying the water temperature on the convective heat transfer coefficient. Figure 6.1 shows the total heat loss from a horizontal coil with different refrigerant temperatures. This figure clearly shows that the total heat loss increases with increasing refrigerant temperature. The data taken at 313.7 K (105°F) contain a discontinuity at 1.5 m/s (4.92 ft/s) that is attributed to ambient temperature changes. The data before the discontinuity were taken one day, and the data after the discontinuity were taken the next day at a different ambient temperature. The true test of the data reduction scheme will be to demonstrate its ability to account for varying ambient conditions. The reproducibility of the heat transfer coefficient data will be confirmed if the convection coefficient in the inertia dominated regimes can be shown to be dependent only on geometry, orientation and air velocity and independent of the ambient temperatures.



Figure 6.1 Typical Total Heat Loss for Different Refrigerant Temperatures

Figure 6.2 shows the convective heat loss for each temperature level after the radiation contribution has been removed. The radiation heat loss is calculated to be 10.5% to 38% of the total heat loss with the largest percentage occurring for the lowest air velocities. It can be noted that the discontinuity for the lowest temperature level was not corrected with the removal of the radiation heat transfer. This means that the discontinuity is due to ambient air temperature changes and not a consequence of different amounts of radiative heat transfer.



Figure 6.2 Typical Convective Heat Loss for Different Refrigerant Temperatures

The coil's convection heat transfer coefficient determined from tests with four different water temperatures is shown in Fig. 6.3. A power curve fit for the data with V > 0.5 m/s (1.64 ft/s) gives an average absolute value error of 0.9%. This demonstrates that the convective heat transfer coefficient is indeed independent of the refrigerant and ambient temperature levels in the inertia dominated regime. With this in mind, the rest of the tests are performed with the bath temperature set to 322.0 K (120.0 °F) in order to increase the temperature drop between the coil and the ambient; hence, this decreases the experimental error. The water temperature's influence in the mixed convection regime is also demonstrated on this figure for air velocities less than 0.35 m/s (1.15 ft/s). Increasing the water temperature increases the magnitude of the buoyant force.



Figure 6.3 Typical Convection Heat Transfer Coefficient for a Coil

6.2 Natural Convection Results

In the natural convection tests, $\psi = 0$ is defined as the case when the gravity vector is normal to the wires, and $\psi = \pi/2$ is defined as the case with the gravity vector normal to the tubes. The angle from horizontal, α , is equal to 0° when the gravity vector is normal to both the tubes and the wires and equal to 90° when the gravity vector is parallel with the plane of the coil. Figure 6.4 shows a plot of the Nusselt number versus the Rayleigh number for a test with a horizontal coil ($\alpha = 0^{\circ}$) and for two tests with a vertical coil ($\alpha = 90$, $\psi = 0$ and $\psi = \pi/2$). The same characteristic length, D_w , is used for all coil orientations. In the Raw range covered, the Nusselt number for the case with $\alpha = 0^{\circ}$ is always greater than the Nusselt number for both cases with $\alpha = 90^{\circ}$. At a Rayleigh number of 3.5, the Nusselt number for Coil 6 with $\alpha = 0^{\circ}$ is approximately 3.6 times the Nusselt number with $\alpha = 90^{\circ}$ and $\psi = \pi/2$. At a Rayleigh number of 5.5, the Nusselt number for Coil 6 with $\alpha = 90^{\circ}$ and $\psi = 0$ and is approximately a coil with $\alpha = 90^{\circ}$ and $\psi = 0$ and is approximately a coil with $\alpha = 90^{\circ}$ and $\psi = 0$ and is approximately a coil with $\alpha = 90^{\circ}$ and $\psi = 0$ and is approximately $\alpha = 90^{\circ}$ and $\psi = 0$ and $\omega = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 0$ and is approximately $\alpha = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 0$ and is approximately $\alpha = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 0$ and is approximately $\alpha = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 0$ and is approximately $\alpha = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 0$ and is approximately $\alpha = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 0$ and is approximately $\alpha = 90^{\circ}$ and $\psi = 90^{\circ}$ and $\psi = 0$ and



Figure 6.4 Influence of Ra_w on Nu_{coil}, $\alpha = 0^{\circ}$ & 90° ($\psi = 0, \pi/2$)

The influence of the angle (measured from a horizontal plane) on the natural convection heat transfer coefficient for Coil 6 is shown in Fig 6.5. These results are for the case of horizontal tubes ($\psi = \pi/2$) at a Rayleigh number of 4.7. The heat transfer coefficient at $\alpha = 90^{\circ}$ (a vertical coil) with horizontal tubes is 46.0% of the heat transfer coefficient for the same coil at $\alpha = 0^{\circ}$. An investigation by Morgan (1975) determined the effect of angle on the natural convective heat transfer from cylinders to air. Morgan's data show that the heat transfer from a vertical cylinder ($\alpha = 90^{\circ}$) is approximately 50% of the heat transfer from a horizontal cylinder ($\alpha = 0^{\circ}$).

The influence of the angle (measured from a horizontal plane) on the natural convection heat transfer coefficient for Coil 6 is shown in Fig. 6.6. These results are for the case of horizontal wires ($\psi = 0$) at a Rayleigh number of 4.6. There is an increase in the heat transfer coefficient with an increase in angle from a horizontal coil to small angles. When the coil is horizontal, the wires on opposite sides of the tube are in-line cylinders. With 10° of rotation, the opposing wires become staggered cylinders which causes an increase in the heat transfer coefficient. As α is increased further, h_{coil} decreases; the minimum h_{coil} occurs at $\alpha = 90^\circ$. The heat transfer coefficient at $\alpha = 90^\circ$.



Figure 6.6 Influence of Angle on h_{coil} , $\psi = 0$, V = 0

6.3 Mixed and Forced Convection Results, Coil 6

Figure 6.7 presents the coil heat transfer coefficient versus angle of attack for various air velocities with flow perpendicular to the tubes ($\psi = \pi/2$). These results are for a small condenser, Coil 6, with an aspect ratio of 0.279 m by 0.285 m (11 in by 11.25 in)

(see Appendix A for coil geometry). Since the height of the wind tunnel is 0.305 m (12 in), this relatively small coil enables us to vary the angle of attack from 0° to 90°. The heat transfer coefficient approaches an asymptotic value as the angle of attack approaches 90°. At a velocity of 2.0 m/s (6.56 ft/s), the heat transfer coefficient with $\alpha = 90^{\circ}$ is 2.6 times larger than the heat transfer coefficient with $\alpha = 0^{\circ}$ and, at a velocity of 0.25 m/s (0.82 ft/s), the heat transfer coefficient with $\alpha = 90^{\circ}$ is 4.8 times greater than the heat transfer coefficient with $\alpha = 0^{\circ}$.



Figure 6.7 Influence of Angle of Attack on h_{coil} , Coil 6, $\psi = \pi/2$

Figure 6.8 is a plot of the heat transfer coefficient versus angle of attack for various air velocities with flow perpendicular to the wires. The heat transfer coefficient increases faster with increasing angle ($\alpha = 0^{\circ}$ to 50°) compared to flow normal to the tubes. The heat transfer coefficient for flow normal to the wires also approaches its asymptotic value faster than the heat transfer coefficient for flow normal to the tubes. Beginning at an angle of attack of 50°, a further increase in angle does not significantly increase the heat transfer coefficient. The heat transfer coefficient exhibits the same decrease, when the coil is rotated from 80° to 90°, as that observed for the natural convection test from horizontal to 5° with horizontal wires. When $\alpha = 90^{\circ}$, the wires on opposite sides of the tube are in-line cylinders. With 10° of rotation to $\alpha = 80^{\circ}$, the

coefficient. As α is decreased further, h_{coil} decreases; the minimum h_{coil} occurs at $\alpha = 0^{\circ}$.



Figure 6.8 Influence of Angle of Attack on h_{coil} , Coil 6, $\psi = 0$

Consider next the influence of the Reynolds number on the Nusselt number. Figures 6.9 and 6.10 show the Nusselt number dependence on the Reynolds number with the flow normal to the tubes and wires, respectively. At angles above 60° for flow normal to tubes and above 50° for flow normal to the wires, the influence of the angle is small at all Reynolds numbers. Since the data for a particular angle on these log-log plots essentially follows a straight line, the following correlation is suggested:

$$Nu_{coil} = CRe_{w}^{n}$$
(6.1)

where C and n are empirically determined quantities. Since the slope and y intercept are different for most of the angles, C and n are dependent on the angle of attack.



Figure 6.9 Influence of Re_w on Nu_{coil}, Coil 6, $\psi = \pi/2$



Figure 6.10 Influence of Re_w on Nu_{coil}, Coil 6, $\psi = 0$

Consider next the variation of C and n with α . Figure 6.11 shows the dependence of C and n on the angle of attack for flow normal to the tubes. Figure 6.12 shows the same dependence of C and n on angle of attack for flow normal to the wires. In deducing

these functional relationships, only the data where the Ri < 0.0013 were considered in order to exclude the mixed convection regime.

The functional relationships for C and n were generated in the following manner. First, a least-squares fit was determined for n versus α . Then, new values for n were determined from this correlation, and those values were used to determine the new C value for each angle. The least squares fits for the data are

i) flow normal to the tubes ($\psi = \pi/2$):

$$C = 0.339 - 0.290\cos(\alpha)\exp(-0.00121\alpha^2)$$
(6.2)

$$n = 0.540 + 0.241\cos(\alpha)\exp(-0.00344\alpha^2)$$
(6.3)

and ii) flow normal to the wires ($\psi = 0$):

$$C = 0.385 - 0.350\cos(\alpha)\exp(-0.00102\alpha^2)$$
(6.4)

$$n = 0.531 + 0.267\cos(\alpha)\exp(-0.00181\alpha^2)$$
(6.5)

with angle of attack, α , in degrees.



Figure 6.11 Influence of Angle on C & n, Coil 6, $\psi = \pi/2$



Figure 6.12 Influence of Angle on C & n, Coil 6, $\psi = 0$

In order to test the C & n correlations, the equations must be able to predict the amount of heat transfer for each condition. Equations 6.2 to 6.5 were used to predict the Nusselt number for each angle and velocity for flow normal to the tubes and for flow normal to the wires. Figure 6.13 is a comparison of the correlation and the experimental measurements. This figure includes all of the tests ($\text{Re}_{W} < 175$) even though the correlation was developed only for the range 50 < $\text{Re}_{W} < 175$. The average absolute difference between the measurements and the correlation for all the data is 7.35% with 95% of the data lying within ±22%. If only the data with $\text{Re}_{W} > 50$ is used, the average absolute difference is only 5.11% with 95% of the data having a difference between ±14%. The increased difference at the lower Reynolds numbers is associated with buoyancy influences which have not been accounted for in the correlation.



Figure 6.13 Comparison of Nucoil Correlation to Nucoil Measured, Coil 6

6.4 Mixed and Forced Convection Results, All Coils

The other coils tested have a greater aspect ratio than Coil 6 (see Appendix A for all dimensions of the coils'). These coils are more typical of the size used for a conventional refrigerator. Due to these large aspect ratios, the maximum angle that can be tested in our 300 mm (12 in) high test section is 20° for flow normal to the tubes and 40° for flow normal to the wires. Coils 3, 4, and 8 are larger square coils that can only be rotated to 20° in either flow orientation. Coil 7, which is the serpentine tubing without any wires, is not analyzed in this study, but results can be found in the thesis by Hoke (1995).

Consider first the influence of velocity on h_{coil} for a typical coil. Figures 6.14 and 6.15 show the effect of the free stream velocity on the coil heat transfer coefficients at $\alpha = 0^{\circ}$ and $\alpha = 20^{\circ}$ for flow normal to the tubes and the wires, respectively. These figures represent data from Coil 1, but the other coils exhibit the same trends. In both figures, the heat transfer coefficient with $\alpha = 0^{\circ}$ dips slightly at low velocities due to the buoyancy influence. It has been hypothesized that the forced flow turns the heated air plume leaving the coil back into the coil downstream, causing a reduction in the heat transfer coefficient. A decrease in the heat transfer coefficient in the mixed convection regime is not observed in either figure with $\alpha = 20^{\circ}$.



Figure 6.14 Influence of V on h_{coil}, Coil 1, $\alpha = 0^{\circ}$ & 20°, $\psi = \pi/2$



Figure 6.15 Influence of V on h_{coil} , Coil 1, $\alpha = 0^{\circ}$ & 20°, $\psi = 0$

A comparison of the mixed convection regime for air flow normal to the tubes ($\psi = \pi/2$) and for air flow normal to the wires ($\psi = 0$) is presented in Fig. 6.16 for $\alpha = 0^{\circ}$ and $\alpha = 20^{\circ}$. At $\alpha = 0^{\circ}$, both orientations show that a minimum occurs in h_{coil} near 0.3 m/s (0.98 ft/s). At 20°, the orientation with the flow normal to the wires always has a higher

coil heat transfer coefficient. From the small coil tests, this can be hypothesized to be true until the angle of attack is above 60° when the increased angle does not significantly improve heat transfer and both orientations approach the same asymptote.



Figure 6.16 Influence of ψ on h_{coil}, Coil 1, $\alpha = 0^{\circ}$ & 20°, $\psi = 0$ & $\pi/2$

Consider next the influence of the angle of attack on h_{coil} for a typical coil. Figure 6.17 shows the angular dependence of the heat transfer coefficient for flow normal to the tubes. For velocities of 0.50 m/s (1.64 ft/s) or greater, equal positive and negative angles have the same heat transfer coefficient. The heat transfer coefficient for data taken at 0.25 m/s (0.82 ft/s) is smaller for the -5° than the 5° angle of attack. Figure 6.18 shows the angular dependence of the heat transfer coefficient for flow normal to the wires. The positive and negative angles have the same heat transfer coefficient for velocities equal to 1.00 m/s (3.28 ft/s) or greater. The heat transfer coefficient for 0.25 and 0.50 m/s (0.82 and 1.64 ft/s) is lower for the negative angles compared to the corresponding positive angle. In these cases, the lowest value occurs when the angle is -5° . The heat transfer coefficient is theorized to be less than the heat transfer coefficient for $\alpha = 0^{\circ}$ and $\alpha = 5^{\circ}$ because the buoyant plume rises into the downstream portion of the coil. The heat transfer coefficient at $\alpha = 0^{\circ}$ with a velocity of 0.25 m/s (0.82 ft/s) is 6% greater than the coefficient at 0.5 m/s (1.64 ft/s). A change in the temperature difference between the coil and the ambient will affect the location and magnitude of the minimum heat transfer coefficient.



Figure 6.17 Influence of Angle of Attack on h_{coil}, Coil 1, $\psi = \pi/2$



Figure 6.18 Influence of Angle of Attack on h_{coil} , Coil 1, $\psi = 0$



Figure 6.19 Influence of ψ on h_{coil}, Coil 1, $\psi = 0 \& \pi/2$

Figures 6.20 and 6.21 show the Nusselt number if η_{coil} is assumed to be one for all seven of the coils measured for an air flow of 2.0 m/s (6.56 ft/s) normal to the tubes ($\psi = \pi/2$) and normal to the wires ($\psi = 0$), respectively. The highest velocity tested was chosen because the temperature gradients in the wires are greatest for this case. Nu_{coil} was calculated using eqs. 5.20 and 5.22 with the wire efficiency equal to one. It can be seen from these figures that there is not a good agreement among the data from the various coils.

Figures 6.22 and 6.23 show the Nusselt number for these coils with the fin efficiency of the wires taken into account. The air flow is again 2.0 m/s (6.56 ft/s) normal to the tubes and the wires, respectively. The scatter between data sets has been reduced significantly. Using the effective wire area in the definition of h_{coil} collapses the data appreciably. The effect of the fin efficiency of the wire is more dramatic when the S_t^* value is larger. For example, the fin efficiency for Coil 1 ($S_t^* = 20.8$) ranges from 0.82 to 0.91 (-40° to 0°) while the fin efficiency for Coil 2 ($S_t^* = 40.9$) ranges from 0.53 to 0.69 (-40° to 0°) with an air flow of 2 m/s (6.56 ft/s) normal to the tubes. The fin efficiency of the wire also plays a larger role in the higher angles of attack because the heat transfer coefficient is higher; thus, the fin efficiency is much lower. Increasing the angle of attack

from 0° to 40° results in a decrease in the fin efficiency of 10% for Coil 1 ($S_t^* = 20.8$) and a decrease of 23% for Coil 2 ($S_t^* = 40.9$).



Figure 6.20 Influence of α on Nu with $\eta_{wire} = 1$, Coils 1-6 & 8, V = 2.0 m/s, $\psi = \pi/2$



Figure 6.21 Influence of α on Nu with $\eta_{wire} = 1$, Coils 1-6 & 8, V=2.0 m/s, $\psi = 0$



Figure 6.22 Influence of α on Nu_{coil}, Coils 1-6 & 8, V = 2.0 m/s, $\psi = \pi/2$



Figure 6.23 Influence of α on Nu_{coil}, Coils 1-6 & 8, V = 2.0 m/s, $\psi = 0$

6.5 General Correlations for All Coils

A least squares fit for the Nusselt number can now be performed for the Reynolds number and angle dependence similar to the analysis completed for the small coil (Coil 6) in Section 6.3 of Swofford. The same Nusselt number correlation applied to Coil 6, Eq.

6.1, is also used for all of the coils for each angle and flow orientation. All correlations are based only on the data where the $Ri_w < 0.0013$ to exclude the mixed convection regime. A least squares fit is now performed for the power, n. The correlation for n is used to determine the new n value for each angle. In order to determine the new C values, the least squares fit for the Nusselt-Reynolds correlation at each angle is redone with the power forced to be equal to the new n values. Figures 6.24 and 6.25 show the dependence of C and n on the angle of attack for flow normal to the tubes and wires, respectively. The equations that were generated from the data are

i) with flow normal to the tubes ($\psi = \pi/2$):

$$C = 0.263 - 0.235\cos(\alpha)\exp(-0.00289\alpha^2)$$
(6.6)

$$n = 0.55 + 0.269\cos(\alpha)\exp(-0.00597\alpha^2)$$
(6.7)

and ii) with flow normal to the wires ($\psi = 0$):

$$C = 0.274 - 0.247 \cos(abs(\alpha) - 4.87) \exp(-0.00234(\alpha + 0.902)^{2})$$

$$n = 0.585 + 0.249 \cos(abs(\alpha) + 20.0) \exp(-0.00441(\alpha + 1.66)^{2})$$
(6.8)

(6.9)

where the angle of attack, α , is in degrees.





