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THESES

THE EFFECTIVENESS OF HEAT EXCHANGERS WITH ONE SHELL PASS AND FIVE TUBE PASSES

by

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September 1985

Thesis Advisor: Allan D. Kraus

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**Title:** The Effectiveness of Heat Exchangers with One Shell Pass and Five Tube Passes

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**Abstract:**

Heat exchangers with one shell pass and n tube passes are often referred to as 1-n exchangers. The heat transfer literature contains many references to studies of 1-n exchangers when n is even but apparently, other than a single study and some work pertaining to the 1-3 exchanger at the Naval Postgraduate School, little work has been done with respect to the 1-n exchanger when n is odd. This thesis expands upon the study of 1-n exchangers with n being odd.
20. (Continued)

While a completely closed form solution was found to be unfeasible, a polynomial approximation has been developed that yields the effectiveness ($\varepsilon$) of the two possible arrangements of the 1-5 exchanger as a function of the capacity rate ratio ($R$) and the number of transfer units ($N_{t,u}$). This will enable the analyst to consider exchangers where the inlet to and outlet from the tubes are at opposite ends of the exchanger.
The Effectiveness of Heat Exchangers 
With One Shell Pass and 
Five Tube Passes

by

Lawrence E. Hess 
Lieutenant Commander, United States Navy 
B.S., The Citadel, 1973

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While a completely closed form solution was found to be unfeasible, a polynomial approximation has been developed that yields the effectiveness (e) of the two possible arrangements of the 1-5 exchanger as a function of the capacity rate ratio (R) and the number of transfer units (N_{tu}). This will enable the analyst to consider exchangers where the inlet to and outlet from the tubes are at opposite ends of the exchanger.
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**NOMENCLATURE**

<table>
<thead>
<tr>
<th>English Letter Symbols</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Exchanger heat-transfer surface, sq m</td>
</tr>
<tr>
<td>$A_m$</td>
<td>Coefficient of the mth value dimensionless</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Coefficient, dimensionless</td>
</tr>
<tr>
<td>$A_1$</td>
<td>1st order coefficient to be multiplied by $N_{tu}$, dimensionless</td>
</tr>
<tr>
<td>$A_2$</td>
<td>2nd order coefficient to be multiplied by $N_{tu}^2$, dimensionless</td>
</tr>
<tr>
<td>$A_3$</td>
<td>3rd order coefficient to be multiplied by $N_{tu}^3$, dimensionless</td>
</tr>
<tr>
<td>$A_4$</td>
<td>4th order coefficient to be multiplied by $N_{tu}^4$, dimensionless</td>
</tr>
<tr>
<td>$A_5$</td>
<td>5th order coefficient to be multiplied by $N_{tu}^5$, dimensionless</td>
</tr>
<tr>
<td>a</td>
<td>Exchanger heat-transfer surface, sq m/m</td>
</tr>
<tr>
<td>C</td>
<td>Capacity rate, W/K. Also designates dimensionless arbitrary constant</td>
</tr>
<tr>
<td>$C_{pc}$</td>
<td>Specific heat at constant pressure of cold fluid, J/kg*K</td>
</tr>
<tr>
<td>$C_{ph}$</td>
<td>Specific heat at constant pressure of hot fluid, J/kg*K</td>
</tr>
<tr>
<td>D</td>
<td>Empirical value of effectiveness (computer generated), dimensionless</td>
</tr>
<tr>
<td>e</td>
<td>Error. Also used as the exponential function</td>
</tr>
<tr>
<td>F</td>
<td>Logarithmic mean temperature difference correction factor, dimensionless</td>
</tr>
<tr>
<td>L</td>
<td>Exchanger length, m</td>
</tr>
<tr>
<td>N</td>
<td>Number of effectiveness empirical data points used to determine a curve for R, dimensionless</td>
</tr>
</tbody>
</table>
\( n \) = Number of tube passes, dimensionless. Also number of equations, dimensionless

\( n_c \) = A related \( N_{tu} \) per unit length cold side, m\(^{-1}\)

\( n_h \) = A related \( N_{tu} \) per unit length hot side, m\(^{-1}\)

\( N_{tu} \) = Number of transfer units, dimensionless

\( P \) = Temperature group, dimensionless

\( q \) = Total rate of heat transfer, W

\( q_{max} \) = Maximum total rate of heat transfer, W

\( R \) = Capacity rate ratio, dimensionless

\( S \) = Temperature group, dimensionless

\( S_r \) = Sum of the squares of the residuals, dimensionless

\( T \) = Hot fluid temperature, °C

\( T_{pi} \) = Particular integral, dimensionless

\( T_1 \) = Hot fluid temperature in, °C

\( T_2 \) = Hot fluid temperature out, °C

\( t_1 \) = Cold fluid temperature in, °C

\( t_2 \) = Cold fluid temperature out, °C

\( t_a \) = Cold fluid temperature 1st pass, °C

\( t_{ab} \) = Cold fluid temperature between 1st and 2nd passes

\( t_b \) = Cold fluid temperature 2nd pass, °C

\( t_{bc} \) = Cold fluid temperature between 2nd and 3rd passes

\( t_c \) = Cold fluid temperature 3rd pass, °C

\( t_{cd} \) = Cold fluid temperature between 3rd and 4th passes

\( t_d \) = Cold fluid temperature 4th pass, °C

\( t_{de} \) = Cold fluid temperature between 4th and 5th passes

\( t_e \) = Cold fluid temperature 5th pass, °C
\( U \) = Overall heat transfer coefficient, \( \text{W/m}^2 \cdot ^\circ \text{C} \)

\( W \) = Mass flow, \( \text{kg/sec.} \)

\( x \) = length coordinate, \( \text{m} \). Also used to represent a constant value in a sequence

\( y \) = Sum of \( m \)th degree polynomial, defined by eq. (5.1), dimensionless

**Greek Letter Symbols**

\( \alpha \) = Root of auxiliary differential equation, \( 1/\text{m} \)

\( \varepsilon \) = Exchanger effectiveness, dimensionless

\( \lambda \) = Combination of variables defined by equation (3.12), dimensionless

\( \Sigma \) = Summation, dimensionless

\( \sigma^2 \) = Variance, dimensionless

\( \theta_m \) = Mean temperature difference for exchanger, \( ^\circ \text{C} \)

\( \partial \) = Indicates partial derivative, dimensionless

\( \beta \) = A combination of terms defined by eq. (3.23)

**Subscripts**

\( c \) = Cold fluid

\( h \) = Hot fluid

\( i,j,k \) = Values in a sequence

\( m \) = Degree or order, an exponent

\( 1 \) = inlet

\( 2 \) = outlet
ACKNOWLEDGEMENT

I wish to thank my wife, Cheri, who has been a sustaining influence from the beginning and to my parents who launched my career. Also my sincere gratitude to Dr. Allan D. Kraus for his time, guidance and patience. Without his assistance and encouragement this thesis would not have been possible.

Finally, I wish to thank Uncle Sam who made one of my life-long goals possible.
In many engineering applications, it is desirable to transfer thermal energy between fluids at different temperatures. This action may be economically accomplished with the aid of a heat exchanger.

The primary function of a non-direct contact heat exchanger is to provide two paths of flow, one for the hot fluid and one for the cold, by means of which heat can be transferred through walls separating the fluids.

The quantity of heat transferred is governed by three factors: 1) the amount and nature of the heat transfer surface to which the two fluids are exposed, 2) the overall heat transfer coefficient, and 3) the mean temperature difference across the intervening wall from one fluid to the other.

Numerous flow arrangements and geometric designs are possible. One of the most common types of heat exchangers is the shell and tube type. Here one fluid flows through the tubes. The tubes are enclosed in a shell with provisions for the other fluid to flow through the spaces between and exterior to the tubes. Overall flow may be either parallel or counter, but in most cases, the latter is preferred. The reason for this will be seen later. One of the most common flow arrangements used in the shell and tube
heat exchangers is a combination of the two, the parallel-counterflow exchanger. Heat exchangers with one shell pass and \( n \) tube passes are therefore referred to as 1-\( n \) heat exchangers.

One example of this flow arrangement is the one shell-pass two tube pass exchanger as shown in Figure 1.1.

![Figure 1.1 A 1-2 Heat Exchanger (One Shell Pass and Two Tube Passes)](image)

This type of exchanger is configured so that all of the tube side fluid flows consecutively through half of the total number of tubes: The baffles in the shell serve to "mix" the shell fluid and to maintain fluid flow at right angles to the tube passes in order to obtain a maximum "shell side" heat transfer coefficient.
O'Hare [Ref. 1] has indicated that, to date, much work has been done on finding the logarithmic mean temperature difference for heat exchangers with an even number of passes but little has been done with exchangers having an odd number of passes. From this basic statement, he proceeded with a theoretical examination of the 1-3 heat exchanger which resulted in some startling conclusions. As a follow up to his work, this thesis will parallel and follow the format of O'Hare [Ref. 1] for the 1-5 parallel counter flow exchanger. One arrangement of the 1-5 exchanger is displayed in Figure 2.