Figure 6.24 Influence of Angle on C & n, Coils 1-6 & 8, $\psi = \pi/2$

Figure 6.25 Influence of Angle on C & n, Coils 1-6 & 8, $\psi = 0$

Figure 6.26 is a plot of the percent difference between the correlation and the experimental data. If the percent difference is greater than zero, the correlation overpredicts the data. It can be seen that the largest difference occurs in the lower Reynolds regime where the buoyancy force is of importance. The influence of the buoyancy force has not been accounted for in the correlation (Eq. 6.1). The two coils with higher Reynolds numbers are coils 4 and 8, which have larger dimensionless wire diameters, S_w^* . The average percent difference for the other coils is less than zero; thus, the correlation underpredicts these coils.

One factor that has not been taken into account is the dimensionless wire spacing, S_w^* . Rudy (1956) determined that, for a fixed wire diameter, the natural convection coefficient decreased when the exact wire spacing was such that the boundary layers between adjacent wires interfered. When the wire pitch approaches the wire diameter $(S_w^* \rightarrow 1)$, the air cannot flow through the coil and must flow around the coil. In order to determine the influence of the wire pitch, Eq. 6.1 is multiplied by a currently unknown function of S_w^* and rearranged to become:

$$g(\mathbf{S}_{\mathbf{w}}^{*}) = \frac{\mathrm{Nu}_{\mathrm{coil}}}{\mathrm{CRe}_{\mathbf{w}}^{\mathrm{n}}}$$
(6.10)

A least squares fit of $\frac{Nu_{coil}}{CRe_w^n}$ versus $g(S_w^*)$ gave: $g(S_w^*) = 0.985 - 98.5 \exp(-2.32S_w^*)$ (6.11)

The final correlation for the Nusselt number takes on the form:

$$Nu_{coil} = C \operatorname{Re}_{w}^{n} \cdot g(S_{w}^{*})$$
(6.12)

where C & n are determined from eqs. 6.6 to 6.9.

Figure 6.27 shows the percent difference between the data and the final correlation for the Nusselt number. There is still a larger difference associated with some mixed convection points but the overall forced convection difference is less. For all data, the average absolute difference is 8.56% with a standard deviation of 13.7%, while the average absolute difference for the data with $\text{Re}_{\text{w}} > 50$ is 6.74% with a standard deviation of 8.34%. With the improved correlation, 95% of the data with $\text{Re}_{\text{w}} > 50$ lie within ±16.7% of the prediction.



Figure 6.26 Percent Difference between Nu'coil Correlation and Nucoil Data



Figure 6.27 Percent Difference between Nucoil Correlation and Nucoil Data

A modification of this plot is shown on Fig. 6.28 with the value determined from the correlation plotted versus all 1507 measured data values. The angles of attack ranging from horizontal to $\pm 10^{\circ}$ result in the largest differences.



Figure 6.28 Comparison of Nucoil Correlation to Nucoil Measured, Coils 1-6 & 8

7. CONCLUSIONS AND RECOMMENDATIONS

The conclusions that follow are based on the analysis performed and experimental results obtained to date. They are only applicable to coils with geometric parameters similar to the seven typical wire and tube condensers studied and are valid for the ranges of the parameters investigated. The heat transfer coefficient referred to in these conclusions is determined from condensers located in a uniform flow field that is essentially infinite in extent. The coil is oriented such that the flow is always normal to the tubes ($\psi = \pi/2$) or normal to the wires ($\psi = 0$). The influence of D_t^* could not be determined in this study because of the small range of D_t^* values.

- 1. Water is a good "refrigerant" for use in the experimental evaluation of the air-side performance of the condensers because:
 - The resulting refrigerant-side resistance is small (typically < 4%) and can be accurately calculated because this problem has been extensively studied. This working fluid also allows the heat transfer rate to be accurately determined because the properties of water are well established.
 - Coils can be rapidly installed in the experimental facility.
 - Since the thermocouples can be installed relatively easily inside the condensers tubes, errors in the measurements due to the air-side convective heat transfer from the thermocouple leads can be eliminated.
- 2. Neither the temperature of the water entering the coil, $T_{r,in}$, nor the difference between this temperature and the ambient temperature at the entrance of the test section, $T_{a,in}$, has a significant influence on the average heat transfer coefficient over the coil at air velocities above approximately 0.30 m/s (1 ft/s), that is, when inertial effects are relatively dominant. This conclusion is based on the temperature range of 313 K $\leq T_{r,in} \leq 322$ K (105°F $\leq T_{r,in} \leq 120$ °F) with $T_{a,in} \cong$ 297 K ($T_{a,in} \cong 75$ °F).
- 3. For the range of Rayleigh numbers tested $(3.2 < \text{Ra}_w < 5.8)$, the natural convection coefficient for a horizontal coil ($\alpha = 0^\circ$) is significantly higher than a vertical coil ($\alpha = 90^\circ$) with either $\psi = 0$ or $\psi = \pi/2$. The natural convection heat transfer coefficient does not significantly decrease with an increase in angle from 0 to 30 degrees.

- 4. The convective heat transfer with flow over a wire-and-tube condenser located in a horizontal plane is a very complex phenomenon. For example, at flow rates less than approximately 0.91 m/s (3 ft/s), a mixed convection regime exists where h_{coil} decreases with increasing velocity.
- 5. If a coil is horizontal or nearly horizontal, its air-side performance with flow normal to the tubes ($\psi = \pi/2$) is nearly the same as with flow normal to the wires ($\psi = 0$) over the velocity range from 0.15 to 2.01 m/s (0.5 to 6.6 ft/s). At velocities above 0.91 m/s (3 ft/s) and angles of attack between 10 and 60 degrees, coils perform significantly better if the flow is normal to the wires. The heat transfer coefficient, h_{coil}, does not significantly increase when increasing the angle of attack from 60 to 90 degrees with V > 0.3 m/s (1 ft/s).
- 6. The fin efficiency of the wires is greater than 0.9 if the angle of attack and velocity are such that h_{coil} is below approximately 42 W/m²-K (7.4 Btu/hr-ft²-°F) for S^{*}_t = 20.8 (Coil 1) and h_{coil} is below approximately 10 W/m²-K (1.8 Btu/hr-ft²-°F) for S^{*}_t = 40.9 (Coil 2). The performance of the coil with S^{*}_t = 40.9 (Coil 2) suffers appreciably when the velocity and angle of attack are such that significantly higher heat transfer coefficients result.
- 7. Assuming buoyancy forces are significantly less than the inertial forces, the Nusselt number for the coil, based on the convective heat transfer coefficient and the wire diameter, is successfully correlated to the Reynolds number by

 $\operatorname{Nu}_{\operatorname{coil}} = \operatorname{CRe}_{\mathbf{w}}^{\mathbf{n}} \cdot g(\mathbf{S}_{\mathbf{w}}^{*})$

where

 $C = f_1(\alpha, \psi)$ and $n = f_2(\alpha, \psi)$

8. The values for C & n in the Nusselt-Reynolds correlation have a different dependency on the angle of attack for each orientation ($\psi = 0$ or $\psi = \pi/2$). The power, n, is determined to have a value approximately equal to 0.8 for a horizontal coil in either orientation and n decreases with increasing angle. When the angle of attack approaches 90°, the power reaches an asymptotic value of

approximately 0.5. This is the same power as that for flow normal to a single cylinder in the same Reynolds number range.

- 9. As the dimensionless spacing of the wire, S_w^* , is decreased, the performance of the coil decreases. A function, $g(S_w^*)$, is derived to include the influence of the dimensionless wire spacing. function, $g(S_w^*)$, is based on a limited number of S_w^* values and should be studied further. A parametric study of the dimensionless wire spacing is in progress at the Air-Conditioning and Refrigeration Center at the University of Illinois at Urbana-Champaign.
- 10. Correlation 6.12 should be especially valuable to refrigerator manufacturers in order to optimize the performance of the wire and tube condenser and minimize the cost of the condenser and the volume occupied by the condenser.

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APPENDIX A: COIL GEOMETRY

Coil Number	Manufacturer	
1	Frigidaire	
2	Frigidaire	
3	Frigidaire	
4	GE	
5	GE	
6	Whirlpool	
7	GE	
8	Bosh	

Table A.1Coil Numbering and Manufacturer

Table A.2a	Metric	Coil Dim	ensions,	Coils	1-4	ŀ
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Variable	Units	Coil 1	Coil 2	Coil 3	Coil 4
D_w	mm	1.22	1.24	1.22	1.62
Sw	mm	5.34	5.22	5.39	4.57
N _w	-	176	168	148	168
L _w	mm	406	446	610	572
Dt	mm	4.80	4.73	4.80	4.92
D _{t,i}	mm	3.18	3.18	3.18	3.57
St	mm	25.4	50.8	25.4	31.8
L _t	mm	660	679	591	578
N _t	-	16	9	24	18
DEPTH	mm	6.25	6.02	6.25	6.60
DELTAP	mm	0.058	0.013	0.058	0.013
A _w	m ²	0.274	0.292	0.345	0.489
A _t	m ²	0.168	0.100	0.228	0.174
Dimensionles	s Variabl	es			
$S_t^* = S_t / D_w$		20.8	40.9	20.8	19.6
$D_t^* = D_t / D_w$		3.94	3.81	3.94	3.03
$S_w^* = S_w/D_w$		4.38	4.21	4.43	2.82
$L_w^* = L_w/D_w$		333	359	500	352
$L_t^* = L_t/D_w$		542	548	485	356
$(Aw/A_{tot})*100$		62	74	60	74

Variable	Units	Coil 5	Coil 6	Coil 7	Coil 8
D_w	mm	1.21	1.35	-	1.58
Sw	mm	4.56	5.68	-	6.81
N _w	-	166	64	0	150
L _w	mm	383	279	-	559
Dt	mm	6.21	4.75	4.74	4.76
D _{t,i}	mm	5.16	3.18	3.05	3.56
St	mm	31.8	25.4	31.8	50.8
Lt	mm	575	256	629	483
Nt	-	12	11	10	11
DEPTH	mm	7.47	6.15	4.74	6.94
DELTAP	mm	0.013	0.013	0.000	0.015
A _w	m ²	0.241	0.076	-	0.415
A _t	m ²	0.145	0.048	0.100	0.091
Dimensionles	s Variable	es			
$S_t^* = S_t / D_w$		26.2	18.8	-	32.2
$D_t^* = D_t / D_w$		5.13	3.52	-	3.02
$S_w^* = S_w/D_w$		3.77	4.21	-	4.32
$L_w^* = L_w/D_w$		316	207	-	354
$L_t^* = L_t/D_w$		475	190	-	101
$(Aw/A_{tot})*100$		62	61	-	82

 Table A.2b
 Metric Coil Dimensions, Coils 5-8

$$A_{t} = \pi D_{t} L_{t} N_{t} + \pi D_{t} \left(\frac{\pi S_{t}}{2}\right) (N_{t} - 1)$$
$$A_{w} = \pi D_{w} L_{w} N_{w}$$
$$A_{tot} = A_{t} + A_{w}$$

Table A.3aEnglish Coil Dimensions, Coils 1-4

Variable	Units	Coil 1	Coil 2	Coil 3	Coil 4
$\overline{\mathrm{D}}_{\mathrm{w}}$	in	0.048	0.049	0.048	0.064
Sw	in	0.210	0.206	0.212	0.180
Nw	—	176	168	148	168
L _w	in	16.00	17.56	24.00	22.50
D _t	in	0.189	0.186	0.189	0.194
$D_{t,i}$	in	0.125	0.125	0.125	0.141
St	in	1	2	1	1.25
L _t	in	26.0	26.75	23.25	22.75
Nt		16	9	24	18
DEPTH	in	0.246	0.237	0.246	0.260
DELTAP	in	0.00	0.0005	0.0023	0.0005
A _w	in ²	424	453	535	759
A _t	in ²	261	156	353	270

(A.1)

(A.2) (A.3)

Variable	Units	Coil 5	Coil 6	Coil 7	Coil 8
D_w	in	0.0476	0.053	N/A	0.062
Sw	in	0.1797	0.224	N/A	0.268
N_w		166	64	0	150
L _w	in	15.0625	11	N/A	22
Dt	in	0.2446	0.187	0.187	0.188
D _{t,i}	in	0.2031	0.125	0.120	0.140
St	in	1.25	1	1.25	2
L _t	in	22.625	10.06	24.75	19
N _t		12	11	10	11
DEPTH	in	0.294	0.242	0.187	0.273
DELTAP	in	0.0005	0.0005	0	0.0006
A _w	in ²	374	117	N/A	643
A _t	in ²	225	74	155	142

Table A.3bEnglish Coil Dimensions, Coils 5-8




Coil 2





















Figure A.1 **Coil Cross Sections**

APPENDIX B. AIR-SIDE RESISTANCE SAMPLE CALCULATION

This appendix will demonstrate how to use the correlation to determine an air side resistance for a wire and tube heat exchanger. Coil 1 will be used for an example with V = 1.0 m/s, $\alpha = 20^{\circ}$, and $\psi = 0$.

1. First determine the geometry that will be used in the calculation:

 $D_{t} = 0.00480 \text{ m}$ $D_{w} = 0.00122 \text{ m}$ $S_{t} = 0.0254$ $S_{w} = 0.00534 \text{ m}$ $L_{t} = 0.6604$ $L_{w} = 0.4064$ $N_{t} = 16$ $N_{w} = 176$

2.

Determine the Dimensionless Parameters and the Surface Areas

31 1 1 5 1

$$D_{t}^{*} = \frac{D_{t}}{D_{w}} = 1.984$$

$$S_{t}^{*} = \frac{S_{t}}{D_{w}} = 20.82$$

$$S_{w}^{*} = \frac{S_{w}}{D_{w}} = 4.381$$

$$A_{t} = \left(\frac{\pi S_{t}}{2} (N_{t} - 1) + L_{t} N_{t}\right) \pi D_{t} = 0.1684 \text{ m}^{2}$$

$$A_{w} = N_{w} L_{w} \pi D_{w} = 0.2741 \text{ m}^{2}$$

3. Determine Re, C, n and $f(S_w^*)$ from the Flow Conditions and Coil orientation

$$\psi = 0$$

$$f(S_{w}^{*}) = 0.985 - 98.5 \exp(-2.32S_{w}^{*}) = 0.981$$

$$\alpha = 20^{\circ}$$

$$C = 0.274 - 0.247 \cos(abs(\alpha) - 4.86) \exp(-0.00234(\alpha + 0.902)^{2})$$

= 0.1883

$$Re = \frac{V_a D_w}{v_a} = 83.59$$

4. Determine Nu using Eq. 6.12, that is:

$$\operatorname{Nu}_{\operatorname{coil}} = \operatorname{CRe}_{\operatorname{coil}}^{n} f(S_{w}^{*}) = 2.737$$

The experimentally determined Nusselt number for this case is 2.72, a difference of 0.62%.

5. Determine the fin parameter, fin efficiency and the heat transfer coefficient from the Nusselt number using eqs. 5.11 and 5.8.

$$m = S_t^* \sqrt{Nu_{coil} \left(\frac{k_a}{k_w}\right)} = 0.7182$$
$$\eta = \frac{\tanh m}{m} = 0.857$$
$$h_{coil} = \frac{Nu_{coil}k_a}{D_w} = 59.00 \text{ W/m}^2\text{-K}$$

6. Determine the air-side resistance using Eq. 5.31.

$$R_{a} = \frac{1}{h_{coil} \left(\frac{A_{t}}{\sqrt{D_{t}^{*}}} + \eta A_{w} \right)} = 0.0478 \text{ K/W} \qquad \left(\frac{1}{R_{a}} = 20.91 \text{ W/K} \right)$$

If one wishes to include the effects of radiation Step 5 should be replaced with the following:

5. Determine the radiation heat transfer coefficient, the effective fin parameter, the effective fin efficiency and the effective heat transfer coefficient.

$$m_{e} = S_{t}^{*} \sqrt{Nu_{coil} \left(\frac{k_{a}}{k_{w}}\right) + \frac{h_{rad}D_{w}}{k_{w}}}$$
$$\eta_{e} = \frac{\tanh m_{e}}{m_{e}}$$
$$h_{coil,e} = \frac{Nu_{coil}k_{a}}{D_{w}} + h_{rad}$$

 $h_{coil,e}$ replaces h_{coil} in the resistance calculation in Step 6.

APPENDIX C. ADDITIONAL REDUCED COIL DATA

This appendix contains the reduced data in the forms of tables and graphs for each of the seven coils analyzed in this study. The first two figures for each coil present the heat transfer coefficient as defined by Eq. 5.20 versus the free stream air velocity for angles ranging from horizontal to the maximum positive angle. These graphs are useful for determining the effect of changing the air velocity with a fixed angle of attack. The third and fourth figure for each coil present the same data except the heat transfer coefficient is plotted versus angle. These graphs can be used to determine the influence of changing the angle of attack with a fixed air velocity.

The tables include the data presented figs. C.1 to C.28; but they also include the wire fin efficiency as defined by Eq. 5.23. Although the fin efficiency can be calculated from the heat transfer coefficient and the coil's geometry, it is included to allow easy comparison between different coils. Other quantities which can also be calculated from the velocity or heat transfer coefficient, such as the Nusselt number and Reynolds number, are not included. SI units are used in tables C.2 to C.15 (see Table C.1).

	velocity	h _{coil}	η _{wire}
Units	m/s	W/m ² -K	Dimensionless

Table C.1 Units used for Subsequent Tables in Appendix C



Figure C.1 Coil 1 h_{coil} Dependence on Velocity with Flow Normal to the Tubes



Figure C.2 Coil 1 h_{coil} Dependence on Velocity with Flow Normal to the Wires



Figure C.3 Coil 1 h_{coil} Dependence on Angle with Flow Normal to the Tubes



Figure C.4 Coil 1 h_{coil} Dependence on Angle with Flow Normal to the Wires



Figure C.5 Coil 2 h_{coil} Dependence on Velocity with Flow Normal to the Tubes



Figure C.6 Coil 2 h_{coil} Dependence on Velocity with Flow Normal to the Wires



Figure C.7 Coil 2 h_{coil} Dependence on Angle with Flow Normal to the Tubes



Figure C.8 Coil 2 h_{coil} Dependence on Angle with Flow Normal to the Wires



Figure C.9 Coil 3 h_{coil} Dependence on Velocity with Flow Normal to the Tubes



Figure C.10 Coil 3 h_{coil} Dependence on Velocity with Flow Normal to the Wires





Figure C.12 Coil 3 h_{coil} Dependence on Angle with Flow Normal to the Wires



Figure C.13 Coil 4 h_{coil} Dependence on Velocity with Flow Normal to the Tubes



Figure C.14 Coil 4 h_{coil} Dependence on Velocity with Flow Normal to the Wires



Figure C.15 Coil 4 h_{coil} Dependence on Angle with Flow Normal to the Tubes



Figure C.16 Coil 4 h_{coil} Dependence on Angle with Flow Normal to the Wires



Figure C.17 Coil 5 h_{coil} Dependence on Velocity with Flow Normal to the Tubes



Figure C.18 Coil 5 h_{coil} Dependence on Velocity with Flow Normal to the Wires





Figure C.20 Coil 5 h_{coil} Dependence on Angle with Flow Normal to the Wires



Figure C.21 Coil 6 h_{coil} Dependence on Velocity with Flow Normal to the Tubes



Figure C.22 Coil 6 h_{coil} Dependence on Velocity with Flow Normal to the Wires



Figure C.23 Coil 6 h_{coil} Dependence on Angle with Flow Normal to the Tubes



Figure C.24 Coil 6 h_{coil} Dependence on Angle with Flow Normal to the Wires



Figure C.25 Coil 8 h_{coil} Dependence on Velocity with Flow Normal to the Tubes



Figure C.26 Coil 8 h_{coil} Dependence on Velocity with Flow Normal to the Wires



Figure C.28 Coil 8 h_{coil} Dependence on Angle with Flow Normal to the Wires

	$\alpha = -40^{\circ}$			α= -30°			α=-20°			α= -15°			α= -10°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.20	24.8223	0.9387	0.20	23.5091	0.9418	0.20	19.6096	0.9508	0.20	16.1807	0.9590	0.20	10.1084	0.9739
0.25	28.3489	0.9308	0.25	25.7198	0.9367	0.25	21.9258	0.9454	0.25	18.5308	0.9534	0.25	12.8190	0.9672
0.35	34.0518	0.9182	0.35	30.5970	0.9258	0.35	26.1695	0.9357	0.35	22.7537	0.9435	0.35	17.2220	0.9565
0.50	41.0168	0.9034	0.50	36.9324	0.9120	0.50	32.2229	0.9222	0.50	28.2243	0.9310	0.50	21.7985	0.9457
0.63	46.4530	0.8922	0.63	41.9788	0.9014	0.63	36.7745	0.9123	0.63	32.7826	0.9210	0.63	25.6988	0.9367
0.76	51,0481	0.8831	0.76	46.4716	0.8922	0.75	40.8316	0.9038	0.75	36.4360	0.9131	0.75	29.0492	0.9292
0.88	55.5338	0.8743	0.87	50.3560	0.8844	0.88	44.4729	0.8963	Ó.88	40.3466	0.9048	0.88	32.6460	0.9213
1.01	59.8368	0.8662	1.01	54.0958	0.8771	1.00	48.2622	0.8886	1.00	43.7577	0.8977	1.00	35.8154	0.9144
1.16	64.4679	0.8576	1.16	58.6354	0.8684	1.17	52.8863	0.8795	1.17	47.9858	0.8892	1.17	39.8425	0.9058
1.33	69.1507	0.8491	1.34	63.0333	0.8602	1.34	57.1831	0.8712	1.34	52.3462	0.8805	1.33	43.8379	0.8976
1.50	73.8745	0.8407	1.50	67.0918	0.8528	1.50	61.3483	0.8633	1.50	56.3546	0.8728	1.50	47.7262	0.8897
1.67	77.9564	0.8337	1.68	71.8163	0.8443	1.67	65.1250	0.8564	1.67	60.6541	0.8646	1.67	51.7805	0.8816
1.83	82.0063	0.8268	1.84	75.7891	0.8374	1.84	69.5719	0.8483	1.84	64.2916	0.8579	1.84	55.3905	0.8746
2.00	84.7772	0.8222	2.00	79.5042	0.8310	2.01	73.2029	0.8419	2.00	67.9841	0.8512	2.00	57.7116	0.8702
	Table C.2 h _{coil} ar					lwire for	Coil 1 with 1	Flow Norm	al to Tul	oes Continue	d			
	α= -5°			α= 0°			α= 5°			α= 10°			α= 15°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire
0.21	7.7648	0.9798	0.19	7.8660	0.9796	0.21	9.8385	0.9740	0.20	12.6199	0.9677	0.20	16.8734	0.9574
0.25	7.939	5 0.9794	0.25	6.9664	0.9818	0.25	10.2461	0.973	0.25	13.2817	0.9661	0.25	18.9651	0.9524
0.35	5 10.643	1 0.9726	0.35	7.7421	0.9799	0.35	11.4271	0.970	0.35	17.6677	0.9555	0.35	22.9836	0.9430
0.50	14.067	5 0.9641	0.50	11.8044	0.9697	0.50	13.6410	0.9652	20.50	22.5758	0.9439	0.50	28.7493	0.9299
0.63	3 16.991	0.9571	0.63	14.3681	0.9634	Q.63	16.1203	0.9592	2 0.63	26.4632	0.9350	0.63	33.0759	0.9203
0.75	5 19.267	6 0.951	0.75	16.6096	0.9580	0.75	18.3590	0.953	3 0.75	29.3368	0.9286	0.75	36.9183	0.9120
0.88	22.309	4 0.944	0.88	19.0472	0.9522	2.0.87	20.8770	0.947	9 0.88	33.0470	0.9204	0.89	41.2694	0.9029
1.0	1 25.179	3 0.937	1.00	21.0804	0.947	1.00	23.5763	0.941	6 1.00	36.4674	0.9130	1.00	44.2616	0.8967
1.1	6 28.637	4 0.930	1 1.17	24.2121	0.940	1 1.18	27.1574	0.933	4 1.17	40.7845	0.903	1.17	48.9217	0.8873
1.3	4 32.030	3 0.922	6 1.34	27.0612	0.933	7 1.33	30.1489	0.926	7 1.34	45.0919	0.8950	1.34	53.5211	0.8782
1.5	1 35.061	8 0.916	0 1.51	30.0984	0.926	9 1.51	33.3260	0.919	8 1.50	49.0144	0.887	1.50	57.4632	0.8706
1.6	7 38.145	7 0.909	4 1.67	32.7583	0.921	0 1.67	36.2080	0.913	5 1.67	52.9388	0.879	1 1.67	61.7167	0.8626
1.8	5 41.250	2 0.902	9 1.84	35.3403	0.915	4 1.83	39.968	5 0.905	6 1.83	56.3852	2 0.872	7 1.84	65.5824	0.8555
2.0	1 44.097	2 0.897	0 2.01	37.656	0.910	5 2.00	42.860	6 0.899	6 2.00	59.8879	0.866	1 2.00	69.161	0.8491

Table C.2 h_{coil} and η_{wire} for Coil 1 with Flow Normal to Tubes

	α= 20°			α= 30°			α=40°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire
0.21	18.6188	0.9532	0.20	23.2660	0.9423	0.20	25.2539	0.9378
0.25	20.9854	0.9476	0.25	25.9453	0.9362	0.25	29.2016	0.9289
0.35	25.5605	0.9371	0.35	31.0766	0.9247	0.35	34.7024	0.9168
0.50	31.6035	0.9235	0.50	37.3911	0.9110	0.50	41.6789	0.9020
0.63	36.3123	0.9133	0.63	42.6170	0.9001	0.63	47.2572	0.8906
0.75	40.4022	0.9047	0.75	46.8806	0.8914	0.75	51.6610	0.8819
0.88	44.1636	0.8969	0.88	50.8680	0.8834	0.88	55.6998	0.8740
1.00	47.8946	0.8893	1.00	54.3009	0.8767	1.00	59.9690	0.8659
1.16	52.2509	0.8807	1.17	58.7498	0.8682	1.17	64.7509	0.8570
1.33	56.5787	0.8723	1.34	63.1427	0.8600	1.34	69.6165	0.8482
1.50	60.6770	0.8646	1.50	67.2124	0.8526	1.50	74.1611	0.8402
1.68	64.8626	0.8568	1.67	71.9678	0.8441	1.67	78.6046	0.8326
1.84	68.7483	0.8498	1.84	76.1054	0.8369	1.84	82.5117	0.8260
2.00	72.4088	0.8433	2.00	79.8841	0.8304	2.00	86.5336	0.8193

Table C.2 h_{coil} and η_{wire} for Coil 1 with Flow Normal to Tubes Continued

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Table C.3 h_{coil} and η_{wire} for Coil 1 with Flow Normal to Wires

·	α= -20°			α= -15°		-	α=-10°			α= -5°			α= 0°	
vel	h _{coil}	Nwire	vel	hcoil	Nwire									
0.20	18.3325	0.9539	0.21	13.4148	0.9657	0.21	12.2229	0.9687	0.20	9.8166	0.9746	0.20	12.9678	0.9668
0.25	21.3642	0.9467	0.25	16.4783	0.9583	0.25	9.6199	0.9751	0.25	8.9424	0.9768	0.25	12.0672	0.9691
0.35	26.9910	0.9338	0.35	22.1046	0.9450	0.35	13.6365	0.9652	0.35	8.2921	0.9785	0.35	10.7695	0.9723
0.50	33.6752	0.9190	0.50	28.7521	0.9299	0.50	20.9571	0.9477	0.50	11.4188	0.9707	0.50	11.3345	0.9709
0.63	39.0987	0.9074	0.63	33.7511	0.9188	0.63	25.3627	0.9375	0.63	15.0089	0.9619	0.63	13.1309	0.9664
0.75	43.9687	0.8973	0.76	38.3046	0.9091	0.76	29.9799	0.9271	0.75	18.0480	0.9545	0.75	15.0008	0.9619
0.88	48.7920	0.8875	0.88	42.5396	0.9002	0.87	33.4297	0.9195	0.88	21.3107	0.9469	0.88	17.1010	0.9568
1.00	53.2263	0.8788	1.00	46.4078	0.8923	1.00	37.1613	0.9115	1.00	23.6618	0.9414	1.00	19.2514	0.9517
1.17	58.6077	0.8685	1.17	51.5036	0.8822	1.17	41.8046	0.9018	1.17	27.2869	0.9331	1.17	22.0137	0.9452
1.34	63.7074	0.8590	1.34	56.3876	0.8727	1.34	46.8704	0.8914	1.34	30.6229	0.9257	1.34	24.9210	0.9385
1.50	68.6332	0.8500	1.50	60.8324	0.8643	1.50	50.9828	0.8832	1.50	33.6762	0.9190	1.50	27.2953	0.9331
1.67	73.6193	0.8412	1.68	65.7972	0.8551	1.67	55.4783	0.8744	1.67	36.9691	0.9119	1.67	29.9291	0.9272
1.84	78.4067	0.8329	1.85	70.5529	0.8466	1.85	59.8940	0.8661	1.84	40.0997	0.9053	1.84	32.5864	0.9214
2.00	82.5228	0.8260	2.01	74.6424	0.8394	1.99	63.3070	0.8597	2.00	42.8343	0.8996	2.00	34.9611	0.9162

	α= 5°			α= 10°			α= 15°			α= 20°	
vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire
0.21	14.6849	0.9626	0.20	17.1398	0.9567	0.20	18.5789	0.9533	0.20	17.5772	0.9557
0.25	15.0046	0.9619	0.25	18.3011	0.9539	0.25	21.3038	0.9469	0.25	24.3072	0.9399
0.35	14.8398	0.9623	0.35	19.5432	0.9510	0.35	24.3255	0.9399	0.35	28.6014	0.9302
0.50	15.8078	0.9599	0.50	23.0790	0.9427	0.50	29.1276	0.9290	0.50	34.9416	0.9163
0.63	17.2616	0.9564	0.63	26.5686	0.9348	0.63	33.5948	0.9192	0.63	40.1719	0.9052
0.75	18.9366	0.9524	0.75	29.6917	0.9278	0.75	37.8919	0.9100	0.75	45.2034	0.8948
U.88	21.0379	0.9475	0.88	32.8432	0.9208	0.88	42.2445	0.9008	0,88	49.9363	0.8853
1.00	23.2209	0.9424	1.00	35.7531	0.9145	1.00	45.9446	0.8933	1,00	54.0532	0.8772
1.17	26.1348	0.9357	1.17	39.9095	0.9057	1.17	50.9724	0.8832	1.17	59.4824	0.8668
1.34	29.1503	0.9290	1.34	44.1797	0.8969	1.33	55.6796	0.8741	1,34	64.7436	0.8571
1.50	32.0022	0.9227	1.50	47.7794	0.8896	1.50	60.2526	0.8654	1,50	69.4208	0.8486
1.67	34.8138	0.9165	1.67	52.3865	0.8804	1.67	64.9474	0.8567	1.67	74.2565	0.8401
1.84	37.7277	0.9103	1.84	55.7815	0.8739	1.84	69.6837	0.8481	1.84	79.0246	0.8319
2.00	40.2369	0.9050	2.00	59.8428	0.8661	2.00	74.1506	0.8403	2.00	83.3381	0.8246

Table C.3 h_{coil} and η_{wire} for Coil 1 with Flow Normal to Wires Continued

Table C.4 h_{coil} and η_{wire} for Coil 2 with Flow Normal to Tubes

	$\alpha = -40^{\circ}$			α= -30°			α=-20°			α= -15°			α= -10°	
vel	h _{coil}	Nwire	vel	h _{coil}	Nwire	vel	h _{coil}	Jwire	vel	h _{coil}	Nwire	vel	h _{coil}	η_{wire}
0.19	24.6012	0.7923	0.20	25.8017	0.7848	0.20	20.8176	0.8173	0.21	18.4411	0.8341	0.19	11.9195	0.8847
0.25	30.1136	0.7592	0.25	28.6096	0.7679	0.25	23.0915	0.8021	0.25	20.6606	0.8184	0.25	15.7813	0.8538
0.35	36.1838	0.7264	0.34	33.6744	0.7395	0.35	27.7907	0.7727	0.35	25.0519	0.7895	0.35	20.5460	0.8192
0.50	43.1629	0.6928	0.50	40.3966	0.7057	0.50	35.6229	0.7293	0.50	30.9205	0.7546	0.50	25.7864	0.7849
0.63	48.2856	0.6706	0.63	45.1268	0.6841	0.64	39.2079	0.7114	0.63	35.5228	0.7298	0.63	30.5610	0.7566
0.75	53.1102	0.6513	0.76	50.0247	0.6635	0.76	43.8420	0.6898	0.75	39.7421	0.7088	0.75	34.0232	0.7376
0.88	58.0064	0.6330	0.89	54.6494	0.6454	0.87	47.2499	0.6750	0.88	43.5940	0.6909	0.88	38.0182	0.7172
1.00	62.1420	0.6187	1.01	58.0970	0.6327	1.00	51.1127	0.6591	1.00	47,5707	0.6736	1.00	41.4332	0.7008
1.16	67.3151	0.6018	1.17	63.0043	0.6158	1.16	55.1630	0.6435	1.17	51.7386	0.6566	1.17	45.6849	0.6817
1.33	72.7995	0.5852	1.33	67.5742	0.6010	1.35	59.9060	0.6263	1.34	55,9629	0.6405	1.34	50.3148	0.6623
1.51	77.9975	0.5705	1.51	72.9438	0.5848	1.50	63.8379	0.6130	1.50	60.6214	0.6238	1.51	54.4259	0.6462
1.68	83.8524	0.5551	1.67	77.3020	0.5724	1.67	68.5796	0.5979	1.67	64.7871	0.6099	1.67	58.6192	0.6309
1.83	87.6977	0.5456	1.84	81.9610	0.5600	1.83	72.3253	0.5866	1.84	68.7217	0.5974	1.84	62.2708	0.6182
2.00	92.0191	0.5354	2.00	86.3253	0.5489	2.00	76.2928	0.5752	2.00	72.4262	0.5863	2.00	65.9005	0.6063

	α= -5°			α= 0°			α= 5°			α= 10°			α=15°	
vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.20	9.6975	0.9037	0.21	9.9937	0.9011	0.22	11.6469	0.8869	0.23	15.8442	0.8533	0.19	16.9977	0.8446
0.25	10.4296	0.8973	0.26	9.8984	0.9019	0.25	12.5381	0.8795	0.25	16.7304	0.8466	0.25	20.1256	0.8221
0.35	13.7798	0.8695	0.36	11.2125	0.8906	0.35	14.8365	0.8611	0.35	20.1094	0.8222	0.36	24.7966	0.7911
0.50	18.2145	0.8357	0.50	14.0843	0.8670	0.50	18.3614	0.8346	0.50	25.5691	0.7863	0.50	30.2806	0.7582
0.63	21.8673	0.8102	0.63	17.1730	0.8433	0.63	21.3353	0.8138	0.63	30.1783	0.7588	0.63	34.6977	0.7341
0.76	25.4488	0.7870	0.76	20.3374	0.8206	0.75	24.7260	0.7916	0.75	34.0121	0.7377	0.75	38.8586	0.7131
0.88	28.8555	0.7664	0.88	22.5154	0.8059	0.87	27.9391	0.7718	0.88	37.7295	0.7186	0.88	43.0867	0.6932
1.01	31.8216	0.7496	1.02	25.4307	0.7871	1.01	31.3463	0.7522	1.00	41.1819	0.7020	1.00	46.1537	0.6796
1.17	35.7508	0.7286	1.18	28.9419	0.7659	1.17	34.8114	0.7335	1,16	44.9677	Q.6848	1.16	50.5409	0.6614
1.34	39.6744	0.7091	1.34	32.2464	0.7472	1.35	39.0365	0.7122	1.34	48.8155	0.6684	1.34	55.2242	0.6432
1.50	43.2685	0.6924	1.51	35.5156	0.7298	1.50	42.0914	0.6977	1,50	52.8282	0.6524	1.51	59.2449	0.6286
1.67	46.9945	0.6760	1.67	38.6335	0.7142	1.67	45.9634	0.6805	1.67	57.1206	0.6362	1.67	63.3458	0.6146
1.84	50.4674	0.6617	1.84	41.7050	0.6995	1.87	50.5840	0.6612	1,83	60.8428	0.6231	1.85	67.6366	0.6008
2.00	53.9694	0.6480	2.01	44.5494	0.6866	2.02	53.6563	0.6492	2.00	64.3111	0.6114	2.00	71.3602	0.5894