Figure 1.2 A 1-5 Heat Exchanger (One Shell Pass and Five Tube Passes)
II. THE DEVELOPMENT OF THE EFFECTIVENESS METHOD

A. HISTORICAL DEVELOPMENT

Nagle [Ref. 2: pp. 604-609], in 1931, credited Davis [Ref. 3] with a simplified method for computing actual temperature differences between two heat-interchanging streams which depart from true counter or concurrent (parallel) flow. This is now the familiar "F factor" method which expresses the actual mean temperature difference $\theta_m$ in $q = UA\theta_m$ as a fraction $F$ of the counterflow logarithmic mean temperature difference, LTMD, $\theta_{mc}$ via $\theta_m = F\theta_{mc}$.

The example of initial interest was the 1-2 exchanger with a single shell pass and two continuous tube passes in counter and concurrent flow with it. The method involved derivation of the actual temperature difference for the flow pattern and formed the ratio $F = \theta_m/\theta_{mc}$. This familiar LMTD correction factor was plotted conveniently as functions of the effectiveness, $\varepsilon$, and the capacity rate ratio $R$ with $R$ as a parameter. These mean temperature difference correction charts are available for many flow arrangements [Ref. 4: pp. 829-833 and Ref. 5]. The effectiveness, $\varepsilon$ (often called $P$ or $S$), is always the cold fluid effectiveness and $R$ is always the capacity rate ratio of cold fluid to hot fluid.
Nagle detailed assumptions and derivations for the 1-2, 1-4 and 1-6 exchangers. The $F$ factors were obtained by Nagle through graphical integration and were accompanied by the comment that $F$ factors for the 1-2 exchanger could be applied with negligible error to 1-4 and 1-6 exchangers. Underwood [Ref. 6: pp. 145-148] rederived the equations of Nagle for 1-2 and 1-4 exchangers to eliminate the need for obtaining $F$ factors by graphical integration.

Bowman [Ref. 7: pp. 541-544] pointed out that for a very large or infinite number of tube passes, the $F$ factor approached, as a limit, its value in crossflow with both fluids completely mixed. It was further stated that even at the limit, the $F$ factors were only 1 to 2 percent lower than those for the 1-2 exchanger. A previous paper by Kraus and Kern [Ref. 8] did not confirm the generalization that 1-n exchangers differed only negligibly from the 1-2 exchanger although this lack of confirmation was obtained on an $\epsilon = f(R, N_{tu})$ basis. Moreover, the Kraus-Kern work does not confirm the generalizations on an $F = f(R, N_{tu}, \epsilon)$ basis.

From the standpoint of usefulness and good accuracy, it is essential that $F$ factors, if they are to be used in preference to $\epsilon = f(R, N_{tu}, \text{flow arrangement})$, be obtained with precision. Plots of $F = f(R, \epsilon, = P \text{ or } S)$ [Ref. 4: pp. 829-833 and Ref. 5] show that the curves for particular values of $R$ approach infinite slope as $F$ decreases. While this can be partially alleviated by restricting $R < 1.0$ (a
constraint used in the $\epsilon = f(R, N_{tu}, \text{flow arrangement})$
approach), it is seen that small errors in the interpolation
for $R$ or $\epsilon = P$ or $S$ can result in large fluctuations in the
value of $F$.

In a comprehensive paper, Bowman, Mueller and Nagle
[Ref. 9: pp. 283-294] presented graphs of $F$ factors for
shells with one through six shell passes and numbers of
continuous tube passes respectively double the number of
shell passes. In view of the earlier references to Nagle
and Bowman, it should be noted that $F$ factors were computed
for the 1-2 exchanger in [Ref. 9: pp. 283-294] using the
equations of Underwood [Ref. 6: pp. 145-158].

Ten Broeck [Ref. 10: pp. 1041-1042] prepared a graph
of the dimensionless groups now known as $\epsilon$, $R$ and $N_{tu}$ for
the 1-2 exchanger. Such a graph had the added versatility
of simplifying the calculation of performance in a given
exchanger when operating at conditions different for those
for which it was designed. Kays and London [Ref. 11:
pp. 63-74] prepared similar graphs and tables of
$\epsilon = f(R, N_{tu}, \text{flow arrangement})$ for the 1-2 exchanger and
for several cases of crossflow and periodic flow.

In the foregoing discussion, it has been observed that
there are two methods for the design and analysis of a heat
exchanger. These are the so-called "F factor" and "$\epsilon-N_{tu}$"
approaches and it is to be noted that the Heat Transfer
Literature contains many references of design equations for
either of these methods for exchangers that have one shell
pass and even numbers of tube passes.

It was O'Hare [Ref. 1] who pointed out that there may be
a virtue in having an odd number of tube passes particularly
in a marine application. Such an arrangement allows the
tube side fluid to enter one side of the exchanger and leave
from the opposite side (see Figure 1.2).

With the possible use for an odd tube pass heat
exchanger established, a literature search was conducted to
uncover any previously solved cases of 1-n heat exchangers
with n, the number of odd tube passes. O'Hare [Ref. 1],
Fischer [Ref. 12], and Stevens, et. al. [Ref. 13] have
dealt with this type of exchanger. Although Stevens,
et. al. deal with multiple crossflow passes, all provide the
foundation for the work reported here as well as additional
work pertaining to the 1-3 exchanger. O'Hare's investiga-
tion centered around the development of a solution for the
1-3 exchanger in the effectiveness-\(N_{tu}\) framework while
Fischer derived an equation using the mean temperature
difference for the 1-3 exchanger. Moreover, Fischer
expressed his results in terms of the correction factor \(F\)
and treats only the case of the 1-3 exchanger. This thesis
will expand on the \(N_{tu}\) method of thermal heat exchanger
design by covering the 1-5 heat exchanger. The work will
treat both the three counterflow and two parallel flow
and the two counterflow and three parallel flow (1-5:3P) cases (see Figures 2.1 and 2.2).
Figure 2.1 1-5:3C Five Tube Passes - Three in Counterflow

Figure 2.2 1-5:3P Five Tube Passes - Three in Parallel Flow
III. AN ATTEMPT AT AN ANALYTIC SOLUTION

A. EFFECTIVENESS AS A FUNCTION OF CAPACITY RATE RATIO AND EXCHANGER SIZE (Ntu)

This section deals with an investigation into the effectiveness, ε, of a one shell pass-five tube pass heat exchanger, in which ε compares the actual heat transfer capability to the thermodynamically limited, maximum possible heat transfer capability. This exchanger heat transfer effectiveness is given by

$$ \varepsilon = \frac{q}{q_{\text{max}}} = \frac{C_h(T_{\text{hot,in}} - T_{\text{hot,out}})}{C_{\text{min}}(T_{\text{hot,in}} - T_{\text{cold,in}})} = \frac{C_c(t_{\text{cold,out}} - t_{\text{cold,in}})}{C_{\text{min}}(T_{\text{hot,in}} - T_{\text{cold,in}})} $$

where $C_{\text{min}}$ is the smaller of the $C_h$ and $C_c$ magnitudes (the capacity rates). Thus, ε possesses the significance of effectiveness of the heat exchanger from a thermodynamic point of view, with the magnitude of the effectiveness completely defining the heat transfer performance. In general we express $\varepsilon = f(N_{tu}, R, \text{and flow arrangement})$ and when the flow arrangement is specified or understood, it is said that $\varepsilon = f(N_{tu}, R)$. [Ref. 11: pp. 14-26].

The number of heat transfer units $N_{tu}$ is a nondimensional expression of the "heat transfer size" of the exchanger. When $N_{tu}$ is small the exchanger effectiveness is low, and when $N_{tu}$ is large, $\varepsilon$ asymptotically approaches the limit
imposed by the flow arrangement and thermodynamic conditions. From inspection of the definition of $N_{tu}$

$$N_{tu} = \frac{AU}{C_{\text{min}}} = \frac{1}{C_{\text{min}}} \int_0^A UdA$$

it is clear that the overall conductance and transfer area affect the costs of attaining a high value for $N_{tu}$, ergo a high $\epsilon$. The capacity rate ratio, $R$, as defined by

$$R = \frac{C_{\text{min}}}{C_{\text{max}}}$$

is simply the ratio of mass flow rate times specific heat capacity for the two streams. These can be considered as flow stream thermal-capacity rates, i.e., the energy storage rate in the stream per unit of temperature change. [Ref. 11: pp. 14-26]

The attempt taken in this thesis to develop a closed form solution has used the basic fundamentals of heat transfer as well as the foregoing definition. A closed form solution for $\epsilon$ was sought for both 1-5 exchangers with one having three out of five tube passes in parallel flow and the other having three out of five tube passes in counterflow. The analytical approach taken, and demonstrated in this section, is for three out of five tube passes in counterflow.
B. ANALYTICAL DEVELOPMENT

The derivation for the effectiveness, $\varepsilon$, of the 1-5 exchanger as a function of the capacity rate ratio, $R$, and number of transfer units, $N_{tu}$, depends on several assumptions.

1. The overall coefficient of heat transfer, $U$, does not vary within the exchanger.
2. The specific heat of both hot side and cold side fluids does not vary.
3. Each fluid is thoroughly mixed, that is, the temperature of both hot and cold side fluids is uniform over any cross section.
4. Steady flow conditions are maintained.
5. Heat losses to or from the environment are negligible.
6. No change of phase takes place; all heat transferred is sensible heat.
7. There is equal heat transfer surface in each pass.

The configuration is shown in Figure 3.1 where the five tube passes are designated with subscripts $a$, $b$, $c$, $d$ and $e$. The temperature of the hot (shell side) fluid is indicated by upper case letters. For the cold (tube side) fluid, lower case letters are used. The subscript 1 always refers to the fluid inlet and the subscript 2 always refers to the fluid outlet.

With $W_h$ and $C_{ph}$ designating mass flow (kg/sec) and specific heat (Joules/kg°C) of hot fluid entering at $T_1$ and leaving at $T_2$ we define a capacity rate for the hot side

$$Ch = W_hC_{ph}$$
Figure 3.1 Three Counter Two Parallel Pass Configuration for Development of the Sought After Effectiveness Relationship
In similar fashion for the cold side (with \( \dot{W}_c \) and \( C_{pc} \)) entering at \( t_1 \) and leaving at \( t_2 \), we have

\[
C_c = \dot{W}_c C_{pc}
\]

We then obtain an energy balance for the entire exchanger

\[
C_h(T_1 - T_2) = C_c(t_2 - t_1)
\]  

(3.1)

Over the right hand side of the exchanger (Figure 3.1)

\[
C_h(T_1 - T) = C_c(t_2 - t_e + t_d - t_c + t_b - t_a)
\]  

(3.2)

and a differentiation gives

\[
C_h dT = C_c(dt_e - dt_d + dt_c - dt_b + dt_a)
\]  

(3.3)

Across \( dx \), with a \((m^2/m)\), the surface per running meter of length of pass so that \( A = 5aL \) is the total surface in the exchanger, we may write the heat transferred to the element \( dx \) in each cold pass.

\[
C_{cdt_a} = U d x (T - t_a)
\]  

(3.4a)

\[
C_{cdt_b} = -U d x (T - t_b)
\]  

(3.4b)

\[
C_{cdt_c} = U d x (T - t_c)
\]  

(3.4c)

\[
C_{cdt_d} = -U d x (T - t_d)
\]  

(3.4d)

\[
C_{d d t_e} = U d x (T - t_e)
\]  

(3.4e)
Here it should be observed that due cognizance has been taken of the direction of the flow in each cold fluid pass with respect to the positive sense of the length coordinate, x, and U is the overall heat transfer coefficient (W/m²°C).

With eqs. (3.4) in eq. (3.3)

\[ C_h dT = U_a (5T - t_a - t_b - t_c - t_d - t_e) dx \]

or

\[ \frac{dT}{dx} = n_h (5T - t_a - t_b - t_c - t_d - t_e) \quad (3.5) \]

where

\[ n_h = \frac{U_a}{C_h} \]

is a sort of \( N_{tu} \) per unit length for the hot side.

Now differentiate eq. (3.5)

\[ \frac{d^2T}{dx^2} = n_h (5 \frac{dT}{dx} - \frac{dt_a}{dx} - \frac{dt_b}{dx} - \frac{dt_c}{dx} - \frac{dt_d}{dx} - \frac{dt_e}{dx}) \]

and with eqs. (3.4) substituted

\[ \frac{d^2T}{dx^2} = 5n_h \frac{dT}{dx} - n_c n_h (T - t_a + t_b - t_c + t_d - t_e) \quad (3.6) \]

where

\[ n_c = \frac{U_a}{C_c} \]

where again the resemblance of \( n_c \) to \( N_{tu} \) can be noted.
From eq. (3.2) we obtain

\[
\frac{C_h}{C_c} (T_1 - T) - t_2 = t_b - t_a - t_c + t_d - t_e \quad (3.7)
\]

and with eq. (3.7) put into eq. (3.6)

\[
\frac{d^2 T}{dx^2} - 5n_h \frac{dT}{dx} = -n_c n_h \left[ T + \frac{C_h}{C_c} (T_1 - T) - t_2 \right]
\]

or

\[
\frac{d^2 T}{dx^2} - 5n_h \frac{dT}{dx} = -n_c n_h \frac{C_h}{C_c} \left[ (R_c - 1)T + T_1 - R_c t_2 \right] \quad (3.8)
\]

where

\[
R_c = \frac{C_c}{C_h}
\]

is the capacity rate ratio for the cold side.

Notice that

\[
n_c n_h \frac{C_h}{C_c} = \frac{U_a}{C_c} \cdot \frac{U_a}{C_h} \cdot \frac{C_h}{C_c} = \left( \frac{U_a}{C_c} \right)^2 = m
\]

and

\[
R_h = \frac{1}{R_c} = \frac{C_h}{C_c}
\]

a capacity rate ratio for the hot side. Then, algebraic adjustment provides
\[
\frac{d^2 T}{dx^2} - 5n_h \frac{dT}{dx} + m \left( \frac{1 - R_h}{R_h} \right) T = m(\frac{t^2}{R_h} - T_1) \tag{3.9}
\]

which is a linear, non-homogeneous, second order differential equation with constant coefficients having a complementary function

\[
T_c = C_1 e^{a_1 x} + C_2 e^{a_2 x} \tag{3.10}
\]

where \(C_1\) and \(C_2\) are arbitrary constants and where

\[
a_1, a_2 = \frac{5n_h}{2} \pm \frac{n_h}{2} \left[ 25n_h^2 - 4m \left( \frac{1 - R_h}{R_h} \right)^{1/2} \right]
\]

But

\[
\frac{m}{n_h^2} = \left( \frac{U_a}{C_c} \right)^2 \cdot \left( \frac{C_h}{C_c} \right)^2 = \left( \frac{U_a}{C_c} \right)^2 = \left( \frac{C_h}{C_c} \right)^2 = R_h^2 = \frac{1}{R_c^2}
\]

so that

\[
a_1, a_2 = \frac{5n_h}{2} \pm \frac{n_h}{2} \left[ 25 - 4R_h^2 \left( \frac{1 - R_h}{R_h} \right)^{1/2} \right]
\]

or

\[
a_1, a_2 = \frac{n_h}{2} (5 \pm \lambda) \tag{3.11}
\]
where

\[ \lambda = \left[ 25 - 4R_h(1 - R_h) \right]^{1/2} \]  \hspace{1cm} (3.12)

Designate the particular integral as \( T_{pi} \) and by the method of undetermined coefficients let \( T_{pi} = P \) so that in eq. (9)

\[ m\left(\frac{1 - R_h}{R_h}\right) P = m\left(\frac{t_2}{R_h} - T_1\right) \]

This makes

\[ T_{pi} = P = \left[ \frac{t_2}{R_h} - T_1 \right] \left[ \frac{R_h}{1 - R_h} \right] \]

so that

\[ T_{pi} = \frac{t_2 - R_h T_1}{1 - R_h} \] \hspace{1cm} (3.13)

The general solution to eq. (3.9) is the sum of eqs. (3.10) and (3.13)

\[ T(x) = C_1 e^{a_1 x} + C_2 e^{a_2 x} + \frac{t_2 - R_h T_1}{1 - R_h} \] \hspace{1cm} (3.14)

where the arbitrary constants, \( C_1 \) and \( C_2 \) are evaluated from conditions at \( x = 0 \) and \( x = L \). At \( x = 0, T(x = 0) = T_2 \) and at \( x = L, T(x = L) = T_1 \). When these are inserted, in turn, into eq. (3.14), one obtains a pair of linear algebraic equations in the unknowns \( C_1 \) and \( C_2 \)
\[ T_2 = C_1 + C_2 + T_{pi} \]
\[ T_1 = C_1 e^{a_1L} + C_2 e^{a_2L} + T_{pi} \]

where \( T_{pi} \) is given by eq. (3.13).

It is only a matter of algebra to show that

\[ C_1 = \frac{(T_1 - T_{pi}) - (T_2 - T_{pi})e^{a_2L}}{e^{a_1L} - e^{a_2L}} \]  
(3.15a)

and

\[ C_2 = \frac{(T_2 - T_{pi})e^{a_1L} - (T_1 - T_{pi})}{e^{a_1L} - e^{a_2L}} \]  
(3.15b)

It is easy to see from eq. (3.1) that

\[ R_h = \frac{C_h}{C_c} = \frac{(t_2 - t_1)}{(T_1 - T_2)} \]

so that

\[ t_2 = t_1 + R_h(T_1 - T_2) \]

Use of this in eq. (3.13) shows that

\[ T_{pi} = \frac{t_1 + R_h(T_1 - T_2) - R_h T_1}{1 - R_h} \]
or
\[
T_{pi} = \frac{t_1 - R_h T_2}{1 - R_h} \quad (3.16)
\]
indicating two alternative forms for \(T_{pi}\) given by eqs. (3.13) and (3.16).