Table C.4 h_{coil} and η_{wire} for Coil 2 with Flow Normal to Tubes Continued

Table C.4 h_{coil} and η_{wire} for Coil 2 with Flow Normal to Tubes Continued

	α= 20°			α= 30°			α=40°	
vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire
0.19	20.4889	0.8196	0.20	24.8970	0,7905	0.21	25,5617	0.7863
0.25	23.7126	0.7980	0.25	27.3401	0.7754	0.25	30.3088	0.7580
0.35	28.1698	0.7705	0.35	32.1780	0.7476	0.35	36.0771	0.7269
0.50	34.2036	0.7367	0.50	38.8616	0.7130	0.50	43.3736	0.6919
0.63	38.8130	0.7133	0.63	43.4024	0.6918	0.63	48,6525	0.6691
0.75	43.0594	0.6933	0.75	47.3746	0.6744	0.75	53.4541	0.6499
0.88	46.8155	0.6768	0.88	51.6044	0.6571	0.88	58.4375	0.6315
1.00	50.0616	0.6633	1.00	55.6487	0.6417	1.00	62.3652	0.6179
1.17	54.7157	0.6451	1.17	60.6012	0.6239	1.17	67.7854	0.6003
1.34	59.0694	0.6293	1.33	65.3174	0.6082	1.34	72.9223	0.5848
1.50	63.1410	0.6153	1.50	69.9030	0.5938	1.50	77.5814	0.5717
1.68	67.6597	0.6007	1.68	75.1089	0.5786	1.67	82.4714	0,5587
1.84	71.8803	0.5879	1.85	79.1655	0.5674	1.84	87.2983	0.5466
2.00	75.4715	0.5775	2.01	83.1565	0.5569	2.00	92.3486	0.5346

	α= -20°		•	α=-15°			α= -10°			α=-5°			α= 0°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.20	19.8229	0.8242	0.22	17.5005	0.8409	0.22	11.0333	0.8921	0.22	11.7645	0.8860	0.20	12.8249	0.8772
0.25	23.6219	0.7986	0.25	19.9802	0.8231	0.25	10.9486	0.8929	0.25	11.1658	0.8910	0.25	12.3793	0.8808
0.35	30.0281	0.7596	0.35	25.7760	0.7850	0.35	17.1553	0.8435	0.35	11,2739	0.8901	0.35	12.5547	0.8794
0.50	36.8593	0.7230	0.50	33.4672	0.7406	0.50	24.1498	0.7952	0.50	14.3503	0.8649	0.50	13.7668	0.8696
0.63	42.4035	0.6963	0.63	38.6926	0.7139	0.63	29.5557	0.7624	0.63	17.8511	0.8383	0.63	16.0363	0.8519
0.75	47.3340	0.6746	0.75	43.3715	0.6919	0.75	33.2758	0.7416	0.75	20.7867	0.8175	0.75	18.5178	0.8335
0.88	52.3322	0.6543	0.88	47.7605	0.6728	0.88	37.7831	0.7183	0.88	23.8553	0.7971	0.88	20.9667	0.8163
1.00	56.8401	0.6373	1.00	52.0254	0.6555	1.00	41.2137	0.7018	1.00	26.9881	0.7775	1.00	23.5319	0.7992
1.17	62.9672	0.6159	1.17	57.5157	0.6348	1.17	46.1404	0.6797	1.17	30.4168	0.7574	1.17	26.9418	0.7778
1.34	68.1681	0.5991	1.34	63.7818	0.6132	1.34	50.6153	0.6611	1.34	34.1655	0.7369	1.34	29.9960	0.7598
1.50	73.0395	0.5845	1.51	68.5559	0.5979	1.50	55.1715	0.6434	1.50	37.5761	0.7194	1.50	32.7121	0.7447
1.67	78.2808	0.5698	1.67	73.1112	0.5843	1.67	59.9272	0.6263	1.68	41.1068	0.7023	1.67	35.7260	0.7287
1.84	83.2155	0.5567	1.85	77.5454	0.5718	1.84	64.6525	0.6103	1.84	44.2795	0.6878	1.84	38.5784	0.7144
2.01	88.3123	0.5441	2.00	81.5100	0.5612	2.00	69.0412	0.5964	2.00	47.4545	0.6741	2.00	41.1898	0.7019

Table C.5 h_{coil} and η_{wire} for Coil 2 with Flow Normal to Wires

Table C.5 h_{coil} and η_{wire} for Coil 2 with Flow Normal to Wires Continued

	α= 5°			α=10°			α=15°			α=20°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire
0.21	15.6815	0.8546	0.21	18.4684	0.8339	0.23	30.6474	0.7561			
0.25	16.0829	0.8515	0.25	19.7249	0.8249	0.25	31.5075	0.7513	0.25	26.2419	0.7821
0.35	17.0538	0.8442	0.35	22.6786	0.8048	0.35	27.1687	0.7764	0.35	31.5957	0.7508
0.50	18.8935	0.8308	0.50	27.6030	0.7738	0.50	33.5579	0.7401	0.50	38.8686	0.7130
0.63	21.3245	0.8139	0.63	31.9272	0.7490	0.63	38.6922	0,7139	0.63	43.7278	0.6903
0.75	23.5726	0.7990	0.75	35.2419	0.7312	0.75	42.8928	0.6941	0.75	49.1932	0.6669
0.88	26.4189	0.7810	0.88	38.6144	0.7142	0.88	47.1024	0.6756	0.88	53.7237	0.6489
1.00	29.0440	0.7653	1.01	42.0063	0.6981	1.00	51.1039	0.6591	1.00	58.2824	0.6321
1.16	32.3822	0.7465	1.17	46.4550	0.6783	1.17	56.7863	0.6375	1.17	64.1527	0.6120
1.33	36.0125	0.7273	1.34	51.0913	0.6592	1.34	62.2895	0.6182	1.35	70.1074	0.5932
1.51	39.6849	0.7091	1.50	55.5867	0.6419	1.50	67.0201	0.6027	1.50	75.1201	0.5785
1.67	43.2705	0.6924	1.67	59.9718	0.6261	1.67	72.2067	0.5869	1.67	80.5030	0.5638
1.84	46.4589	0.6783	1.84	64.7323	0.6101	1.84	77.0213	0.5732	1.84	85.4979	0.5510
2.00	49.7582	0.6645	2.00	68.9235	0.5968	2.00	81.3703	0.5615	2.00	90.2338	0.5395

	α= -20°			α=- 50°			α= -10°			α=-5°			α=0°	
vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.19	18.8206	0.9527	0.21	16.4393	0.9584	0.21	10.4204	0.9731	0.20	7.7797	0.9798	0.23	9.6840	0.9750
0.25	21.3206	0.9468	0.25	18.3585	0.9538	0.25	12.7043	0.9675	0.25	7.9008	0.9795	0.25	9.2808	0.9760
0.35	25.7241	0.9367	0.35	22.4295	0.9443	0.35	17.2261	0.9565	0.35	10.0784	0.9740	0.35	8.0544	0.9791
0.50	31.2227	0.9244	0.50	28.1669	0.9312	0.50	22.2181	0.9447	0.50	13.7885	0.9648	0.50	10.3818	0.9732
0.63	35.8494	0.9143	0.63	32.4011	0.9218	0.63	26.2829	0.9354	0.63	16.7878	0.9576	0.63	12.9136	0.9670
0.75	39.6038	0.9063	0.75	36.2132	0.9135	0.75	29.8612	0.9274	0.75	19.1772	0.9519	0.75	14.9538	0.9620
0.87	43.4860	0.8983	0.88	40.0505	0.9054	0.88	33.3112	0.9198	0.88	21.8262	0.9457	0.88	17.0978	0.9568
1.00	47.3064	0.8905	1.00	43.5037	0.8982	1.00	36.4552	0.9130	1.00	24.3736	0.9398	1.00	19.3478	0.9515
1.16	51.7635	0.8817	1.17	47.6030	0.8899	1.17	40.4631	0.9045	1.17	27.7790	0.9320	1.17	22.1246	0.9450
1.34	56.1873	0.8731	1.34	52.1123	0.8810	1.34	44.5732	0.8961	1.34	30.8326	0.9252	1.34	24.7124	0.9390
1.50	60.2193	0.8654	1.51	56.2095	0.8730	1.50	48.5196	0.8881	1.50	33.8725	0.9186	1.50	27.0463	0.9337
1.67	64.4697	0.8576	1.65	59.7203	0.8664	1.67	52.2084	0.8808	1.67	37.0658	0.9117	1.67	29.5589	0.9281
1.85	68.7018	0.8499	1.83	64.7751	0.8570	1.84	56.0901	0.8733	1.84	40.1046	0.9053	1.84	31.8308	0.9230
2.01	72.5335	0.8431	2.00	68.4030	0.8504	2.00	59.3970	0.8670	2.00	41.9226	0.9015	2.00	34.4378	0.9174

Table C.6 h_{coil} and η_{wire} for Coil 3 with Flow Normal to Tubes

Table C.6 h_{coil} and η_{wire} for Coil 3 with Flow Normal to Tubes Continued

	α= 5°			α= 10°			α=15°			α= 20°	
vel	h _{coil}	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.21	11.5981	0.9702	0.21	14.0904	0.9641	0.21	16.4194	0.9584	0.20	19.3726	0.9514
0.25	11.4490	0.9706	0.25	15.1894	0.9614	0.25	18.6979	0.9530	0.25	21.7254	0.9459
0.35	12.1884	0.9688	0.35	17.9081	0.9549	0.35	22.2960	0.9446	0.35	26.1508	0.9357
0.50	13.8978	0.9646	0.50	21.7278	0.9459	0.50	27.5903	0.9325	0.50	31.8524	0.9230
0.63	16.3682	0.9586	0.63	25.3813	0.9375	0.63	31.8833	0.9229	0.63	36.2696	0.9134
0.75	18.7655	0.9528	0.75	28.5907	0.9302	0.75	35.7797	0.9145	0.75	40.5892	0.9043
0.88	21.1578	0.9472	0.88	31.9869	0.9227	0.88	39.6318	0.9063	0.88	44.1005	0.8970
1.00	23.3486	0.9421	1.00	35.0674	0.9160	1.00	43.0153	0.8993	1.00	47.7392	0.8897
1.17	26.2969	0.9354	1.17	38.9362	0.9078	1.17	47.2629	0.8906	1.17	52.1628	0.8809
1.34	29.1171	0.9290	1.34	42.6598	0.9000	1.34	51.5010	0.8822	1.34	56.2274	0.8730
1.50	31.8051	0.9231	1.50	46.3263	0.8925	1.50	55.3762	0.8746	1.50	60.4446	0.8650
1.67	34.4458	0.9173	1.67	49.8574	0.8854	1.67	59.2026	0.8674	1.67	64.4662	0.8576
1.84	37.3851	0.9110	1.84	53.4274	0.8784	1.84	63.2433	0.8598	1.84	68.4416	0.8504
2.00	39.8335	0.9059	2.00	56.7505	0.8720	2.00	66.9273	0.8531	2.00	72.2464	0.8436

	α= -20°			α= -15°			α= -10°			α=- 5°			α= 0°	
vel	hcoil	Nwire	vel	hcoil	ηwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.21	21.1503	0.9472	0.21	17.7208	0.9553	0.21	12.9424	0.9669	0.21	7.5003	0.9805	0.22	9.2044	0.9762
0.25	23.6508	0.9414	0.25	19.9895	0.9500	0.25	14.4413	0.9632	0.25	8.1792	0.9788	0.25	8.7844	0.9772
0.35	29.1146	0.9290	0.35	24.8082	0.9388	0.35	18.1698	0.9543	0.35	10.4932	0.9730	0.35	8.3480	0.9783
0.50	35.8607	0.9143	0.50	31,0297	0.9248	0.50	23.1558	0.9426	0.50	13.9708	0.9644	0.50	10.6526	0.9726
0.63	41.4471	0.9025	0.63	36.2163	0.9135	0.63	27.4964	0.9327	0.63	16.8062	0.9575	0.63	12.8363	0.9672
0.75	46.4750	0.8922	0.75	40.8769	0.9037	0.75	31.2980	0.9242	0.75	19.8228	0.9503	0.75	14.7447	0.9625
0.88	51.5347	0.8821	0.88	45.2219	0.8947	0.88	34.6190	0.9170	0.88	22.6968	0.9436	0.88	17.2918	0.9564
1.00	55.7664	0.8739	1.00	49.1387	0.8869	1.00	38.0757	0.9096	1.00	25.4433	0.9373	1.00	19.3060	0.9516
1.17	61.3219	0.8634	1.17	54.1277	0.8771	1.17	42.3685	0.9006	1.17	28.8689	0.9296	1.17	22.0311	0.9452
1.34	66.6942	0.8535	1.34	59.3033	0.8672	1.34	46.9230	0.8913	1.34	32.3894	0.9218	1.34	24.7658	0.9389
1.50	71.7985	0.8444	1.50	64.0563	0.8583	1.50	51.1850	0.8828	1.50	35.2792	0.9155	1.50	27.1642	0.9334
1.67	76.7239	0.8358	1.67	68.7911	0.8497	1.67	55.6025	0.8742	1.67	38.8465	0.9079	1.67	29.6977	0.9277
1.84	81.1323	0.8283	1.84	73.0522	0.8422	1.84	59.7534	0.8663	1.84	41.7053	0.9020	1.84	32.1986	0.9222
2.00	85.0389	0.8218	2.00	77.5664	0.8343	2.00	63.3982	0.8595	2.00	44.4984	0.8962	2.00	34.2729	0.9177

Table C.7 h_{coil} and η_{wire} for Coil 3 with Flow Normal to Wires

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Table C.7 h_{coil} and η_{wire} for Coil 3 with Flow Normal to Wires Continued

	α= 5°			α=10°			α= 15°			α= 20°	
vel	h _{coil}	Nwire	vel	h _{coil}	η_{wire}	vel	h _{coil}	Nwire	vel	hcoil	η_{wire}
0.20	11.0189	0.9716	0.21	14.0167	0.9643	0.21	17.6013	0.9556	0.22	21.1386	0.9473
0.25	11.0389	0.9716	0.25	15.2090	0.9614	0.25	19.3317	0.9515	0.25	22.6524	0.9437
0.35	12.3227	0.9684	0.35	17.8268	0.9551	0.35	23.7521	0.9412	0,35	27.6973	0.9322
0.50	14.2751	0.9636	0.50	22.2984	0.9446	0.50	30.0594	0.9269	0.50	34.2702	0.9177
0.63	16.2934	0.9587	0.63	26.5414	0.9348	0.63	34.7765	0.9166	0.63	39.5518	0.9065
0.75	18.8101	0.9527	0.75	30.1444	0.9268	0.75	39.3762	0.9068	0.76	44.6382	0.8959
0.87	21.2265	0.9471	0.88	33.4827	0.9194	0.88	43.4995	0.8983	0.88	49.1808	0.8868
1.01	23.7814	0.9411	1.00	36.6186	0.9127	1.00	47.0190	0.8911	1.01	53.4536	0.8784
1.17	26.8259	0.9342	1.17	40.8242	0.9038	1.17	52.1961	0.8808	1.17	58.7077	0.8683
1.33	29.8498	0.9274	1.34	44.9582	0.8953	1.34	57.1270	0.8713	1.34	63.3325	0.8597
1.51	32.8875	0.9207	1.50	48.9275	0.8873	1.50	61.1965	0.8636	1.50	68.5632	0.8501
1.67	35.8147	0.9144	1.67	52.8823	0.8795	1.67	65.5002	0.8557	1.68	73.4965	0.8414
1.83	38.5927	0.9085	1.84	56.7601	0.8720	1.84	70.3776	0.8469	1.84	77.2920	0.8348
2.00	41.5608	0.9023	2.00	60.5454	0.8648	2.00	74.2383	0.8401	2.00	81.6243	0.8275

	α=-20°			α=-15°			α= -10°			α=-5°			α= 0°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.20	14.5051	0.9538	0.21	10.2635	0.9668	0.20	6.5938	0.9784	0.20	7.3743	0.9759	0.20	6.7803	0.9778
0.25	17.5013	0.9449	0.25	13.7680	0.9560	0.25	7.9233	0.9741	0.25	5.7003	0.9812	0.25	6.3704	0.9791
0.35	21.7811	0.9325	0.35	18.0327	0.9434	0.35	13.0111	0.9583	0.35	6.2093	0.9796	0.35	5.8873	0.9806
0.50	26.8471	0.9184	0.50	23.0019	0.9291	0.50	17.9682	0.9435	0.50	10.0001	0.9676	0.50	8.1709	0.9733
0.63	31.1337	0.9068	0.63	27.0788	0.9177	0.63	21.9699	0.9320	0.63	13.2813	0.9575	0.63	10.1514	0.9671
0.75	34.6635	0.8975	0.75	30.4840	0.9085	0.75	24.9033	0.9237	0.75	15.5227	0.9508	0.75	11.1444	0.9641
0.88	37.6036	0.8900	0.88	33.3405	0.9010	0.88	27.7045	0.9160	0.88	17.5699	0.9447	0.88	13.2345	0.9577
1.00	40.4259	0.8829	1.00	35.9603	0.8942	1.00	30.4945	0.9085	1.00	19.4508	0.9392	1.00	15.0741	0.9521
1.16	44.2703	0.8734	1.17	39.7480	0.8846	1.17	33.8011	0.8998	1.17	21.6891	0.9328	1.17	16.9400	0.9466
1.33	47.9049	0.8647	1.34	43.3775	0.8756	1.34	37.1436	0.8911	1.34	24.6081	0.9246	1.34	19.2381	0.9398
1.50	51.3332	0.8567	1.50	46.2648	0.8686	1.50	40.6001	0.8824	1.50	27.2344	0.9173	1.50	21.0907	0.9345
1.68	54.8257	0.8487	1.67	49.2581	0.8615	1.67	43.4737	0.8754	1.67	29,7291	0.9105	1.67	23.0352	0.9290
1.84	58.5117	0.8405	1.84	52.6759	0.8536	1.84	46.4946	0.8681	1.84	32.1063	0.9042	1.84	25.0397	0.9234
2.01	61.6322	0.8336	2.00	55.4397	0.8473	2.00	49.0584	0.8620	2.00	34.1946	0.8987	2.00	26.6885	0.9188