Insertion of eqs. (3.13) and (3.16) in eqs. (3.15) for \(C_1\) and \(C_2\) will yield after some algebra
\[
C_1 = \frac{\frac{T_1 - t_2}{1 - R_h} - \frac{T_2 - t_1}{1 - R_h}}{e_1^L - e_2^L} \quad (3.17a)
\]
and
\[
C_2 = \frac{\frac{T_2 - t_1}{1 - R_h} e_1^L - \frac{T_1 - t_2}{1 - R_h}}{e_1^L - e_2^L} \quad (3.17b)
\]

Equation (3.14) is an expression for the hot side temperature at any location in the exchanger in terms of the extreme temperatures, \(t_1\), \(t_2\), \(T_1\) and \(T_2\).

Next take eq. (3.5) and set it equal to the derivative of eq. (3.14) noting that \(C_1\), \(C_2\) and \(T_{pi}\) are all known constants.
\[
\frac{dT}{dx} = n_h (5T - t_a - t_b - t_c - t_d - t_e) = a_1 C_1 e^{a_1 x} + a_2 C_2 e^{a_2 x} \quad (3.18)
\]
At \(x = 0\), where \(T = T_2\), \(t_a = t_1\), \(t_b = t_c = t_{bc}\), \(t_d = t_e = t_{de}\)
\[
\frac{dT}{dx} = n_h(5T_2 - t_1 - 2t_{bc} - 2t_d) = \alpha_1C_1 + \alpha_2C_2 \quad (3.19)
\]

and if we subtract eq. (3.4a) from eq. (3.4c) we obtain

\[
\frac{dt_a - dt_c}{t_a - t_c} = -\frac{Ua}{C_c} \, dx = -n_c \, dx
\]

which can be integrated using \(C_3\) as the constant of integration

\[
t_a - t_c = C_3 e^{-n_c x}
\]

At \(x = 0\) where \(t_a = t_1\) and \(t_c = t_{bc}\)

\[
t_1 - t_{bc} = C_3
\]

or

\[
t_{bc} = t_1 - C_3
\]

In addition at \(x = L\), \(t_a = t_{ab}\) and \(t_c = t_{cd}\) so that

\[
t_{ab} - t_{cd} = C_3 e^{-n_c L}
\]

or

\[
C_3 = \frac{t_{ab} - t_{cd}}{e^{-n_c L}} = (t_{ab} - t_{cd}) e^{n_c L}
\]

This gives a relationship between \(t_{ab}\) and \(t_{bc}\)

\[
t_{bc} = t_1 - (t_{ab} - t_{cd}) e^{N_c} \quad (3.20)
\]
where \( N_c = n_c L \) can be considered as the total number of transfer units for the cold side.

The same procedure may be employed to find \( t_{de} \).

Subtract eq. (3.4c) from eq. (3.4e)

\[
\frac{dt_c - dt_e}{t_c - t_e} = -\frac{Ua}{C_c} \, dx = -n_c \, dx
\]

and by integration

\[ t_c - t_e = C_4 e^{-n_c x} \]

At \( x = 0 \) where \( t_c = t_{bc} \) and \( t_e = t_{de} \)

\[ t_{bc} - t_{de} = C_4 \]

or

\[ t_{de} = t_{bc} - C_4 \]

At \( x = L \) where \( t_c = t_{cd} \) and \( t_e = t_2 \)

\[ t_{cd} - t_2 = C_4 e^{-n_c L} \]

and again with \( n_c L = N_c \)

\[ C_4 = (t_{cd} - t_2)^{N_c} \]

and

\[ t_{de} = t_{bc} - (t_{cd} - t_2)^{N_c} \]  \hspace{2cm} (3.21)
As before substract eq. (3.4b) from eq. (3.4d)

\[
\frac{dt_b - dt_d}{t_b - t_d} = \frac{U_a}{C_c} dx = n_c dx
\]

and by integrating find that

\[t_b - t_d = C_5 e^{n_c x}\]

at \(x = 0\), \(t_b = t_{bc}\) and \(t_d = t_{de}\) so that

\[t_{bc} - t_{de} = C_5\]

and at \(x = L\), \(t_b = t_{ab}\) and \(t_d = t_{cd}\). This shows that

\[t_{ab} - t_{cd} = C_5 e^{n_c L}\]

and

\[t_{cd} = t_{ab} - (t_{bc} - t_{de}) e^{n_c N_c}\]  \hfill (3.22)

where \(N_c = n_c L\).

Return to eq. (3.18) and look at the conditions at \(x = L\)

where \(t_a = t_b = t_{ab}\), \(t_c = t_d = t_{cd}\), \(t_e = t_2\) and \(T = T_1\).

These conditions in eq. (3.18) give

\[n_h(5T_1 - 2t_{ab} - 2t_{cd} - t_2) = a_1 C_1 e^{a_1 L} + a_2 C_2 e^{a_2 L}\]  \hfill (3.23)

where again we remember that \(C_1\) and \(C_2\) are known constants.

Now with four equations, eq. (3.20), eq. (3.21), eq. (3.22), and eq. (3.23) and four unknown variables we
can solve for the four variables, $t_{ab}$, $t_{bc}$, $t_{cd}$, and $t_e$. Cramer's rule will be used to solve for two of them; $t_{bc}$ and $t_{de}$.

First arrange eqs. (3.20) to (3.23) in standard form with the unknowns appearing in columns.

\[
\begin{align*}
t_{ab} + t_{bc}e^{-Nc} - t_{cd} &= t_1e^{-Nc} \\
-t_{bc} + t_{cd}e^{Nc} + t_{de} &= t_2e^{Nc} \\
t_{ab} - t_{bc} + t_{cd} + t_{de} &= 0 \\
t_{ab} + t_{cd} &= \beta
\end{align*}
\]

where $\beta = 1/2(5T_1 - t_2 - \frac{1}{n_h}(a_1C_1e^{\alpha_1L} + a_2C_2e^{\alpha_2L}))$

If

\[
AX = B = \begin{bmatrix}
1 & e^{-Nc} & -1 & 0 \\
0 & -1 & e^{Nc} & 1 \\
1 & e^{Nc} & -1 & e^{Nc} \\
1 & 0 & 1 & 0
\end{bmatrix}
\]

The solution for $t_{bc}$ and $t_{de}$ is

\[
t_{bc} = \frac{\det A_{bc}}{\det A}, \quad t_{de} = \frac{\det A_{de}}{\det A}
\]
where, $A_{bc}$ and $A_{de}$ are the matrices obtained by replacing the entries in the second and fourth columns of $A$ by the entries in matrix $B$.

Compute the determinant, $\det A$ of matrix $A$ (the matrix of coefficients)

\[
\begin{vmatrix}
1 & e^{-Nc} & -1 & 0 \\
0 & -1 & e^{Nc} & 1 \\
1 & e^{Nc} & -1 & e^{Nc} \\
1 & 0 & 1 & 0
\end{vmatrix}
\]

\[
\det A = -(e^{Nc} + 2e^{-Nc})
\]

Since $\det A \neq 0$, the system should have a unique solution. Continue by computing $\det A_{bc}$ and $\det A_{de}$. Thus

\[
\begin{vmatrix}
1 & t_1e^{-Nc} & -1 & 0 \\
0 & t_2e^{Nc} & e^{Nc} & 1 \\
1 & 0 & -1 & e^{Nc} \\
1 & \beta & 1 & 0
\end{vmatrix}
\]

\[
= e^{2Nc}(\beta - 2t_2) - t_1(e^{Nc} + 2e^{-Nc})
\]
and

\[
\begin{vmatrix}
1 & e^{-Nc} & -1 & t_1 e^{-Nc} \\
0 & -1 & e^{Nc} & t_2 e^{Nc} \\
1 & -e^{Nc} & -1 & 0 \\
1 & 0 & 1 & \beta
\end{vmatrix}
\]

\[= (e^{2Nc} + 1)(\beta - 2t_2) - t_1(e^{Nc} + 2e^{-Nc})\]

Therefore

\[
t_{bc} = \frac{\det A_{bc}}{\det A} = \frac{e^{2Nc}(\beta - 2t_2) - t_1(e^{Nc} + 2e^{-Nc})}{-(e^{Nc} + 2e^{-Nc})}
\]

or

\[
t_{bc} = t_1 - \frac{e^{Nc}(\beta - 2t_2)}{1 + 2e} \quad (3.24)
\]

and

\[
t_{de} = \frac{\det A_{de}}{\det A} = \frac{(e^{2Nc} + 1)(\beta - 2t_2) - t_1(e^{Nc} + 2e^{-Nc})}{-(e^{Nc} + 2e^{-Nc})}
\]

or

\[
t_{de} = t_1 - \left( \frac{(e^{2Nc} + 1)(\beta - 2t_2)}{e^{Nc} + 2e^{-Nc}} \right) \quad (3.25)
\]
Then with eq. (3.24) and (3.25) in eq. (3.19) and some algebraic manipulation

\[ a_1C_1 + a_2C_2 = n_h\left(5(T_2 - t_1) + 2\left(\frac{(\beta - 2t_2)(2e^{N_c} + e^{-N_c})}{(1 + 2e^{-N_c})}\right)\right) \]

Equation (3.26) is similar to the one derived by O'Hare [Ref. 1: eq. (22)]. At this point he continued to attempt a closed form solution for \( \epsilon \) as a function of \( R \) and \( N_{tu} \). It is to be noted, however, that he was unable to obtain the solution because of the presence of terms deriving from dimensional parameters such as \( n_h \) with dimensions \( m^{-1} \) [Ref. 1: pp. 46]. Since \( n_h \) is present in eq. (3.26), it must be concluded that a further attempt at an analytic solution for the effectiveness of the 1-5 exchanger will suffer a similar fate and be also unachievable.