Table C.8 h_{coil} and η_{wire} for Coil 4 with Flow Normal to Tubes

Table C.8 h_{coil} and η_{wire} for Coil 4 with Flow Normal to Tubes Continued

	α= 5°	÷ 1		α= 10°			α= 15°			α= 20°	
vel	h _{coil}	η _{wire}	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire
0.21	9.0025	0.9707	0.21	11.2934	0.9636	0.21	14.6495	0.9534	0.21	17.0209	0.9463
0.25	9.0860	0.9705	0.25	12.0558	0.9613	0.25	15.9432	0.9495	0.25	18.2180	0.9428
0.35	10.0836	0.9673	0.35	13.8570	0.9558	0.35	18.8287	0.9410	0.35	21.9601	0.9320
0.50	11.5211	0.9629	0.50	17.5348	0.9448	0.50	23.0889	0.9288	0.50	26.8288	0.9184
0.63	13.3202	0.9574	0.63	20.4244	0.9364	0.63	26.8482	0.9184	0.63	30.7787	0.9077
0.75	15.0689	0.9521	0.75	23.0704	0.9289	0.75	29.8577	0.9102	0.75	33.8602	0.8996
0.88	17.0907	0.9461	0.88	25.6976	0.9215	0.88	32.8277	0.9023	0.88	36.9629	0.8916
1.00	19.0112	0.9405	1.00	28.0044	0.9152	1.00	35.5457	0.8952	1.00	39.7927	0.8844
1.17	21.5384	0.9332	1.17	31.0933	0.9069	1.17	38.7366	0.8871	1.17	43.4168	0.8755
1.34	24.1208	0.9259	1.34	34.2205	0.8987	1.34	42.0051	0.8790	1.34	46.9656	0.8669
1.50	26.3737	0.9197	1.50	37.3657	0.8906	1.50	44.9890	0.8717	1.50	49.9379	0.8599
1.67	28.7479	0.9132	1.67	40.0940	0.8837	1.67	47.7442	0.8651	1.67	52.9343	0.8530
1.84	31.0878	0.9069	1.84	42.9059	0.8767	1.84	50.8369	0.8578	1.84	55.9324	0.8462
2.00	33.1491	0.9015	2.00	45.6519	0.8701	2.00	53.3753	0.8520	2.00	58.6830	0.8401

	α= -20°			α=- 15°			α= -10°			α=-5°			α= 0°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	h _{coil}	Ŋwire
0.20	16.5259	0.9478	0.20	12.9142	0.9586	0:20	8.1738	0.9733	0.20	5.6091	0.9815	0.20	6.9674	0.9772
0.25	18.5881	0.9417	0.25	15.8753	0.9497	0.25	10.9323	0.9647	0.25	5.4144	0.9821	0.25	5.4975	0.9819
0.35	23.3603	0.9281	0.35	20.0504	0.9375	0.35	14.5464	0.9537	0.35	6.7484	0.9779	0.35	5.9819	0.9803
0.50	29.7840	0.9104	0.50	25.9605	0.9208	0.50	18.8052	0.9411	0.50	10.2178	0.9669	0.50	8.0993	0.9736
0.63	34.7400	0.8973	0.63	30.7677	0.9078	0.63	22.3895	0.9308	0.63	12.7596	0.9591	0.63	10.3933	0.9664
0.75	39.1960	0.8859	0.75	34.5003	0.8979	0.75	25.5868	0.9218	0.75	14,9646	0.9524	0.75	12.4644	0.9600
0.88	43.5353	0.8752	0.88	38.2160	0.8884	0.88	28.4960	0.9139	0.88	17.1178	0.9460	0.88	14.2571	0.9546
1.00	47.4213	0.8658	1.00	41.7786	0.8795	1.00	31.2457	0.9065	1.00	19.6591	0.9386	1.01	15.9795	0.9494
1.17	52.2726	0.8545	1.17	45.7355	0.8699	1.17	34.9796	0.8967	1.17	21.8196	0.9324	1.17	18.0649	0.9433
1.34	56.4892	0.8449	1.34	50.2121	0.8593	1.34	38.5773	0.8875	1.34	24.4439	0.9250	1.34	20.4495	0.9363
1.50	60.6674	0.8357	1.50	54.0051	0.8505	1.50	41.8268	0.8794	1.50	27,0177	0.9179	1.50	22.4728	0.9306
1.67	65.0293	0.8264	1.67	57.9616	0.8417	1.67	44.9794	0.8717	1.67	29.5693	0.9110	1.67	24.5336	0.9248
1.84	69.0386	0.8180	1.84	61.7696	0.8333	1.84	48.4618	0.8634	1.84	32.1059	0.9042	1.84	26.6827	0.9188
2.00	72.6079	0.8107	2.00	65.3343	0.8257	2.00	51.6263	0.8560	2.00	34.5690	0.8978	2.01	28.7764	0.9131

Table C.9 h_{coil} and η_{wire} for Coil 4 with Flow Normal to Wires

Table C.9 h_{coil} and η_{wire} for Coil 4 with Flow Normal to Wires Continued

	α= 5°			α= 10°			α=15°			α= 20°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	h _{coil}	Nwire
0.20	9.6894	0.9686	0.20	12.2049	0.9608	0.20	15.0786	0.9521	0.20	18.2014	0.9429
0.25	9.6330	0.9688	0.25	13.6221	0.9565	0.25	16.8709	0.9468	0.25	20.6282	0.9358
0.35	10.6959	0.9654	0.35	15.9232	0.9496	0.35	20.3880	0.9365	0.35	24.9788	0.9235
0.50	12.4533	0.9600	0.50	19.7322	0.9384	0.50	25.5223	0.9220	0.50	30.9235	0.9073
0.63	14.1854	0.9548	0.63	22.9088	0.9293	0.63	29.9545	0.9099	0.63	35.6577	0.8949
0.75	15.8311	0.9499	0.75	25.9604	0.9208	0.75	33.6898	0.9001	0.75	40.0588	0.8838
0.88	17.7205	0.9443	0.88	29,1263	0.9122	0.88	37.4437	0.8904	0.88	43.9492	0.8742
1.00	19.7778	0.9383	1.00	32.1080	0.9042	1.00	40.9570	0.8815	1.01	47.8614	0.8648
1.17	22.1107	0.9316	1.17	35.8213	0.8945	1.17	45.4068	0.8707	1.17	52.6792	0.8536
1.34	24.9194	0.9237	1.34	39.4008	0.8854	1.34	49.7099	0.8605	1.34	57.5248	0.8426
1.50	27.2543	0.9173	1.50	42.8164	0.8770	1.50	53.6505	0.8514	1.50	62.0897	0.8326
1.67	29.7095	0.9106	1.67	46.0246	0.8692	1.67	57.8048	0.8420	1.67	66.0580	0.8242
1.84	32.8886	0.9022	1.84	49.7243	0.8604	1.84	61.6411	0.8336	1.84	70.3875	0.8152
1.99	35.1086	0.8964	2.00	52.9936	0.8529	2.00	65.2279	0.8259	2.00	74.2176	0.8075

	$\alpha = -40^{\circ}$			α= -30°			α=-20°			α=- 15°			α= -10°	
vel	hcoil	Nwire	vel	hcoil	ηwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.21	29.4075	0.8859	0.22	25.9707	0.8976	0.21	19.2703	0.9215	0.20	17.0572	0.9298	0.22	12.5625	0.9471
0.25	32.0346	0.8772	0.25	27.4962	0.8923	0.25	21.4643	0.9135	0.25	19.2258	0.9217	0.25	14.2152	0.9406
0.35	37.5376	0.8596	0.35	32.9780	0.8741	0.35	26.3904	0.8961	0.35	23.3055	0.9069	0.35	17.9345	0.9265
0.50	45.5158	0.8356	0.50	39.6472	0.8531	0.50	31.5235	0.8788	0.50	28.7273	0.8882	0.50	22.7091	0.9090
0.63	51.3113	0.8192	0.63	45.2773	0.8363	0.63	37.2950	0.8604	0.63	33.3483	0.8729	0.63	26.6212	0.8953
0.76	56.0441	0.8064	0.75	49.6860	0.8237	0.75	41.7577	0.8467	0.75	37.0950	0.8610	0.75	30.0045	0.8839
0.87	60.3978	0.7950	0.88	54.0665	0.8117	0.88	46.2464	0.8335	0.88	40.9816	0.8491	0.88	33.6464	0.8719
1.00	64.7153	0.7841	1.00	58.2414	0.8006	1.00	49.9425	0.8230	1.00	44.9922	0.8372	1.00	37.0800	0.8610
1.17	69.9841	0.7713	1.16	62.7276	0.7891	1.17	54.7453	0.8099	1.17	49.5450	0.8241	1.17	41.0542	0.8488
1.34	75.2662	0.7590	1.34	68.0733	0.7759	1.34	59.4770	0.7974	1.34	54.4188	0.8107	1.34	45.5559	0.8355
1.51	80.2611	0.7478	1.51	72.8460	0.7646	1.50	63.7127	0.7866	1,50	57.8253	0.8017	1.50	49.2416	0.8250
1.67	85.1430	0.7373	1.67	77.5391	0.7539	1.67	68.7981	0.7742	1.67	62.4574	0.7898	1.67	53.4921	0.8132
1.85	90.0679	0.7270	1.83	81.9881	0.7441	1.84	73.1472	0.7639	1.84	66.6377	0.7794	1.84	57.8615	0.8016
2.00	94.0555	0.7190	2.00	86.0965	0.7353	2.00	77.2297	0.7546	2.00	70.7443	0.7695	2.00	61.7600	0.7915

Table C.10 h_{coil} and η_{wire} for Coil 5 with Flow Normal to Tubes

Table C.10 h_{coil} and η_{wire} for Coil 5 with Flow Normal to Tubes Continued

	α= -5°			α= 0°			α= 5°			α= 10°			α= 15°	
vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	η_{wire}	vel	h _{coil}	Nwire
0.20	7.9242	0.9658	0.20	7.7149	0.9667	0.21	9.9933	0.9574	0.21	13,5474	0.9432	0.20	16.6791	0.9312
0.25	8.3373	0.9641	0.25	7.0946	0.9693	0.25	10.4316	0.9556	0.25	15.0054	0.9376	0.25	18.8831	0.9229
0.35	10.7460	0.9543	0.35	8.0498	0.9653	0.35	11.9469	0.9495	0.35	17.9825	0.9263	0.35	22.7541	0.9089
0.50	14.2737	0.9404	0.50	12.1591	0.9487	0.50	15.0152	0.9376	0.50	22.8359	0.9086	0.50	28.5613	0.8887
0.63	17.4776	0.9282	0.63	15.6773	0.9350	0.63	18.0119	0.9262	0.63	27.2748	0.8931	0.63	33.4352	0.8726
0.75	20.1995	0.9181	0.75	18.3569	0.9249	0.75	20.5410	0.9169	0.75	30.8447	0.8811	0.75	37.7890	0.8588
0.88	22.9768	0.9081	0.88	20.5529	0.9168	0.88	23.3015	0.9069	0.88	34.3269	0.8697	0.87	41.6562	0.8470
1.00	25.7363	0.8984	1.00	22.8598	0.9085	1.00	26.1278	0.8970	1.00	37.4229	0.8600	1.00	45.2205	0.8365
1.17	29.2701	0.8863	1.17	26.1989	0.8968	1.17	29.6771	0.8850	1.17	42.1794	0.8455	1.17	49.9363	0.8230
1.33	32.9157	0.8743	1.34	29.3380	0.8861	1.34	33.0254	0.8739	1.34	46.2140	0.8336	1.33	54.3211	0.8110
1.51	36.4720	0.8629	1.50	32.6854	0.8750	1.50	36.5346	0.8627	1.50	49.9230	0.8231	1.50	58.6984	0.7994
1.67	39.7481	0.8528	1.67	35.5682	0.8658	1.67	39.6388	0.8531	1.67	54.0922	0.8116	1.67	63.2010	0.7879
1.84	42.9848	0.8431	1.84	38.4148	0.8569	1.84	43.0033	0.8430	1.84	58.3627	0.8003	1.84	67.4259	0.7775
2.00	46.2729	0.8334	2.00	41.3112	0.8481	2.00	46.2527	0.8335	2.00	62.3818	0.7900	2.00	71.4174	0.7679

	α= 20°	
vel	hcoil	Nwire
0.20	19.9694	0.9189
0.25	22.4960	0.9098
0.35	27.2534	0.8932
0.50	33.3959	0.8727
0.63	38.6016	0.8563
0.75	43.2867	0.8422
0.88	47.1791	0.8308
1.00	50.9683	0.8202
1.17	56.2510	0.8058
1.34	60.9593	0.7936
1.51	65.5463	0.7821
1.67	69.7720	0.7718
1.85	74.5341	0.7607
2.00	78.6634	0.7514

Table C.10 h_{coil} and $\underline{\eta_{wire}}$ for Coil 5 with Flow Normal to Tubes Continued

Table C.11 h_{coil} and η_{wire} for Coil 5 with Flow Normal to Wires

	α=-20°			α=- 15°			α=-10°			α=-5°			α=0°	
vel	hcoil	η_{wire}	vel	h _{coil}	η_{wire}	vel	h _{coil}	η_{wire}	vel	h _{coil}	Nwire	vel	hcoil	η_{wire}
0.21	19.5352	0.9205	0.21	13.1645	0.9447	0.20	9.6227	0.9589	0.21	9.3244	0.9601	0.21	12.9216	0.9457
0.25	22.5874	0.9095	0.25	16.4443	0.9321	0.25	11.4016	0.9517	0.25	8.1372	0.9650	0.25	11.9490	0.9495
0.35	28.8146	0.8879	0.35	22.5639	0.9096	0.35	16.8382	0.9306	0.35	9.4607	0.9595	0.35	11.2490	0.9523
0.50	36.4918	0.8629	0.50	28.9965	0.8872	0.50	22.8253	0.9086	0.50	12.8924	0.9458	0.50	12.4866	0.9474
0.63	41.9042	0.8463	0.63	34.3487	0.8697	0.63	27.3111	0.8930	0.63	16.8908	0.9304	0.63	14.6107	0.9391
0.76	48.2156	0.8279	0.75	39.0218	0.8550	0.75	31.7409	0.8781	0.75	19.9428	0.9190	0.75	17.1875	0.9293
0.88	52.7475	0.8153	0.88	43.1018	0.8427	0.88	35.4694	0.8661	0.88	22.9743	0.9081	0.88	19.4061	0.9210
1.00	58.1055	0.8010	1.00	47.9099	0.8287	1.00	39.0231	0.8550	1.00	25.8102	0.8981	1.00	21.6226	0.9129
1.17	64.1539	0.7855	1.17	53.0800	0.8144	1.17	43.8669	0.8404	1.17	29.2989	0.8862	1.17	24.1498	0.9039
1.34	69.8166	0.7717	1.34	58.4199	0.8001	1.34	48.6305	0.8267	1.34	32.8512	0.8745	1.34	27.2636	0.8931
1.51	75.2166	0.7591	1.50	63.7076	0.7866	1.50	53.4582	0.8133	1.50	36.2726	0.8636	1.50	29.8942	0.8842
1.67	80.2448	0.7479	1.67	68.6613	0.7745	1.67	57.8993	0.8015	1.67	39.7185	0.8529	1.67	32.5179	0.8756
1.84	85.5036	0.7365	1.84	73.4963	0.7631	1.84	62.2946	0.7902	1.84	42.9175	0.8433	1.84	34.9697	0.8677
2.00	90.4056	0.7263	2.00	78.0461	0.7527	2.00	66.5265	0.7797	2.00	45.9552	0.8344	2.00	37.3459	0.8602

	α= 5°			α= 10°			α= 15°			α=20°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire
0.20	16.2937	0.9327	0.20	19.4132	0.9210	0.21	22.1083	0.9112	0.22	24.1598	0.9039
0.25	16.3009	0.9326	0.25	20.0671	0.9186	0.25	23.3553	0.9067	0.25	25.3157	0.8998
0.35	16.2506	0.9328	0.35	22.0512	0.9114	0.35	26.7433	0.8949	0.35	29.7957	0.8846
0.50	18.2072	0.9255	0.50	25.7978	0.8982	0.50	32.4029	0.8760	0.50	36.2329	0.8637
0.63	19.7602	0.9197	0.63	29.4477	0.8857	0.63	37.5097	0.8597	0.63	42.0759	0.8458
0.75	21.3796	0.9138	0.75	32.9096	0.8743	0.76	42.4169	0.8447	0.75	47.3819	0.8303
0.88	23.6489	0.9057	0.88	36.0922	0.8641	0.88	46.7410	0.8321	0.88	51.9286	0.8175
1.00	26.0300	0.8974	1.00	39.4384	0.8537	1.00	50.7772	0.8207	1.00	57.0685	0.8037
1.17	29.3756	0.8860	1.17	44.0067	0.8400	1.17	56.4202	0.8054	1.16	62.5870	0.7895
1.34	32,4692	0.8758	1.34	48.6664	0.8266	1.34	61.8158	0.7914	1.33	69.0537	0.7736
1.50	35.6205	0.8656	1.50	53.2429	0.8139	1.50	67.2433	0.7779	1.50	74.8264	0.7600
1.67	38.6534	0.8562	1.67	57.9006	0.8015	1.68	72.4006	0.7656	1.67	80.1513	0.7481
1.84	41.9604	0.8461	1.84	62.5125	0.7896	1.84	77.2619	0.7545	1.84	85.7100	0.7361
2.00	44.9737	0.8372	2.00	66.3205	0.7802	2.00	82.6976	0.7425	2.00	90.1845	0.7268

Table C.11 h_{coil} and η_{wire} for Coil 5 with Flow Normal to Wires Continued

Table C.12 h_{coil} and η_{wire} for Coil 6 with Flow Normal to Tubes

	α= 0°			α= 5°			α= 10°			α=15°			α= 20°	
vel	hcoil	η_{wire}	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire
0.20	8.0842	0.9796	0.20	11.4223	0.9715	0.20	15.0336	0.9628	0.20	18.5929	0.9545	0.20	21.7582	0.9473
0.25	7.7020	0.9805	0.25	11.2364	0.9719	0.25	16.7390	0.9588	0.25	20.3201	0.9505	0.25	23.6834	0.9429
0.50	13.6591	0.9661	0.50	15.9334	0.9607	0.50	23.4931	0.9433	0.50	29.0416	0.9311	0.50	33.4665	0.9215
0.75	19.5473	0.9523	0.75	21.4674	0.9479	0.75	31.6699	0.9254	0.75	38.0268	0.9120	0.75	42.8511	0.9021
1.00	25.2504	0.9394	1.00	27.5306	0.9344	1.00	38.5241	0.9109	1.00	44.8456	0.8981	1.00	50.5890	0.8868
1.50	35.0046	0.9183	1.50	38.0796	0.9119	1.50	51.1065	0.8858	1.50	58.3226	0.8722	1.50	63.9364	0.8619
2.00	42.8735	0.9021	2.00	48.2825	0.8913	2.00	63.2401	0.8632	2.00	70.7852	0.8498	2.00	76.5426	0.8399

	α= 30°			α=40°			α= 50°			α=60°			α= 70°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.20	24.6483	0.9407	0.20	27.5202	0.9344	0.20	29.1646	0.9308	0.20	31.4661	0.9258	0.20	32.6424	0.9233
0.25	26.8575	0.9358	0.25	30.2283	0.9285	0.25	32.5319	0.9235	0.25	34.7152	0.9189	0.25	35.5513	0.9171
0.50	38.0315	0.9120	0.50	42.4897	0.9028	0.50	47.3483	0.8932	0.50	48.8015	0.8903	0.50	50.6118	0.8868
0.75	47.9779	0.8919	0.75	53.3012	0.8816	0.75	58.4310	0.8720	0.75	60.7224	0.8677	0.75	62.2374	0.8650
1.00	56.2717	0.8760	1.00	62.3119	0.8648	1.00	66.7745	0.8568	1.00	71.0334	0.8493	1.00	71.8541	0.8479
1.50	71.5416	0.8485	1.50	77.3112	0.8386	1.50	83.0624	0,8290	1.50	87.7978	0.8214	1.50	89.4088	0.8188
2.00	84.5370	0.8266	2.00	91.1010	0.8161	2.00	97.3911	0.8063	2.00	103.0379	0.7978	2.00	105.1160	0.7947

Table C.12 h_{coil} and η_{wire} for Coil 6 with Flow Normal to Tubes Continued

Table C.12 h_{coil} and η_{wire} for Coil 6 with Flow Normal to Tubes Continued

l		$\alpha = 80^{\circ}$			<u>α=90°</u>	
	vel	hcoil	nwire	vel	h _{coil}	η_{wire}
	0.20	32.0116	0.9246	0.20	33.3630	0.9218
	0.25	36.4859	0.9152	0.25	37.0255	0.9141
	0.50	51.5148	0.8850	0.50	52.1488	0.8838
	0.75	64.0839	0.8616	0.75	65.3184	0.8594
	1.00	74.2812	0.8437	1.00	76.0589	0.8407
	1.50	93.1302	0.8129	1.50	93.9014	0,8117
	2.00	108.7184	0.7895	2.00	111.2035	0.7859

Table C.13 h_{coil} and η_{wire} for Coil 6 with Flow Normal to Wires

α=0°			α= 5°			α=10°			α=15°			α= 20°		
vel	h _{coil}	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	η_{wire}	vel	hcoil	ηwire
0.20	8.9048	0.9776	0.20	12.5795	0.9687	0.20	15.4107	0,9619	0.20	19.3153	0.9528	0.20	23.0125	0.9444
0.25	8.5508	0.9784	0.25	12.3562	0.9692	0.25	16.8165	0,9586	0,25	21.3520	0.9482	0.25	25.2741	0.9394
0.50	11.6983	0.9708	0.50	15.7537	0.9611	0.50	23.4765	0,9434	0.50	31.2367	0.9263	0.50	37.7782	0.9125
0.75	17.4664	0.9571	0.75	21.4536	0.9479	0.75	31.8174	0,9251	0,75	41.3583	0.9051	0.75	47.8265	0.8922
1.00	23.8597	0.9425	1.00	28.1549	0.9330	1.00	39,1955	0.9096	1.00	49.8887	0.8882	1.00	58.6797	0.8715
1.50	33.8878	0.9206	1.50	39.4175	0.9091	1.50	53.9259	0.8804	1.50	66.8877	0.8566	1.50	75.7068	0.8413
2.00	41.7971	0.9042	2.00	49.6563	0.8886	2.00	66.5329	0.8573	2.00	81.6189	0.8314	2.00	90.7870	0.8166

	α= 30°			α= 40°			α= 50°			α=60°				
vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire
0.20	27.1020	0.9353	0.20	30.5183	0.9279	0.20	33.5049	0.9215	0.20	34.5719	0.9192	0.20	35.6436	0.9169
0.25	30.0615	0.9288	0.25	33.8609	0.9207	0.25	37.2413	0.9136	0.25	38.2600	0.9115	0.25	39.3352	0.9093
0.50	44.3628	0.8991	0.50	48.8272	0.8903	0.50	52.6347	0.8829	0.50	54.6556	0.8791	0.50	54.7895	0.8788
0.75	55.6325	0.8772	0.75	59.4695	0.8701	0.75	65.6217	0.8589	0.75	68.0443	0.8546	0.75	67.9199	0.8548
1.00	65.2980	0.8595	1.00	70.4499	0.8503	1.00	76.4974	0.8400	1.00	78.8790	0.8360	1.00	79.1997	0.8354
1.50	83.4623	0.8284	1.50	89.4403	0.8187	1.50	94.9493	0.8101	1.50	97.8888	0.8056	1.50	98.8018	0.8042
2.00	98.4687	0.8047	2.00	105.5891	0.7940	2.00	111.4833	0.7855	2.00	114.6725	0.7809	2.00	114.0448	0.7818

Table C.13 h_{coil} and η_{wire} for Coil 6 with Flow Normal to Wires Continued

Table C.13 h_{coil} and η_{wire} for Coil 6 with Flow Normal to Wires Continued

L		α= 80°			α= 90°	
	vel	h _{coil}	Nwire	vel	h _{coil}	η_{wire}
	0.20	35.2436	0.9178	0.20	34.2307	0.9199
	0.25	38.5807	0.9108	0.25	38.2748	0.9115
	0.50	54.8753	0.8786	0.50	52.9337	0.8823
	0.75	68.3924	0.8540	0.75	66.2181	0.8578
	1.00	78.7132	0.8362	1.00	76.5965	0.8398
	1.50	98.2010	0.8051	1.50	95.9713	0.8085
	2.00	113.8071	0.7822	2.00	110.9201	0.7863

	α= -10°			α= -5°			α= 0°			α= 5°		α= 10°		
vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.20	7.6699	0.9372	0.20	6.8188	0.9437	0.20	8.4890	0.9311	0.20	10.6012	0.9156	0.20	13.2434	0.8972
0.25	9.5422	0.9233	0.25	5.8477	0.9513	0.25	7.5240	0.9383	0.25	10.7632	0.9145	0.25	14.1376	0.8912
0.35	14.7694	0.8870	0.35	8.9970	0.9273	0.35	8.6775	0.9297	0.35	11.3805	0.9101	0.35	16.3355	0.8767
0.50	18.8740	0.8608	0.50	11.8209	0.9070	0.50	10.1689	0.9187	0.50	13.1091	0.8981	0.50	19.9088	0.8545
0.63	21.9299	0.8425	0.63	14.4833	0.8889	0.63	12.0539	0.9054	0.63	15.1881	0.8842	0.63	22.5954	0.8386
0.75	24.6675	0.8269	0.75	17.0541	0.8721	0.75	13.7940	0.8935	0.75	17.4506	0.8696	0.75	25.1213	0.8243
0.88	27.6842	0.8105	0.88	19.5423	0.8567	0.88	15.8113	0.8801	0.88	19.7934	0.8552	0.88	27.7976	0.8099
1.00	30.0725	0.7981	1.00	21.7958	0.8432	1.00	17.3802	0.8701	1.00	21.7793	0,8433	1.00	30.3371	0.7967
1.17	33.6791	0.7802	1.17	24.8097	0.8261	1.17	20.1725	0.8529	1.17	24.9243	0,8254	1.17	33.9200	0.7790
1.34	37.1087	0.7641	1.34	27.3535	0.8122	1.34	22.8394	0.8372	1.34	27.6526	0,8106	1.34	37.5081	0.7623
1.50	40.2666	0.7500	1.50	30.0733	0.7981	1.50	25.1673	0.8241	1.50	30.1549	0.7976	1.50	40.3959	0.7494
1.67	43.7436	0.7352	1.67	32.5328	0.7858	1.67	27.4699	0.8116	1.67	32.5471	0.7857	1.67	43.6196	0.7357
1.84	46.4380	0.7242	1.84	35.0646	0.7736	1.84	29.6567	0.8002	1.84	35.1691	0.7731	1.84	46.6577	0.7233
2.00	49.2720	0.7131	2.00	37.4397	0.7626	2.00	31.5814	0.7905	2.00	37.5641	0.7620	2.00	49.3335	0.7129

Table C.14 h_{coil} and η_{wire} for Coil 8 with Flow Normal to Tubes

Table C.14 h_{coil} and η_{wire} for Coil 8 with Flow Normal to Tubes Continued

	α= 15°			a= 20°	
vel	h _{coil}	Nwire	vel	hcoil	Nwire
·			0.20	18,4149	0.8636
0.25	16.9601	0.8727	0.25	19.6930	0.8558
0.35	20.1695	0.8529	0.35	23.2282	0.8350
0.50	24.0810	0.8301	0.50	27.5951	0.8109
0.63	27.6197	0.8108	0,63	31.0752	0.7930
0.75	30.6853	0.7949	0.75	33.9849	0.7787
0.88	33.5786	0.7807	0.88	36.9674	0.7647
1.00	36.2616	0.7680	1.00	39.6303	0.7528
1.17	40.0203	0.7510	1.17	42.9806	0.7384
1.34	43.1776	0.7375	1.34	46.3864	0.7244
1.50	46.4600	0.7241	1.50	49.1333	0.7136
1.67	49.1543	0.7136	1.67	52.6763	0.7003
1.84	52.3645	0.7015	1.84	55.8884	0.6888
2.00	55.0146	0.6919	2.00	58.5997	0.6794

	α= -10°			α= -5°			α= 0°			α= 5°			α= 10°	
vel	hcoil	Nwire	vel	hcoil	Nwire	vel	h _{coil}	Nwire	vel	hcoil	Nwire	vel	hcoil	Nwire
0.20	10.3706	0.9173	0.20	6.5083	0.9461	0.20	7.7111	0.9369	0.20	10.7716	0.9144	0.20	13.5658	0.8950
0.25	12,7974	0.9002	0.25	6.6352	0.9451	0.25	7.3238	0.9398	0.25	11,2102	0.9113	0.25	15.0430	0.8851
0.35	17,1397	0.8716	0.35	8.7813	0.9289	0.35	9.0341	0.9270	0.35	12.6094	0.9015	0.35	17.8789	0.8669
0.50	21.8678	0.8428	0.50	13.1582	0.8978	0.50	11.5850	0.9087	0.50	14.7774	0.8869	0.50	21.9080	0.8426
0.63	26.1493	0.8187	0.63	16.2978	0.8770	0.63	13.1127	0.8981	0.63	17.2188	0.8711	0,63	25.6254	0.8216
0.75	29.3911	0.8015	0.75	18.6984	0.8618	0.75	14.6025	0.8881	0.75	19.2463	0.8585	0.75	28.4403	0.8065
0.88	32.8823	0.7840	0.88	21.4773	0.8451	0.88	16.8068	0.8737	0.88	21.5175	0.8449	0,88	31.6247	0.7902
1.00	36.0624	0.7689	1.00	23.8388	0.8315	1.00	18.9612	0.8602	1.00	23.7278	0.8321	1.00	34.6241	0.7757
1.17	40.5588	0.7487	1.17	26.8441	0.8150	1.17	21.9611	0.8423	1.17	26.8134	0.8151	1.17	38.7070	0.7569
1.34	44.5182	0.7320	1.34	29.8474	0.7992	1.34	24.5860	0.8273	1.34	29.7105	0.7999	1.34	42.5842	0.7400
1.50	48.3565	0.7166	1.50	32.3447	0.7867	1.50	26.7744	0.8153	1.50	32.3166	0.7868	1.50	46.4003	0.7244
1.67	52.2366	0.7019	1.67	34.9316	0.7742	1.67	29.2722	0.8022	1.67	35.0967	0.7734	1.67	50.1835	0.7096
1.84	55.9328	0.6886	1.84	37.6155	0.7618	1.84	31.5669	0.7905	1.84	37.6981	0.7614	1.84	53.6772	0.6967
2.00	59.0323	0.6780	2.00	39.8169	0.7519	2.00	33.9223	0.7790	2.00	40.4100	0.7493	2.00	56.9587	0.6850

Table C.15 h_{coil} and η_{wire} for Coil 8 with Flow Normal to Wires

Table C.15 h_{coil} and η_{wire} for Coil 8 with Flow Normal to Wires Continued

	α= 15°			α= 20°	
vel	h _{coil}	η_{wire}	vel	hcoil	η_{wire}
0.20	16.7728	0.8739			
0.25	18.9515	0.8603	0.25	21.2240	0.8466
0.35	23.1051	0.8357	0.35	26.4931	0.8168
0.50	28.6487	0.8054	0.50	32.2539	0.7871
0.63	33.1876	0.7826	0.63	37.2951	0.7632
0.75	36.8635	0.7652	0.75	41.4668	0.7448
0.88	40.9769	0.7469	0.88	45.7869	0.7268
1.00	44.1823	0.7334	1.00	49.3006	0.7130
1.17	49.0765	0.7139	1.17	54.3088	0.6944
1.34	53.6977	0.6966	1.34	58.6518	0.6792
1.50	57.7907	0.6822	1.50	63.2873	0.6640
1.67	62.0763	0.6679	1.67	67.6951	0.6502
1.84	66.1648	0.6549	1.84	72.2695	0.6368
2.00	69.7049	0.6442	2.00	75.8298	0.6267

APPENDIX D: UNCERTAINTY ANALYSIS

There are two types of uncertainties in our investigation. The first type is a combination of a fixed bias error and a random error equal to the difference between the experimentally measured value and the actual value for variables such as temperature and mass flow rate. This error can be estimated using a multiple sample experiment in which the maximum uncertainty is determined without changing any of the outside influences. The second type is an uncertainty associated with approximations used in the calculation of the convective heat transfer coefficient, such as predicting the radiative contribution and the internal resistances. The second type of error, based on a possible error, is more difficult to predict than the first type.

The majority of this investigation involves single sample experiments. Ideally, the experiments would be repeated enough times to obtain an average for a specific data point. This investigation involved approximately 1600 data points with a large range of different parameters; the time restrictions on the project prevent the use of a complete multiple sample experiment.

A crucial step in the uncertainty analysis is the propagation of the error in the results. The result R from an experiment is assumed to be a function of the measurements taken represented by:

$$\mathbf{R} = f(\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3, \dots, \mathbf{X}_n) \tag{D.1}$$

The propagation of uncertainty was determined by applying the method of Kline and McClintock (1953). The basic equation used to combine individual uncertainties is the root-sum square method shown by:

$$\mathbf{w}_{\mathbf{R}} = \left\{ \sum_{j=1}^{n} \left(\frac{\partial \mathbf{R}}{\partial \mathbf{X}_{i}} \mathbf{w}_{\mathbf{X}_{i}} \right)^{2} \right\}^{1/2}$$
(D.2)

where each term represents the contribution made by the individual variables.

Consider the equation used to calculate the heat loss from the coil:

$$q = \dot{m}_r C_{p,r} \left(T_{r,in} - T_{r,out} \right)$$
(D.3)

where

$$\dot{m}_r = \frac{m_r}{t} \tag{D.4}$$

and m_r , t, and $T_{r,in/out}$ are experimentally measured quantities and Cp,r is a property of water. A multiple-sample experiment was performed in order to determine the random error associated with the mass flow rate. This test showed that the random error associated with the mass flow rate measurement is approximately 0.3%. The total error on the mass and time measurements, however, can be biased by the equipment and the particular operator. The mass is measured on a gram balance with an accuracy of ± 8 grams. The mass flow is taken for at least the time required to collect 2500 grams or 180 s, whichever occurs last. The error on the time, determined by using a stopwatch, is estimated to be within 0.3 s. The maximum bias error incurred in the mass flow rate measurement is 0.36% caused by the scale nonlinearity. The total uncertainty interval, w_{tota} , is defined by Moffat (1988) as:

$$\mathbf{w}_{\text{total}} = \left\{ \left(\mathbf{w}_{\text{bias}} \right)^2 + \left(\mathbf{w}_{\text{random}} \right)^2 \right\}^{1/2}$$
(D.5)

and is equal to 0.47% for the mass flow rate measurement.

The temperature measurements are accurate to ± 0.05 K after the thermocouples are calibrated with an isothermal bath. There are two thermocouples which are averaged to determine the inlet refrigerant temperature and two which are averaged to determine the outlet refrigerant temperature. Because the inlet and outlet temperatures are averaged with two thermocouples, the error in measuring either temperature is calculated using Eq. (C.2) to be ± 0.035 K. The maximum error of the difference between the inlet and outlet refrigerant temperature is calculated to be 0.075 K. With a minimum refrigerant temperature difference of 3 K, the error in the measurement of the refrigerant temperature drop through the condenser coil is 2.5%.

 $C_{p,r}$ is assumed to be 4.180 kJ/kg-K and may be different by less than 0.001 kJ/kg-K, a 0.02% error.

The error associated with q using Eq. (D.3) and Eq. (D.2) is found by:

$$\frac{\mathbf{w}_{q}}{q} = \left(\frac{\mathbf{w}_{\dot{m}}}{\dot{m}}\right)^{2} + \left(\frac{\mathbf{w}_{C_{p,r}}}{C_{p,r}}\right)^{2} + 2\left(\frac{\mathbf{w}_{T_{r}}}{T_{r,in} - T_{r,out}}\right)^{2}$$
(D.6)
and is equal to 2.4%.

The uncertainty in the reduction scheme is extremely difficult to calculate and is dependent on the particular experiment. Ranges for the uncertainties incurred in reducing the data to a coil heat transfer coefficient are estimated and propagated using the methods previously outlined and are shown if Table D.1. The uncertainty in η was neglected in determining the uncertainty in h_{coil} since it was calculated to be less than 1%.