This conclusion should be obvious because, when dealing with an equation derived from \( n \) equations with \( n+1 \) unknowns, one cannot create an additional equation by merely multiplying one of the \( n \) equations by a constant. This leads to a linearly dependent set which has no unique solution.

Thus, after observing that O'Hare's attempt failed, this thesis, like O'Hare's, turns to a numerical analysis to achieve the requisite objective.
IV. NUMERICAL AND COMPUTER ANALYSIS

As O'Hare discovered with the 1-3 heat exchanger [Ref. 1], an analytic solution for effectiveness as a function of the capacity rate ratio, R, and \( N_{tu} \) was also unattainable for the 1-5 exchanger. Hence, an alternate approach had to be taken and this involved utilizing a finite-difference thermal analyzer combined with a linearizing scheme for the solution of a set of nonlinear algebraic equations [Ref. 14]. This thermal analyzer has been employed to provide solutions for temperature that lead to effectiveness, \( \varepsilon \), value for the 1-5:3C and 1-5:3P heat exchangers as a function of R and \( N_{tu} \).

A. THERMAL ANALYZER TVSSI

The computer program TVSSI used in the development of the \( \varepsilon = f(R, N_{tu}) \) graphs for the 1-5 heat exchanger [Ref. 1: Appendix A], was adapted from TVSS2 listed by Kern and Kraus [Ref. 14: Appendix C]. This adaptation consisted of modifying TVSS2 to compute solutions in the SI system and accept an input file specifically designed for the 1-5 heat exchanger. This program also had to be adapted to the IBM 3033 AP system. The program utilizes the Cholesky decomposition scheme, and because of the linearization of the radiation terms (not used in this study) the program is iterative.
B. DEVELOPMENT OF THE 1-5:3C AND 1-5:3P HEAT-EXCHANGER MODELS

As indicated in the foregoing, TVSSI uses an input file to generate a solution for temperatures that will lead to the sought after effectiveness as a function of R and Ntu. This input file is created by a program which requires an input of given capacity rates (hot and cold), overall coefficient, surface area and inlet stream temperatures (hot and cold) values.

This required the development of a program which created such a file. O'Hare [Ref. 1: pp. 53-55] first developed a program using the 1-4 heat exchanger that would create an input file for TVSSI. He compared the effectiveness from the computer generated results and a known analytic solution of effectiveness developed by Kraus and Kern [Ref. 8]. Once O'Hare established confidence in his results, he proceeded to develop a program which would create an input file for the 1-3 exchanger. In this study, a similar technique was used to develop a computer program for the 1-5:3C and 1-5:3P heat exchangers. These programs are called NTU53C and NTU53P (see Appendices A and B) and, in them, the following parameters and techniques were utilized.

1. 300 nodes were used.

2. The initial temperature for the computer to begin the iterative process was set at 200°C.

3. An eventual accuracy of .05 between the final and next to last iterations was used.
4. A radiation coefficient convergence factor of 0.66667 between iterations was used. This is required by the program even if radiation is not considered as a node.

5. The maximum number of iterations that the computer was allowed to perform was set at 12.

6. A damping factor of .8 was set as an initial damping based on the number of non-linear terms in all of the node equations.

With the values of $C_h$, $C_c$, $U$, $A$, $T_1$ and $t_1$ set, the input is set and an input file for TVSSI was generated. In this file all node equations and internode conductance values were determined. This program specified the nodes that interact with each other and the methods by which the thermal interaction takes place such as in the forced convection and fluid flow modes.

Both programs make use of the fact that each term in a node equation shows three things. The first is the node that is coupled for heat flow with the node in question. The second is the method of heat flow between the nodes. In this case, forced convection and fluid flow are used. Finally, the node equation shows the magnitude of the internode heat flow. Here all the pieces of information are collected and presented for use by TVSSI as an input file with all items in the proper format.

It is the output values of both NTU53C and NTU53P (a typical result is shown in Appendix C) that are used by the thermal analyzer (as an input file) to determine
the temperatures $T_2$ and $t_2$ for the specific set of given initial parameters $C_h$, $C_c$, $R$, $A$, $T_1$, and $t_1$.

C. SCOPE OF COMPUTER ANALYSIS

With the development of NTU53C and NTU53P computer programs, the files that they generated could then be used to solve for temperatures which in turn could yield effectiveness values for a given $R$ and $Ntu$. Of course, it must be realized that many computer runs are required to generate enough data to ensure confidence in the results which cover a wide range of capacity rate ratios and $Ntu$ values.

To efficiently expedite the computer task, the Multiple Virtual System (MVS) with Job Entry Subsystem and Networking (JES3) was employed. The MVS coupled with JES3 is more commonly referred to as batch processing. Based on trial and error, it was determined that in order to build a solid data base, eleven different values for effectiveness were needed to best represent a particular value of $R$. Thus, a range of $R$ from $R = 0.01$ to $1.0$ was used. Due to the enormous amount of computer time required to solve a 300 node problem, $R$ increments of $0.05$ were used for this study and this thesis reports on this basis. In all, 42 curves for both the 1-5:3C and 1-5:3P heat exchangers were required. With this change in the increments between $R$ values (O'Hare's work showed that an increment in $R$ of $0.01$ was not necessary), a linear interpolation was found to be acceptable to less than $0.02$ percent error.

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TVSSI was slightly modified in accordance with the appropriate guidelines of the job control language (JCL) needed to run on the batch processing system. These modifications were few and were needed only at the beginning and end of TVSSI. The modified version of TVSSI has been called TVCOUNT with changes shown in [Ref. 1: Appendix F]. It was TVCOUNT that was then used to activate TVSSI.

It also became necessary to modify the two input file programs NTU53P and NTU53C so that they needed to be compiled only once. They were then loaded in a library file to be used when called by another program. New programs utilizing the batch system were written that could easily be loaded with the appropriate input data for a specific R value. These, which are referred to as "sister programs," were used to go from the library file to TVSSI and cause TVSSI to be executed eleven times under TVCOUNT covering the desired range of Ntu for a specific R value. The modified input files and their associated "sister execution programs are found in Appendices D through G.

A flow chart of how all of the foregoing is accomplished is provided by O'Hare [Ref. 1: Figures 4.4 and 4.5]. It is noted that in these figures, TVSSI is referred to as TVSSIA through TVSSIV. These are the same programs as TVSSI but for bookkeeping purposes by the computer they are labeled A through V.
D. INTERPRETATION OF GRAPHS

Once all the data had been collected and the effectiveness for a given $R$ and $N_{tu}$ values had been computed, plots of effectiveness as a function of $N_{tu}$ for the entire range of $R$ values were plotted for both parallel and counterflow heat exchangers. These plots are shown in Appendices H and I.

It may be observed that for a particular value of $R$, the plot of effectiveness as a function of $N_{tu}$ indicates that the 1:5-3C exchanger outperforms the 1-4, 1-3:2P and the 1-5:3P exchangers but not the 1-3:2C exchanger. This may be explained by the quite apparent fact that the 1-5:3C exchanger has one more counterflow pass than the 1-4 exchanger. Indeed, this argument can be extended to the fact that the 1-5:3C has one more parallel flow pass than the 1-3:2C. Figure 4.1. displays the graphical picture to support this contention.
Figure 4.1 Comparison of Analytical (1-4) and Computer Results (1-3:2C and 1-3:2P) to Computer Results (1-5:3C and 1-5:3P) at R = 0.5
V. POLYNOMIAL REGRESSION

A. DEVELOPMENT OF POLYNOMIAL EQUATIONS

The empirical data obtained for the two 1-5 heat exchangers was designed to cover an extensive range of $R$ values varying from 0.01 to 1.0 in increments of 0.05. As discussed earlier in Section IV, the data obtained at a specific value of $R$ is the computer evaluated result of the effectiveness, for an associated $N_{tu}$ value. With this accomplished, it then becomes possible to graph separate curves for each of the different $R$ values as shown in Appendices H and I. Through a polynomial regression technique, as discussed in this section, it is also possible to develop implicit equations for the curves with $\epsilon = f(N_{tu}, R)$. It is also apparent from an inspection of the graphical representation of the empirical data in Appendices H and I, that the curves conform to a high degree polynomial. However, further analytical investigation is needed to ascertain the exact order of the polynomial terms. This investigation will not only lead to the order of the polynomial, but to the specific equation for each curve.

By use of polynomial regression, the least-squares method can be readily extended to best fit the data to the $m$th-degree for the polynomial

$$y = A_0 + A_1x + A_2x^2 + \ldots + A_mx^m \quad (5.1)$$
with the error defined by

\[ e_i = D_i - y_i = D_i - A_0 - A_1 x_i - A_2 x_i^2 - ... - A_m x_i^m \]

where \( D_i \) represents the empirical data value corresponding to \( x_i \), \( x_i \) being free of error.

The objective is to minimize the sum of the squares of the residuals, \( S_r \),

\[ S_r = \sum_{i=1}^{m} e_i^2 = \sum_{i=1}^{m} (D_i - A_0 - A_1 x_i - A_2 x_i^2 - ... - A_m x_i^m)^2 \]  

(5.2)

Because at a minimum, the partial derivatives \( \frac{\partial S_r}{\partial A_0} \), \( \frac{\partial S_r}{\partial A_1} \) ... \( \frac{\partial S_r}{\partial A_m} \) vanish, after taking the derivative of \( S_r \) with respect to each of the coefficients of the polynomial, it can be seen that

\[ \frac{\partial S_r}{\partial A_0} = 0 = -2 \sum e_i (D_i - A_0 - A_1 x_i - A_2 x_i^2 - ... - A_m x_i^m) \]

\[ \frac{\partial S_r}{\partial A_1} = 0 = -2 \sum x_i e_i (D_i - A_0 - A_1 x_i - A_2 x_i^2 - ... - A_m x_i^m) \]

\[ \frac{\partial S_r}{\partial A_2} = 0 = -2 \sum x_i^2 e_i (D_i - A_0 - A_1 x_i - A_2 x_i^2 - ... - A_m x_i^m) \]

\[ \vdots \]

\[ \frac{\partial S_r}{\partial A_m} = 0 = -2 \sum x_i^m e_i (D_i - A_0 - A_1 x_i - A_2 x_i^2 - ... - A_m x_i^m) \]
Then by dividing by -2 and rearranging we obtain

\[A_0 N + A_1 \sum x_i + A_1 x_i^2 + \ldots + A_m \sum x_i^m = \sum D_i\]
\[A_0 \sum x_i + A_1 \sum x_i^2 + A_2 \sum x_i^3 + \ldots + A_m \sum x_i^{m+1} = \sum x_i D_i\]
\[A_0 \sum x_i^2 + A_1 \sum x_i^3 + A_2 \sum x_i^4 + \ldots + A_m \sum x_i^{m+2} = \sum x_i^2 D_i\]
\[\ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \]
\[A_0 \sum x_i^m + A_1 \sum x_i^{m+1} + A_2 \sum x_i^{m+2} + \ldots + A_m \sum x_i^{2m} = \sum x_i^{m+1} D_i\]

where all summations are from \(i=1\) through \(n\). All of the foregoing \(m+1\) equations are linear and have \(m+1\) unknowns: \(A_0, A_1, A_2, \ldots, A_m\). The coefficients of the unknowns can be calculated directly from the observed data. Thus, the problem of determining a least-squares polynomial of degree \(m\) is equivalent to solving a system of \(m+1\) simultaneous linear equations. Putting the equations in matrix form yields

\[
\begin{bmatrix}
N & \sum x_i & \sum x_i^2 & \sum x_i^3 & \ldots & \sum x_i^m \\
\sum x_i & \sum x_i^2 & \sum x_i^3 & \sum x_i^4 & \ldots & \sum x_i^{m+1} \\
\sum x_i^2 & \sum x_i^3 & \sum x_i^4 & \sum x_i^5 & \ldots & \sum x_i^{m+2} \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
\sum x_i^m & \sum x_i^{m+1} & \sum x_i^{m+2} & \sum x_i^{m+3} & \ldots & \sum x_i^{2m}
\end{bmatrix}
\begin{bmatrix}
A_0 \\
A_1 \\
A_2 \\
\vdots \\
A_m
\end{bmatrix} =
\begin{bmatrix}
\sum D_i \\
\sum x_i D_i \\
\sum x_i^2 D_i \\
\vdots \\
\sum x_i^{m+1} D_i
\end{bmatrix}
\]

[Ref. 15: pp. 302-309 and Ref. 16: 468-474].
From this point on, one finds that it is best to use a computer to assist in solving the simultaneous equations and this will also help alleviate any ill-conditioning that may otherwise occur. An existing "curvefit" program available through NON-IMSL [Ref. 16] was used although some modifications were made to the original program to best accommodate the goals of this work.

To determine the order of polynomial that should eventually be used, one increases the degree of the approximating polynomial as long as there is a statistically significant decrease in the variance $\sigma^2$, which is computed by

$$
\sigma^2 = \frac{\sum e_i^2}{N - m - 1}
$$

(5.3)

In other words, the selection of the optimum degree polynomial is contingent upon a decreasing variance and once the variance begins to increase, the degree of the polynomial becomes too high. For all cases, it was found that the $\epsilon - N_{tu}$ developed curves are of the 5th order.

As shown in Figures 5.1 and 5.2 the computed values of effectiveness vs. $N_{tu}$ for $R = 0.1, 0.5$ and $1.0$ for both flow arrangements, (1-5:3P) and (1-5:3C), have been graphed and fitted by a 5th degree polynomial. Because all computed values for effectiveness follow a predictable trend, only a sample of the data covering the whole range of
Figure 5.1 1-5:3C Data Fit by a 5th Order Polynomial
Figure 5.2 1-5:3P Data Fit by a 5th Order Polynomial
values of R have been shown. It is clear that the graphical interpretation strongly backs what is known numerically from the polynomial regression technique. Thus, the relationship for $\varepsilon = f(N_{tu}, R)$ can be found explicitly from

$$\varepsilon = A_5 N_{tu}^5 + A_4 N_{tu}^4 + A_3 N_{tu}^3 + A_2 N_{tu}^2 + A_1 N_{tu} + A_0$$  \hspace{1cm} (5.4)

where the coefficients $A_5$, $A_4$, $A_3$, $A_2$, $A_1$, and $A_0$ relating to a specific value of R are found in Tables 1 and 2 for the (1-5:3C) and (1-5:3P) configurations.

In order to better utilize the coefficients found in Tables 1 and 2, an interactive program has been developed using equation (5.4) and the 1-5 heat exchanger polynomial approximation coefficients. This program was written for the IBM 3033 using the FORTRAN VS compiler (See Appendix J). By entering the values for NTU, R and the type of heat exchanger the effectiveness values are readily obtained directly or by linear interpolation.

An example of how to work with the effectiveness by using the Equation (5.4) follows.

B. NUMERICAL EXAMPLE

1. Statement of Problem

A 1-5:3C heat exchanger uses sea water ($C_p = 4.045 \text{ kJ/kg}^\circ\text{C}$) at an initial temperature of 20°C to cool engine oil, flowing at 200 kg/s from 60°C to 40°C. The sea water flow rate is 80 kg/s. If the overall heat transfer
coefficient is 40 W/m²°C, how much surface area is required in the exchanger?

2. **Solution**

At an average oil temperature of 50°C, the specific heat is \( C_p = 2.004 \text{ kJ/kg-°C} \) and an energy balance gives

\[
(WC_p \Delta T)_{\text{sea water}} = (WC_p \Delta T)_{\text{engine oil}}
\]

\[
(80 \text{ kg/s})(4.045 \text{ kJ/kg-°C})(t_2 - 20)°C
\]

\[
= (200 \text{ kg/s})(2.004 \text{ kJ/kg-°C})(60 - 40)°C
\]

\[
t_2 = 20 + \frac{200(2.004)(20)}{10(4.045)} = 44.8°C
\]

The number of transfer units is given by \( N_{tu} = \frac{UA}{C_{\min}} \). To determine \( C_{\min} \) we must compare the products of mass-flow rate and specific heat for sea water and oil.

\[
(WC_p)_{\text{sw}} = (80 \text{ kg/s})(4.045 \text{ kJ/kg-°C})
\]

\[
= 323.6 \text{ kW/°C}
\]

\[
(WC_p)_{\text{oil}} = (200 \text{ kg/s})(2.004 \text{ kJ/kg-°C})
\]

\[
= 400.8 \text{ kW/°C}
\]

Therefore \( C_{\min} = 323.6 \text{ kW/°C} \).