Table D.1 Check tainty of Dimensional Variables				
Variable	Range	Absolute Uncertainty	Uncertainty [%]	
T _{r,in/out}	321.5-306.2 [K]	.0303	± 0.01	
Ta	299-293.5 [K]	0.06	± 0.02	
, m _r	0.024-0.003 [kg/s]	0.0001	± 0.47	
C _{p,r}	4180 [J/kg-K]	1.0	± 0.02	
$T_{r,in} - T_{r,out}$	1.7-13.8 [K]	0.0323	± 1.6	
q	744-29 [W]	0.5-12.7	± 1.7	
A _t	0.034-0.233 [m ²]	0.002	±1	
Aw	0.077-0.497 [m ²]	0.005	±1	
R _i	0.0005-0.001 [K/W]	0.0002	± 20	
$T_{r,avg} - T_a$	16-26 [K]	0.045-0.073	± 0.28	
Te	318-310 [K]	0.16	± 0.05	
3	0.95-1.0	0.05	±5	
F _{ij}	0-1.0	0.1	± 10	
Ts	294.2 302.6 [K]	0.9	±0.3	
grad	12-50 [W]	3.2-13.5	±27	
q _{conv}	15-690 [W]	3.2-18.6	± 2.7 - 21	
h _{coil}	5-111 [W/m ² -K]	1-3.3	± 3 - 21	
V	0-2 [m/s]	0.02	±1	

 Table D.1
 Uncertainty of Dimensional Variables

APPENDIX E: CUT WIRE ANALYSIS

To separate the relative contributions of the wires and tubes, a 2" tube pitch condenser coil was tested, and then altered to decreased the contribution of the wires. The coil is then retested and the diffence between the tests is used to separate the heat transfer coefficients from the wires from the total. By examining the fin equations, a method for deducing the contribution of the wires is determined.





If T_i is assumed to equal T_{i+1} (a reasonable first approximation), then the plane at x = L is a plane of symmetry, see Fig E.1. The wire represents a constant area $(A = \frac{\pi D_w^2}{4})$ constant perimeter ($P = \pi D_w$) extended surface. If the heat transfer

coefficient h_w is assumed to be constant over this fin, it can easily be shown that:

$$T^{*} \equiv \frac{T - T_{b}}{T_{b} - T_{a}} = \frac{\cosh[m(1 - x^{*})]}{\cosh(m)}$$
(E.1)

$$q^* = \frac{qL}{kA(T_{base} - T_a)} = -\frac{dT^*}{dx^*}\Big|_{x^* = 0} = m \tanh(m)$$
 (E.2)

$$\eta = \frac{q}{q_{\text{max}}} = \frac{\tanh(m)}{m}$$
(E.3)

where

$$q = hA_{fin}\eta(T_{base} - T_a)$$
(E.4)

$$q_{\max} = hA_{fin}(T_{base} - T_a)$$
(E.5)

$$m^2 = \frac{hPL^2}{kA} = \frac{4hL^2}{kD_w}$$
(E.6)

Since q is a function of η , see Eq. (E.4), one way to change the contribution of the wires on a condenser coil is to change η . This then enables the separation of the contribution of the wires from that of the tubes.

Looking at eqs. (E.3) and (E.6), there are several parameters which can be changed to alter the efficiency of the wires. The perimeter and area are functions of the diameter of the wire and changing these parameters will change h since h is a function of the D_w . The conductivity of the wire could be changed by exchanging the steel wire with an aluminum wire which would have almost three times the conductivity. However, this would be a difficult process. The only parameter left is the length of the fin.

By cutting the wire close to one of the tubes, the length of the fin can be approximately doubled. This will decrease the efficiency of the fin. This decrease comes without affecting the geometry of the coil so that the hydrodynamic flow field is the same in both cases. The thermal boundary layers will be slightly different, however.

The difference in the heat transfer between a cut coil and an uncut coil can be used to seperate the heat transfer from the wires from that leaving the tubes. This procedure will not work when free convection dominates because the heat transfer coefficient is a function of the temperature difference and the cut wire has a much lower temperature. In addition, the change in heat rejected between the cut and uncut coil is small which gives rise to large errors.

The diagram in Fig. E.2 depicts an approximate model for the resistance to heat flow from the tube and wire paths.



Figure E.2 Resistance Diagram

	Table E.1	Coll Resistances	
Wire Path	Resistance	Tube Path	Resistance
R _{spot}	$=\frac{1}{\eta_t A_i h_r}$	R _r	$=\frac{1}{A_ih_r}$
R _{eff}	$=\frac{1}{\eta_{\text{eff}}h_{w_{\text{eff}}}A_{w}}$	R _s	$=\frac{\ln \frac{D_t}{D_{t_i}}}{2\pi Lk_s}$
R _p	$=\frac{\ln\frac{D_{w}+2\delta P}{D_{w}}}{2\pi k_{p}dx}$	R _p	$=\frac{\ln\frac{D_t + 2\delta P}{D_t}}{2\pi Lk_p}$
R _{conv}	$=\frac{1}{h_{w}\pi D_{w}dx}$	R _{conv}	$=\frac{1}{h_tA_t}$
R _{rad}	$=\frac{1}{h_{radw}\pi D_w dx}$	R _{rad}	$=\frac{1}{h_{radt}A_{t}}$

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Most of the resistances above are right out of a reference book. The R_{spot} may not be familiar. The η_t in this formula is an efficiency parameter describing the constrictive heat flow in the tube wall to the tube/wire interface. η_t was determine to be 0.254 in our case based on the results presented by McGill (1994).

 R_{eff} is the effective resistance on the fin. Since the resistance to axial heat flow along the paint is much greater than that along the steel wire, the paint can be viewed as a resistance soley to radial heat flow. As such, it is combined with the resistance to convection and radiation on a differential section of a wire to determine an effective hweff which is used to calculate Reff. Rrad is assumed to be constant along the wire.



Figure E.3 Reff on Wire

$$h_{w_{eff}} = \frac{1}{\pi D_{w} dx \left[R_{p} + \frac{R_{conv} \bullet R_{rad}}{R_{conv} + R_{rad}} \right]}$$
(E.7)

All of these resistance can be calculated except R_{conv} and R_{rad} , for both wires and tubes. When the wires are cut, the same kind of resistance diagram applies but the efficiency of the wires has been decreased. If R_{conv} and R_{rad} for the tubes are assumed to change insignificantly between the two tests and it is assumed that h_w does not change, then the tube contribution can be removed by subtracting the equations for the heat transfer, see eqs. (E.8) and (E.9), where the subscript 1 represents the uncut coil test and subscript 2 represents the cut coil test.

$$\frac{q_1}{\Delta T_1} = \frac{1}{R_{w1}} + \frac{1}{R_{r1}} + \frac{1}{R_{text}} \quad \text{uncut}$$
(E.8)

$$\frac{q_2}{\Delta T_2} = \frac{1}{R_{w2}} + \frac{1}{R_{r2}} + \frac{1}{R_{text}} \quad cut$$
(E.9)

where

$$R_{\text{text}} = R_{\text{s}} + R_{\text{p}} + \frac{R_{\text{conv}}R_{\text{rad}}}{R_{\text{conv}} + R_{\text{rad}}}$$
(E.10)

Here the external tube resistance have been combined into R_{text} and the wire resistances have been combined into R_w . Subtracting these two equation removes the external tube resistance and the resulting equation is only a function of h_w .

$$\frac{q_1}{\Delta T_1} - \frac{q_2}{\Delta T_2} = \frac{1}{R_{w1}} - \frac{1}{R_{w2}} + \frac{1}{R_{r1}} - \frac{1}{R_{r2}}$$
(E.11)

$$R_{w1} = R_{spot} + \frac{1}{\eta_1 h_w A_w}$$
(E.12)

$$R_{w2} = R_{spot} + \frac{1}{\eta_2 h_w A_w}$$
(E.13)

An effective h_{wire} is used which includes the paint resistance as well as the convective and radiative resistances. By iterating, h_w can be calculated. After this is done, h_{tube} can be calculated.

To determine the convective coefficient on the wires, the paint resistance is calculated and subtracted out and then the radiation contribution is calculated by the methods outlined in Section 4.4 of Hoke.

APPENDIX F: DATA REDUCTION PROGRAM

program overall с Program to remove the internal resistance and radiation from measurements taken from wire and tube condenser coils С Originally written by John Hoke with revisions by John Hoke and Dean Swofford С с SW=wire spacing DW= wire diameter С DEPTH= coil depth (center of top wire to center of bottom wire С ST= tube spacing С с NT= number of tubes С NW= number of wires XLW= length of wire С С XLT= length of tube Ftt= view factor tube to tube с Ftw= view factor tube to wire С Fww= view factor wire to wire С Fwt= view factor wire to tube С Fts= view factor tube to surroundings С С Fws= view factor wire to surroundings с XKS= conductivity of steel XKP= conductivity of paint С С XKR= conductivity of refrigerant RS= resistance of steel с с RP= resistance of paint с Rr= resistance of refrigerant DT= outer diameter С DTI= inner diameter с с PT= paint thickness с RED= reynolds number M= mass flow rate С С XMUR= viscosity of refrigerant CPR= specific heat of refrigerant С REAL RED, HI, NUD, NUDR, F, M, T (20), TB (20), TASW (20), TAVB (20), NT, NW, dTemp, ETA, hwire, htube REAL ANGLE, NUtube, NUwire, NUWCORR, MH STRING AGAIN, TEXT, COIL, DIRECTORY, RESULTS, VERSION, SPACE CHARACTER*7 FILENAME CHARACTER*2 TEXTS CHARACTER*1 TEXTANGLE INTEGER TEN, ONE CHARACTER*1 SIGN COMMON /GEOMETRY/ ETA, SW, DW, DEPTH, ST, NT, NW, XLW, XLT, DT, TUBEAREA, WIREAREA, xks VERSION='VER 8/02/95' SPACE=' С CONSTANTS PI=3.14159 CPR=4180 !J/kg-K XKR=.6376 ! W/m-K XKS=60.5 ! W/m-K XKP=.167 ! W/m-K RESTRICTED FLOW TO WIRE BASE PARAMETER ETAT=.254 1 PRR=4.004 AGAIN='Y' M = 0.0! kq/sС have user select file to reduce

```
write (*,*) 'pick a geometry file. Note: program must be rerun to change
 geometry files'
        OPEN (FILE='coils', UNIT=7, STATUS='OLD')
        READ(7, *) FILES
        I=0
        DO 4 WHILE (I<FILES)
               I=I+1
               READ(7,*) COIL
               WRITE (*, *) COIL
        END DO
 4
        READ COIL NUMBER SELECTED
 С
        READ(*,*) NUMBER
 С
        read coil file and directory selected
        READ(7, *) DIRECTORY
        J=0
        DO 5 WHILE (J<NUMBER)
               J=J+1
               READ(7, *)COIL
 5
        ENDDO
        DIRECTORY=DIRECTORY//COIL
        CLOSE (7)
        open geometry file for coil chosen
 c
        OPEN ( FILE=COIL, UNIT=11, STATUS='OLD')
        WRITE (*, *) 'GEOMETRY FILENAME CHOSEN IS ', COIL
        READ(11,*) TEXT
        READ(11,*) DW, SW, NW, XLW, PT, DT, DTI, ST, XLT, NT
        coil geometry parameters, convert from inches to meters
С
        DW=DW*2.54/100.0
                                    ! m
        SW=SW*2.54/100.0
                                    ! m
       XLW=XLW*2.54/100.0
                                    ! m
       PT=PT*2.54/100.0
                                    ! m
       DT=DT*2.54/100.0
                                    ! m
       DTI=DTI*2.54/100.0
                                    ! m
       ST= ST*2.54/100.0
                                    ! m
       XLT= XLT*2.54/100.0
                                    ! m
       DEPTH=DW+DT
                                           ! m
с
       compute total wire area and total tube area
       Tubearea=pi*DT*NT*XLT+PI*DT*PI/2.0*ST*(NT-1.0)
       wirearea=pi*DW*NW*XLW
       WRITE (*, *) TUBEAREA, WIREAREA
       WRITE (*, *) DW, SW, NW, XLW, PT, DT, DTI, ST, XLT, NT
       record geometric parameters used in reducing data for reference
С
       CALL VIEWFACTOR (FTT, FWW, FTW, FWT, FWS, FTS)
       TEXT=DIRECTORY//':GEOMETRY'
       open(unit=13, file=TEXT, status='UNKNOWN')
       FORMAT (F7.4,',',F7.4,',',F7.4,',',F7.4,',',F8.4,',',F7.4,',',F7.4,',',F7.4,',',F7.4)
6
       write(13,*) 'tubearea,wirearea,DW,SW,NW,XLW,PT,DT'
       write(13,6) tubearea, wirearea, DW, SW, NW, XLW, PT, DT
       write(13,*) 'DTI,ST,XLT,NT,ftw,ftt,fwt,fww'
       write (13,6) DTI, ST, XLT, NT, ftw, ftt, fwt, fww
       close(13)
       OPEN FILES TO SAVE ANGLE DEPENDENCE
С
26
       Format (A13, ', ANGLE, REW, NUWIRE', f4.2, ', hwire', f4.2, ', ETA', f4.2, ', Ret, XNudt', f4.2
,',Ev')
```

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TEXT=DIRECTORY//':'//COIL//'PARA025' OPEN (UNIT=31, FILE=TEXT, STATUS='UNKNOWN') v=.25 WRITE (31, 26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PARA050' OPEN (UNIT=32, FILE=TEXT, STATUS='UNKNOWN') v=.50 WRITE (32,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PARA100' OPEN (UNIT=33, FILE=TEXT, STATUS='UNKNOWN') V=1.0 WRITE (33,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PARA150' OPEN (UNIT=34, FILE=TEXT, STATUS='UNKNOWN') V=1.5 WRITE (34,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PARA200' OPEN (UNIT=35, FILE=TEXT, STATUS='UNKNOWN') V=2.0 WRITE (35,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PERP025' OPEN (UNIT=36, FILE=TEXT, STATUS='UNKNOWN') V=.25 WRITE (36,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PERP050' OPEN (UNIT=37, FILE=TEXT, STATUS='UNKNOWN') V=.5 WRITE (37,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PERP100' OPEN (UNIT=38, FILE=TEXT, STATUS='UNKNOWN') V=1.0 WRITE (38,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PERP150' OPEN (UNIT=39, FILE=TEXT, STATUS='UNKNOWN') V = 1.5WRITE (39,26) VERSION, v, v, v, v TEXT=DIRECTORY//':'//COIL//'PERP200' OPEN (UNIT=40, FILE=TEXT, STATUS='UNKNOWN') V=2.0 WRITE (40,26) VERSION, v, v, v, v begin loop to remove radiation FORMAT (A7) READ (11,3) AGAIN DO 1 WHILE (AGAIN .NE. 'QUITNOW') file to remove radiation from TEXT=DIRECTORY//':'//AGAIN OPEN (FILE=TEXT, UNIT=10, STATUS='OLD') WRITE (*, *) 'THE SELECTED FILE IS ', AGAIN READ(10,*) TEXT file to save data in RESULTS=DIRECTORY//':'//COIL//AGAIN//'.RSLT' OPEN (1, FILE=RESULTS, STATUS='UNKNOWN') REWIND (1) FILENAME=AGAIN V=0 determine the angle TEXTS=FILENAME(1:2) IF (TEXTS.EQ.'PA') THEN PSI=0

С

3

с

с

с

```
ELSE
                       PSI=90
                ENDIF
                TEN=0
                ONE=0
                TEXTANGLE=FILENAME(6:6)
                IF (TEXTANGLE.EQ.'O') THEN
                       ANGLE=0.0
               ELSE
                      TEN=ICHAR (TEXTANGLE)-48
               ENDIF
               TEXTANGLE=FILENAME(7:7)
                IF (TEXTANGLE .EQ. 'R') THEN
                      ANGLE =0.0
               ELSE
                      ONE=ICHAR (TEXTANGLE)-48
               ENDIF
               ANGLE=10.0*REAL (TEN) +REAL (ONE)
               SIGN=FILENAME (5:5)
               IF (SIGN.EQ.'N') THEN
                      ANGLE=-1.0*ANGLE
               END IF
 21
        Format (A14, ', Velocity
 [m/s], REW, NUW', I3, ', HW', I3, ', ETA', I3, ', RET, NUDT', I3, ', EV, %RINT, %QRAD')
               WRITE (1,21) VERSION, int (ANGLE), int (ANGLE), int (ANGLE), int (ANGLE)
 с
        this loop goes through the velocities one at a time till 2m/s is reached
         DO 2 WHILE (V<2.5)
               READ(10,*) V, QR, DUM2, TAI, TRAVG, DELT, TS1, TS2
               HOLD=QR/(TRAVG-TAI)/(TUBEAREA+WIREAREA)
               TRI=TRAVG+DELT/2.0
               TRO=TRAVG-DELT/2.0
               TS=((TS1+TS2)/2.0-TAI)*.667+TAI
               M=QR/CPR/DELT
С
              WRITE(*,*) 'M',M
С
       calculate internal resistance to find surface temperature
       xmur=(4.9202e5-5787.4*TRI+25.679*TRI**2-.050828*TRI**3+3.7827E-
5*TRI**4)/1000000
       Rer=4.0*M/DTI/XMUR/PI
       F = (.79 \times LOG(RER) - 1.64) \times -2
       NUDR=(F/8.0)*(RER-1000.0)*PRR/(1.0+12.7*SQRT(F/8.0)*(PRR**.6667-1.0))
       HR=NUDR*XKR/DTI
       HLAM=4.36*XKR/DTI
       IF (HR < HLAM) THEN
              HR=HLAM
       END IF
       AI=NT*PI*DTI*XLT+PI*DTI*PI*ST/2.0*(NT-1.0)
       RR=1.0/(AI*HR)
       WRITE (*, *) 'RER, HR', RER, HR
С
       CALCULATE TOTAL RESISTANCE
       RTOT= (TRAVG-TAI) /QR
       CALCULATE STEEL TUBE RESISTANCE
С
       RS=LOG((DT-2.0*PT)/DTI)/(2.0*PI*XKS*(NT*XLT+(NT-1)*PI*ST/2.0))
       PERCRR= (RR+RS) / (RTOT) *100.0
       CALCULATE INLET AND OUTLET SURFACE TEMPERATURES BASED ON RESISTANCES
С
```