The effectiveness is a function of \( R \) and \( N_{tu} \). The capacity rate ratio, \( R \), is
\[ R = \frac{C_{\text{min}}}{C_{\text{max}}} = \frac{323.6}{400.8} = 0.8074 \]

Because \( C_C = C_{\text{min}} \), the required effectiveness is

\[ \frac{t_2 - t_1}{T_1 - t_1} = \frac{44.8 - 20}{60 - 20} = 0.6193 \]

We must now go to Table 1 for the 1-5:3C arrangement with \( R = 0.8 \) and \( R = 0.85 \) and find the coefficients

For \( R = 0.8 \):

- \( A_0 = 3.63419 \times 10^{-3} \)
- \( A_1 = 0.93822 \)
- \( A_2 = -0.67053 \)
- \( A_3 = 0.27531 \)
- \( A_4 = -0.60558 \times 10^{-1} \)
- \( A_5 = 0.54393 \times 10^{-2} \)

For \( R = 0.85 \):

- \( A_0 = 3.82659 \times 10^{-3} \)
- \( A_1 = 0.93407 \)
- \( A_2 = -0.67841 \)
- \( A_3 = 0.28109 \)
- \( A_4 = -0.62088 \times 10^{-1} \)
- \( A_5 = 0.55850 \times 10^{-2} \)

A trial and error solution (assuming values of \( N_{tu} \) and by interpolating) gives a result

\[ N_{tu} = 2.352 \]

for which

\[ A = N_{tu} \frac{C_{\text{min}}}{U} \]

\[ A = 19.03 \text{ m}^2 \]
3. Observations

The primary observation made here is that by using the 5th order polynomial equation with the appropriate coefficients found in Table 1 or 2, an accurate value for effectiveness can be found thus allowing one to solve for a wide variety of heat exchanger parameters.

By comparing the value for effectiveness just computed with that of the 1-5:3P, 1-3:2P [Ref. 1] and 1-4 to 1-12 even pass exchangers [Ref. 8], the 1-5:3C has a higher effectiveness than all (see Table 3).

From this observation it is evident that the 1-5:3C exchanger outperforms not only the 1-4 to 1-12 even pass arrangements but also its counterpart, the 1-5:3P exchanger for these given values by at least 0.614%.
<table>
<thead>
<tr>
<th>R</th>
<th>(A_0 \times 10^3)</th>
<th>(A_1)</th>
<th>(A_2)</th>
<th>(A_3)</th>
<th>(A_4 \times 10^1)</th>
<th>(A_5 \times 10^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.01</td>
<td>0.57463</td>
<td>0.99093</td>
<td>-0.47938</td>
<td>0.13879</td>
<td>-0.23075</td>
<td>0.16779</td>
</tr>
<tr>
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<td>0.14654</td>
<td>-0.25068</td>
<td>0.18647</td>
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</tr>
<tr>
<td>.15</td>
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<td>0.98238</td>
<td>-0.52072</td>
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<td>-0.30947</td>
<td>0.24635</td>
</tr>
<tr>
<td>.20</td>
<td>1.42506</td>
<td>0.97866</td>
<td>-0.53259</td>
<td>0.17545</td>
<td>-0.32772</td>
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</tr>
<tr>
<td>.25</td>
<td>1.33145</td>
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<td>0.28213</td>
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</tr>
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<td>0.21718</td>
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<td>0.38122</td>
</tr>
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</tr>
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<td>0.54393</td>
</tr>
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<td>0.55850</td>
</tr>
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TABLE 1 (cont'd)
1-5:3C COEFFICIENTS

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<th>R</th>
<th>$A_0 \times 10^3$</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4 \times 10^1$</th>
<th>$A_5 \times 10^2$</th>
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<td>-0.70365</td>
<td>0.30046</td>
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</tr>
<tr>
<td>R</td>
<td>A₀ x 10³</td>
<td>A₁</td>
<td>A₂</td>
<td>A₃</td>
<td>A₄ x 10¹</td>
<td>A₅ x 10²</td>
</tr>
<tr>
<td>-----</td>
<td>----------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
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<td>-0.23283</td>
<td>0.16989</td>
</tr>
<tr>
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</tr>
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<td>0.98309</td>
<td>-0.52246</td>
<td>0.16811</td>
<td>-0.30968</td>
<td>0.24604</td>
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<td>0.17485</td>
<td>-0.32443</td>
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</tr>
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<td>-0.54593</td>
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</tr>
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<td>A₄ x 10^1</td>
<td>A₅ x 10²</td>
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</tr>
</tbody>
</table>
# Table 3

**Comparison of Example Results**

For \( Ntu = 2.352 \) and \( R = 0.8074 \)

<table>
<thead>
<tr>
<th>Number of Tube Passes</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:2P</td>
<td>.5990</td>
</tr>
<tr>
<td>4</td>
<td>.6155</td>
</tr>
<tr>
<td>5:3C</td>
<td>.6193</td>
</tr>
<tr>
<td>5:3P</td>
<td>.6067</td>
</tr>
<tr>
<td>6</td>
<td>.6145</td>
</tr>
<tr>
<td>8</td>
<td>.6141</td>
</tr>
<tr>
<td>10</td>
<td>.6140</td>
</tr>
<tr>
<td>12</td>
<td>.6139</td>
</tr>
</tbody>
</table>
VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The objective of this thesis was to provide effectiveness values for the 1-5:3C and 1-5:3P heat exchangers. Although these objectives were analytically unachievable, they became attainable through a fifth order polynomial approximation from numerical data. The data obtained covers a wide range of capacity rate ratios for values of $N_{tu}$ from 0 to 3.25. With the knowledge of the 1-5 heat exchanger type (1-5:3C or 1-5:3P), size (surface area), the overall heat transfer coefficient and the fluid flow rates, the $N_{tu}$ and capacity rate ratios may be computed and the exchanger effectiveness may then be determined from the appropriate coefficient tables or the effectiveness program provided.

It is indeed obvious that the effectiveness parameter is most useful in performance estimation and analysis for all types of heat exchangers. The work done here pertaining to the 1-5 exchanger is very helpful in constructing a comprehensive picture of the performance attainable for the 1-2 consecutively through the 1-6 for a diverse range of known conditions.
B. RECOMMENDATIONS

With proof in this thesis, and that of O'Hare [Ref. 1], that an odd number of tube passes per shell has a slightly better effectiveness when more than half the tube fluid flows in counterflow to the shell fluid, it is recommended that a feasibility study be conducted with regard to the structural and thermal problems that may arise in manufacturing and designing such heat exchangers.
APPENDIX A

NTU53C COMPUTER GENERATED INPUT ANALYZER PROGRAM

THIS IS PROGRAM NTU53C

IT GENERATES AN INPUT FILE FOR THERMAL ANALYZER TO OBTAIN
1-5 EFFECTIVENESS-NTU RELATIONSHIP THAT IS NOT AVAILABLE IN
OPEN LITERATURE (3C MEANING TWO PARALLEL PASS AND THREE
COUNTERFLOW PASSES).

DIMENSION COEF(300,6),KCON(300,6),L1(8),L2(3),L3(6),SET2(2),FL4(4)

CHARACTER *79 TITLE
CHARACTER *12 FNAME

DATA IOT,IN,IPR,IWR/6,5,4,8/

OPEN PRINTER OUTPUT FILE

OPEN( IPR, FILE= 'PRN', STATUS= 'NEW', FORM= 'FORMATTED', IOSTAT= ICK)
IF( ICK. NE. 0) WRITE(IOT,920)
920 FORMAT(' Trouble opening printer output file' )

WRITE(IOT,917)
917 FORMAT(/ ' Input the title of this study - 79 columns only. ',
& ' This title will appear',/ , ' at the top of every printed page',
& ' of output: ' )
READ(IN,918) TITLE
918 FORMAT(A79)

WRITE(IOT,901)
901 FORMAT(/ ' INPUT HOT SIDE CAPACITY RATE:' )
READ(IN,902) CHOT
902 FORMAT(BN,F10.0)

WRITE(IOT,903)
903 FORMAT(/ ' INPUT COLD SIDE CAPACITY RATE:' )
READ(IN,902) CCLD

WRITE(IOT,904)
904 FORMAT(/ ' INPUT OVERALL HEAT TRANSFER COEFFICIENT:' )
READ(IN,902) U

WRITE(IOT,905)
905 FORMAT(/' INPUT TOTAL HEAT TRANSFER SURFACE:')
READ(IN,902) SURFTO
C
WRITE(IOT,906)
906 FORMAT(/' INPUT HOT SIDE INLET TEMPERATURE:')
READ(IN,902) THOTIN
C
WRITE(IOT,907)
907 FORMAT(/' INPUT COLD SIDE INLET TEMPERATURE:')
READ(IN,902) TCLDIN
C
VALK1 = CHOT
VALK2 = CCLD
VALK3 = U*SURFTO/250.
TINIT = 125.
C
FRONT END
C
L1(1) = 300
L1(2) = 2
DO 10 I=3,8
10 L1(I) = 0
C
DO 20 I=1,3
20 L2(I) = 0
C
L3(1) = 300
L3(2) = 50
L3(3) = 6
L3(4) = 2
L3(5) = 4
L3(6) = 6
C
FL4(1) = .05
FL4(2) = .66667
FL4(3) = .8
FL4(4) = TINIT
L4 = 12
C
CONSTANT TEMPERATURES
C
SET2(1) = THOTIN
SET2(2) = TCLDIN
C
READY FOR INPUT SET 4
C
NODE 1
C
KCON(1,1) = 1004
KCON(1,2) = 1014
KCON(1,3) = 2004
KCON(1,4) = 2014
KCON(1,5) = 3004
KCON(1,6) = 3015
COEF(1,6) = VALK1