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```

```
TSI=TRI-(RR+RS) * (TRI-TAI) /RTOT
        TSO=TRO-(RR+RS) * (TRO-TAI) /RTOT
С
        calculate average tube surface temperatures for each pass
        I=0
        DO 10 WHILE (I<NT)
               I=I+1
               T(I)=TSI-(I-.5) * (TSI-TSO) /NT
               WRITE(*,*) T(I)
C
10
         END DO
               determine eta based on guessed h value
с
               dTemp=(TSI+TSO)/2.0-TAI
               CALL findhwire (QR, dTemp, hwire, eta)
c
        calculate average wire temperature based on estimated eta and refrigerant temp
        TFILM=0
        T=0
       DO 25 WHILE (I<NT)
               I=I+1
               TASW(I) = ETA*(T(I) - TAI) + TAI
               TFILM=TFILM+TASW(I)/NT
25
       END DO
       TFILM=(TFILM+TAI)/2.0
       call radiation subroutine to remove the radiation contribution
С
       CALL RADREMOVE (T, TASW, TAI, TS, QRADT, QRADW)
       QC=QR-QRADT-QRADW
       PERCQR= (QRADT+QRADW) /QR*100.0
       call gas properties subroutine
С
       CALL GASPT (1, TFILM, RHO, XMU, XK, CP, GRB, PR, IER)
       REW= RHO*V*DW/XMU
       RET=RHO*V*DT/XMU
       XNUDT=QC/WIREAREA/DTEMP*DT/XK
       CONVERT FROM METRIC TO ENGLISH
С
       EV=V*3.28084
c find hwire using Newton-Raphson routine
       dTemp=(TSI+TSO)/2.0-TAI
       write (*,*) 'qc,dtemp',qc,dtemp
С
       HWIRE=QC/(DTEMP*(TUBEAREA*(DW/DT)**.5+ETA*WIREAREA))
       NuWire=hwire*DW/XK
       Mh=sqrt (St**2/xks/Dw)
       ETAC=tanh (Mh*SQRT (hwire)) / (Mh*SQRT (hwire))
С
       DETERMINE VELOCITY AND PRINT TO APPROPRIATE FILE
       IF (psi=0) THEN
              IF (V>.24.AND.V<.26) THEN
                     WRITE (31, 210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
              ELSE IF (V>.49.AND.V<.51) THEN
                     WRITE (32,210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
              ELSE IF (V>.99.AND.V<1.025) THEN
                     WRITE (33,210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
              ELSE IF (V>1.49.AND.V<1.52) THEN
                     WRITE (34,210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
              ELSE IF (V>1.99.AND.V<2.03) THEN
                     WRITE (35,210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
              END IF
      ELSE
              IF (V>.23.AND.V<.27) THEN
                     WRITE (36, 210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
             ELSE IF (V>.49.AND.V<.51) THEN
                     WRITE (37,210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
```

```
ELSE IF (V>.99.AND.V<1.025) THEN
                        WRITE (38,210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
                ELSE IF (V>1.49.AND.V<1.52) THEN
                       WRITE (39, 210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
                ELSE IF (V>1.99.AND.V<2.03) THEN
                       WRITE (40,210) SPACE, ANGLE, REW, NUWIRE, hwire, ETAC, Ret, XNudt, Ev
                END IF
         END IF
 210
        FORMAT
 (A3, ', ', F4.0, ', ', F6.2, ', ', F7.4, ', ', F8.4, ', ', F6.4, ', ', F6.2, ', ', F8.5, ', ', F6.3)
        FORMAT (A3, ', ', F4.2, ', ', F6.2, ', ', F7.4, ', ', F8.4, ', ', F6.4, ', ', F6.2,
 200
        2
                ',',F8.5,',',F6.3,',',F6.3,',',F6.3)
        WRITE (1,200) SPACE, V, REW, NUWIRE, hwire, etaC, Ret, XNudt, Ev, PERCRR, PERCQR
        CHECK=1.95-V
        IF (CHECK < 0.0) THEN
               V=3.0
        END IF
 2
        END DO
        CLOSE(1)
        CLOSE (10)
        READ(11,3) AGAIN
1
        END DO
        CLOSE (11)
        CLOSE (31)
        CLOSE (32)
        CLOSE (33)
        CLOSE (34)
        CLOSE (34)
        CLOSE (35)
        CLOSE (36)
        CLOSE (37)
        CLOSE (38)
        CLOSE (39)
        CLOSE (40)
       END
        SUBROUTINE RADREMOVE (TT, TASW, TAI, TS, QRADT, QRADW)
       written by John Hoke
с
       REAL
C, B, F (5, 5), A (5, 5), V (5), Q (5), TOTAL, FTT, FTW, FWT, FWS, FTS, FWW, TT (20), T (6), E (5), TASW (20)
       REAL TAI, TS, NT, NW
       COMMON /GEOMETRY/ ETA, SW, DW, DEPTH, ST, NT, NW, XLW, XLT, DT, TUBEAREA, WIREAREA, **
       DW= wire diameter
с
       depth= coil depth (center of top wire to center of bottom wire
с
       ST= tube spacing
С
       DT= tube diameter
С
       NT= number of tubes
с
       NW= number of wires
с
       XLW= lenght of wire
с
       XLT= lenght of tube
С
       Ftt= view factor tube to tube
С
       Ftw= view factor tube to wire
с
       Fww= view factor wire to wire
с
       Fwt= view factor wire to tube
с
с
       Fts= view factor tube to surroundings
с
       Fws= view factor wire to surroundings
```

```
С
        1=primary tube
        2=tube behind
 с
        3=tube ahead
 с
 с
        4=wire
        5=surroundings
 с
        pi=3.14159
        C=0.0
        B=0.0
        DEPTH=DT+DW
        TOTALT=0.0
        TOTALW=0.0
        SIGMA=5.67E-8
        k=0
        E(1) = .95
        E(2) = .95
        E(3)=.95
        E(4) = .95
        E(5) = 1.0
        T(5)=TS
        J=0
        do 7 WHILE (J<5)
               J=J+1
               Q(J) = 0.0
7
       END DO
       CALL VIEWFACTOR (FTT, FWW, FTW, FWT, FWS, FTS)
       do 30 while (k<NT)
               K=K+1
               X=0
               DO 40 WHILE (X<5)
                      X=X+1
                       I=0
                       DO 50 WHILE (I<5)
                              I=I+1
                              F(X, I) = 0
50
                      END DO
40
               END DO
С
               calculate view factors
               F(1,5) = 1.0 - ftw
               IF (K.NE.INT(NT)) THEN
                      F(1,2) = FTT
                      F(1,5) = F(1,5) - ftt
                      F(2,1) = FTT
                      F(2,4) = FTW
                      F(2,5) = 1.0 - ftw - 2.0 + ftt
                      T(2) = TT(K+1)
              else
                      t(2) = 0.0
              ENDIF
              IF (K.NE.1) THEN
                      F(1,3) = FTT
                      F(1,5) = F(1,5) - ftt
                      F(3, 1) = FTT
                      F(3, 4) = FTW
                      F(3,5) = 1.0 - ftw - 2.0 + ftt
```

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```
T(3) = TT(K-1)
                else
                        t(3) = 0.0
                ENDIF
                F(4, 4) = FWW
                F(1, 4) = FTW
                f(4,5) = fws
                F(4, 1) = FWT
                T(1) = TT(K)
                T(4) = TASW(K)
 С
                build matrix
 С
                       SOLUTION COLUMN
                       X=0
                       DO 60 WHILE (X<5)
                               X=X+1
                               V(X) = E(X) * SIGMA * T(X) * 4
                       END DO
 60
 С
                       MATRIX
                               X=0
                               DO 70 WHILE (X<5)
                                      X=X+1
                                      T=0
                                      DO 80 WHILE (I<5)
                                              I=I+1
                                              A(X, I) = -(1.0 - E(X)) * F(X, I)
80
                                      END DO
                                      A(X, X) = A(X, X) + 1.0
70
                              END DO
С
                reduce matrix
        CALL GAUSS (5, A, V, Q)
С
        Calculate energy leaving tubes and wires for first pass
        X=0
        DO 100 WHILE (X<5)
               X=X+1
               Q(1) = Q(1) - F(1, X) * Q(X)
               Q(4) = Q(4) - F(4, X) * Q(X)
100
       END DO
        TOTALT=TOTALT+Q(1) *TUBEAREA/NT
        TOTALW=TOTALW+Q(4) *WIREAREA/NT
30
       END DO
       QRADT=TOTALT
       QRADW=TOTALW
С
       WRITE (*, *) 'TOTAL HEAT LOST DUE TO RADIATION', TOTAL
       RETURN
       END
       SUBROUTINE VIEWFACTOR (FTT, FWW, FTW, FWT, FWS, FTS)
       coil view factor program
С
с
       written by John Hoke
       REAL NT, NW
       COMMON /GEOMETRY/ ETA, SW, DW, DEPTH, ST, NT, NW, XLW, XLT, DT, TUBEAREA, WIREAREA, xks
       SW=wire spacing (length/wire
с
       DW= wire diameter
с
       depth= coil depth (center of top wire to center of bottom wire
с
с
       ST= tube spacing
```

с с с с с	DT= tube diameter NT= number of tubes NW= number of wires XLW= lenght of wire XLT= lenght of tube
с	Ftt= view factor tube to tube
с	Ftw= view factor tube to wire
с	Fww= view factor wire to wire
с	Fwt= view factor wire to tube
с	Fts= view factor tube to surroundings
с	Fws= view factor wire to surroundings pi=3.14159

Fww=0 Ftt=0

c Calculate wire to wire view factor

c View factor to adjacent wires in plane

```
x=SW/DW
Fww=2.0/pi*(sqrt(x*x-1.0)+asin(1.0/x)-x)
Fws1=(1.0-Fww)/2.0
write(*,*) 'Fws1 = ',Fws1
Fs1w=(PI*DW/(2.0*SW))*Fws1
```

```
c write(*,*) 'Fs1w= ',Fs1w
Fws1s2=(1.0-2*Fs1w)
```

c Tube View factor

x=ST/DT

С

с

Ftt=1.0/pi*(sqrt(x*x-1.0)+asin(1.0/x)-x)
Fts1=(1.0-2.0*Ftt)/2.0
write(*,*) 'Fts1= ',Fts1

Fslt=(PI*DT/(2.0*ST))*Ftsl
c write(*,*) 'Fslt= ',Fslt
Ftsls2=1.0-2.0*Fslt

Ftw=4.0*Fts1*Fs1w
Fwt=Fws1*Fs1t*2.0

AtFtw=PI*DT*SW*Ftw AwFwt=2.0*PI*DW*ST*Fwt

c write(*,*) 'AtFtw= ',AtFtw
c write(*,*) 'AwFwt= ',AwFwt

```
c View factor to wire directly below
x=depth/DW
Fww=Fww+(1.0/pi*(sqrt(x*x-1.0)+asin(1.0/x)-x))*Fts1s2
```

c View factor to other wires below

i=1 Do 10 while (i<2*depth/DW)

```
x=sqrt(depth**2+(i*SW)**2)/DW
Fww=Fww+(2.0/pi*(sqrt(x*x-1.0)+asin(1.0/x)-x))*Fts1s2
i=i+1
```

```
10 End do
```

```
Fts= 1-Ftt-Ftw
        write(*,*) 'Tube to surroundings Fts=',Fts
 С
        write(*,*) 'Fww', Fww
 С
        write(*,*) 'Fwt', Fwt
 С
        Fws= 1-Fww-Fwt
 С
        write(*,*) 'Wire to surroundings Fws=', Fws
        VFAC= (tubearea*Fts+wirearea*Fws)/(tubearea+wirearea)
 C
 C
        write(*,*) 'Total Viewfactor coil to surroundings=',VFAC
        RETURN
        End
        subroutine gauss(n, a, b, x)
        real a(5,5), b(5), x(5), temp
        integer j, k, l, inx, n
        elimination
 с
        do 10 k=1,n
              do 20 j=1,n
              if(j.gt. k) then
              temp = a(j,k)/a(k,k)
                     do 30 l=k,n
  30
                     a(j,l) = a(j,l) - temp*a(k,l)
                     b(j) = b(j) - temp*b(k)
              endif
 20
       continue
 10
       continue
       back substitution
С
       do 40 k=1,n
              inx = n-k+1
              x(inx) = b(inx)/a(inx,inx)
              do 50 j=1,n
                     if (inx + j) .le. n) then
                     x(inx) = x(inx) - (a(inx,inx+j)/a(inx,inx)) * x(inx+j)
                     endif
 50
              continue
 40
       continue
       return
       end
       SUBROUTINE GASPT (NGAS, T, RHO, XMU, XK, CP, GRB, PR, IER)
C PROGRAMMED BY: A. M. CLAUSING; VERSION: APRIL 1982
C PROPERTIES OF GASES IN SI UNITS (T.GT.0) OR ENGLISH UNITS (T.LT.0)
C FUNCTIONAL REPRESENTATIONS USED ARE OF THE FORM: Y=A*T**B.
C ARRAYS A AND B CONTAIN THE RESPECTIVE CONSTANTS.
C INPUT:
C NGAS
              NGAS=1 IS AIR; NGAS=2 IS NITROGEN
C T ABSOLUTE TEMP. (K); OR NEGATIVE OF ABSOLUTE TEMP. (R)
C OUTPUT:
С
  RHO DENSITY (KG/M3) OR (LBM/FT3)
  XMU VISCOSITY (KG/M-S) OR (LBM/FT-S)
С
С
  XK THERMAL CONDUCTIVITY (W/M-K) OR (BTU/HR-FT-R)
C CP SPECIFIC HEAT (J/KG-K) OR (BTU/LBM-R)
C GRB G*BETA/XNU**2 (1/M3-K) OR (1/FT3-R)
C PR PRANDTL NUMBER (DIMENSIONLESS)
```

```
C IER ERROR PARAMETER
 C INFORMATIVE ERRORS:
        IER=1 GAS NUMBER DOES NOT EXIST. GAS IS ASSUMED TO BE AIR.
 С
        IER=2 TEMPERATURE OUT OF RANGE OF PROPERTY SUBROUTINE
 С
 C RESTRICTIONS:
 С
        NGAS:
                      MUST BE 1 (AIR) OR 2 (NITROGEN)
 С
        Т:
                      T MUST LIE BETWEEN 150K AND 2100K FOR AIR, AND BETWEEN
 С
                      83K AND 450K FOR NITROGEN. RANGES ARE SPECIFIED WITH ARRAY R.
 С
        DIMENSION A (15,2), B (15,2), R (3,2)
       DATA A/364.1,.1764E-6,.1423E-3,990.8,.4178E20,1.23,
       2 350.6,.4914E-6,.2494E-3,299.4,.4985E19,.59,3*.0,
       3 432.4,9.1E-8,1.239E-4,1553.,4.379E20,1.137,
        4 351.6, 18E-6, 221E-3, 1031., 408E20, 841, 3*.0/
       DATA B/-1.005,.814,.9138,.00316,-4.639,-.09685,
       2 -.999,.6429,.8152,.1962,-4.284,.0239,3*.0,
       3 -1.046, .938, .9466, -.079, -5.102, -.0872,
       4 -1.005, .8058, .8345, .00239, -4.636, -.02652, 3*.0/
       DATA R/150.,400.,2100.,83.,160.,450./
       IER=0
       IF((NGAS.GT.0).AND.(NGAS.LT.3)) GO TO 1
       TER=1
       NGAS=1
1
       I=1
       TP=T
       IF(T.LT..0) TP=-T/1.8
       IF((TP.LT.R(1,NGAS)).OR.(TP.GT.R(3,NGAS))) IER=2
       IF(TP.GT.R(2,NGAS))I=7
       RHO=A(I,NGAS)*TP**B(I,NGAS)
       XMU=A(I+1,NGAS)*TP**B(I+1,NGAS)
       XK=A(I+2, NGAS) * TP * * B(I+2, NGAS)
       CP=A(I+3, NGAS) *TP**B(I+3, NGAS)
       GRB=A(I+4, NGAS) *TP**B(I+4, NGAS)
       PR=A(I+5, NGAS) * TP * * B(I+5, NGAS)
       IF (T.GT..0) RETURN
       RHO = RHO / 16.02
       XMU=XMU/1.488
       XK=XK/1.731
       CP=CP/4187.
       GRB=GRB/63.57
       RETURN
       END
       subroutine findhwire(q,dTemp,hwire,etah)
       This subroutine solves the transcendental equation for the wire heat transfer
 С
coefficient
              using the Newton Raphson technique.
 С
 с
       written by Dean Swofford with additional modifications by Dean and John Hoke
       REAL Q, HWIRE, ETAh, mh, F, Ct, nt, mt, Cw, mw, dTemp, dF, Fnew, Fcheck
       COMMON /GEOMETRY/ ETA, SW, DW, DEPTH, ST, NT, NW, XLW, XLT, DT, TUBEAREA, WIREAREA, XKS
       Mh=sqrt (St**2/xks/Dw)
      PI=3.14159
      Find constant which is ratio of htube/hwire
с
      hratio=(dw/dt)**.5
      Fcheck=10.0
      hwtemp=30.0
      do while (Fcheck>.0001)
      F=hwtemp*dTemp*(TUBEAREA*hratio+(tanh(Mh*sqrt(hwtemp))/(Mh*sqrt(hwtemp)))*WIREA
```

```
REA) -q
```

```
dF=dTemp* (TUBEAREA*hratio+(tanh (Mh*sqrt (hwtemp)) / (Mh*sqrt (hwtemp))) *WIREAREA) +W IREAREA*dTemp*
```

```
2 ((1/(2*(cosh(Mh*sqrt(hwtemp)))**2))-
((tanh(Mh*sqrt(hwtemp)))/(2*sqrt(hwtemp)*Mh)))
c write(*,*) F,dF,hwtemp
hwtemp=hwtemp-F/dF
```

Fnew=hwtemp*dTemp*(TUBEAREA*hratio+(tanh(Mh*sqrt(hwtemp))/(Mh*sqrt(hwtemp)))*WI
REAREA)-q

```
Fcheck=ABS(Fnew)
end do
hwire=hwtemp
if (hwire<0) then
write(*,*) 'you stupid idiot 2'
end if
etah=tanh(Mh*SQRT(hwire))/(Mh*SQRT(hwire))
c write(*,*)'guessed/computed',hratio,htube/hwire,hwire,htube
return
end</pre>
```