DO 50 I = 1,5
50 COEF(1,I) = VALK3

NODES 2 TO 50

DO 75 I = 2,50
   J = 101 - I
   K = 100 + I
   L = 201 - I
   N = I - 1
   M = 200 + I
   MM = 300 - I
   KCON(I,1) = 10*N + 5
   KCON(I,2) = 10*K + 4
   KCON(I,3) = 10*L + 4
   KCON(I,4) = 10*M + 4
   KCON(I,6) = 10*MM + 4
   COEF(I,1) = VALK1
   COEF(I,2) = VALK3
75 CONTINUE

NODE 51

KCON(51,1) = 3025
KCON(51,2) = 504
COEF(51,1) = VALK2
COEF(51,2) = VALK3

NODES 52 TO 300

DO 120 I = 52,300
   K = I - 1
   IF(I.GT.100) GO TO 122
   L = I - 50
   M = 2*L - 1
   J = I - M
   GO TO 135
122 IF(I.GT.150) GO TO 124
   J = I - 100
   GO TO 135
124 IF(I.GT.200) GO TO 126
   L = I - 150
   GO TO 135
M = 2*L - 1
N = M + 100
J = I - N
GO TO 135
126 IF(I.GT.250) GO TO 128
   J = I - 200
   GO TO 135
128 L = I - 250
   M = 2*L - 1
   N = M + 200
   J = I - N
135 KCON(I,1) = 10*I + 4
   KCON(I,2) = 10*K + 5
   COEF(I,1) = VALK3
   COEF(I,2) = VALK2

END OF DATA SETUP
NOW CREATE INPUT FOR ANALYZER

WRITE(IOT,922)
922 FORMAT(/'ENTER NAME OF INPUT FILE, INCLUDING DRIVE',
&' DESIGNATION: ')
READ(IN,923) FNAME
923 FORMAT(A12)

OPEN INPUT FILE
OPEN(IWR,FILE=FNAME,S,ATUS='NEW',FORM='FORMATTED',IOSTAT=ICK)
   IF(ICK.GT.0) WRITE(IOT,924)
924 FORMAT(/' Trouble opening input file')

WRITE(IOT,925) FNAME
WRITE(IOT,925)
925 FORMAT(/' WRITING FILE : A14',)
925 FORMAT(/' WRITING FILE : TVSS1')
WRITE(IWR,919) TITLE
919 FORMAT(IX,A79)
WRITE(IWR,908)(L1(I),I=1,8)
908 FORMAT(14)
WRITE(IWR,908)(L2(I),I=1,3)
WRITE(IWR,908)(L3(I),I=1,6)
WRITE(IWR,911) FL4(1),FL4(2),L4,FL4(3),FL4(4)
911 FORMAT(F8.3,F8.5,F8.5,F8.5)
WRITE(IWR,912) SET2(1),SET2(2)
912 FORMAT(2F8.0)

DO 200 I = 1,50
   WRITE(IWR,913)(KCON(I,J),J=1,6)
913 FORMAT(9I8)
   WRITE(IWR,914)(COEF(I,J),J=1,6)
914  FORMAT(6F8.4)
200  CONTINUE
C
   DO 250 I=51,300
      WRITE(IWR,913) KCON(I,1),KCON(I,2)
      WRITE(IWR,914) COEF(I,1),COEF(I,2)
250  CONTINUE
C
   CLOSE(IWR,IOSTAT=ICK)
   IF(ICK.NE.0) WRITE(IOT,921) EE
921  FORMAT( ' Trouble closing printer output file' )
C
   STOP
   END
APPENDIX B
NTU53P COMPUTER GENERATED INPUT ANALYZER PROGRAM

THIS IS PROGRAM NTU53P
IT GENERATES AN INPUT FILE FOR THERMAL ANALYZER TO OBTAIN
L-5 EFFECTIVENESS-NTU RELATIONSHIP THAT IS NOT AVAILABLE IN
OPEN LITERATURE (3P MEANING THREE PARALLEL PASSES AND ONE
COUNTERFLOW PASS).

DIMENSION COEF(300,6),KCON(300,6),L1(8),L2(3),L3(6),SET2(2),FL4(4)

CHARACTER *79 TITLE
CHARACTER *12 FNAME

DATA IOT,IN,IPR,IWR/6,5,4,8/

OPEN PRINTER OUTPUT FILE
OPEN(IPR,FILE='PRN',STATUS='NEW',FORM='FORMATTED',IOSTAT=ICK)
IF(ICK.NE.0) WRITE(IOT,920)

920 FORMAT(' Trouble opening printer output file' )

WRITE(IOT,917)

917 FORMAT(/' Input the title of this study - 79 columns only. ',
& ' This title will appear', '/', ' at the top of every printed page',
& ' of output: ') READ(IN,918) TITLE

WRITE(IOT,918)

918 FORMAT(A79)

WRITE(IOT,901)

901 FORMAT('/ INPUT HOT SIDE CAPACITY RATE: '
READ(IN,902) CHOT

WRITE(IOT,902)

902 FORMAT(BN,F10.0)

WRITE(IOT,903)

903 FORMAT('/ INPUT COLD SIDE CAPACITY RATE: '
READ(IN,902) CCILD

WRITE(IOT,904)

904 FORMAT('/ INPUT OVERALL HEAT TRANSFER COEFFICIENT: '
READ(IN,902) U

WRITE(IOT,905)
905 FORMAT(/' INPUT TOTAL HEAT TRANSFER SURFACE: '/)
READ(IN,902) SURFTO
C
906 FORMAT(/' INPUT HOT SIDE INLET TEMPERATURE: '/)
READ(IN,902) THOTIN
C
907 FORMAT(/' INPUT COLD SIDE INLET TEMPERATURE: '/)
READ(IN,902) TCLDIN
C
VALK1 = CHOT
VALK2 = CCLD
VALK3 = SURFTO/250.
TINIT = 125.

C FRONT END
C
L1(1) = 300
L1(2) = 2
10 L1(I) = 0
C
DO 20 I = 1,3
20 L2(I) = 0
C
L3(1) = 300
L3(2) = 50
L3(3) = 6
L3(4) = 4
L3(6) = 6
C
FL4(1) = .05
FL4(2) = .66667
FL4(3) = .8
FL4(4) = TINIT
L4 = 12

C CONSTANT TEMPERATURES
C
SET2(1) = THOTIN
SET2(2) = TCLDIN
C
READY FOR INPUT SET 4
C
NODE 1
C
KCON(1,1) = 514
KCON(1,2) = 1504
KCON(1,3) = 1514
KCON(1,4) = 2504
KCON(1,5) = 2514
KCON(1,6) = 3015
COEF(1,6) = VALK1
DO 50 I = 1,5
   50 COEF(I,I) = VALK3

NODGES 2 TO 50
   DO 75 I = 2,50
      J = I + 50
      K = 151 - I
      L = 150 + I
      N = I - 1
      M = 251 - I
      MM = 250 + I
      KCON(I,1) = 10*N + 5
      KCON(I,2) = 10*J + 4
      KCON(I,3) = 10*K + 4
      KCON(I,4) = 10*L + 4
      KCON(I,5) = 10*MM + 4
      COEF(I,I) = VALK1
   DO 80 II = 2,6
      COEF(I,II) = VALK3
   80 CONTINUE
75 CONTINUE

NODE 51
   KCON(51,1) = 3025
   KCON(51,2) = 14
   COEF(51,1) = VALK2
   COEF(51,2) = VALK3

NODGES 52 TO 300
   DO 120 I = 52,300
      K = I - 1
      IF(I.GT.100) GO TO 122
      J = I - 50
      GO TO 135
   122 IF(I.GT.150) GO TO 124
      L = I - 100
      M = 2*L - 1
      N = M + 50
      J = I - N
      GO TO 135
   124 IF(I.GT.200) GO TO 126
J = I - 150
GO TO 139
126 IF(I.GT.250) GO TO 128
L = I - 200
M = 2*X*L - 1
N=M+150
J = I - N
GO TO 135
128 J = I - 250
135 KCON(I,1) = 10*X + 4
KCON(I,2) = 10*K + 5
COEF(I,1) = VALK3
120 COEF(I,2) = VALK2

C END OF DATA SETUP
C NOW CREATE INPUT FOR ANALYZER
C
WRITE(IOT,922)
922 FORMAT(/' Enter name of input file, including drive',
& ' DESIGNATION: ') READ(IN,923) FNAME
923 FORMAT(A12)

C OPEN INPUT FILE
C
OPEN(IWR,FILE=FNAME,STATUS='NEW',FORM='FORMATTED',IOSTAT=ICK)
IF(ICK.GT.0)WRITE(IOT,924)
924 FORMAT(/' Trouble opening input file'

C WRITE(IOT,925) FNAME
925 FORMAT(/' Writing file : ',A14)
WRITE(IWR,919) TITLE
919 FORMAT(A14)
WRITE(IWR,908)(L1(I),I=1,8)
908 FORMAT(9I4)
WRITE(IWR,908)(L2(I),I=1,3)
WRITE(IWR,908)(L3(I),I=1,6)
WRITE(IWR,911)(FL4(I),FL4(2),L4,FL4(3),FL4(4))
911 FORMAT(F8.3,F8.5,F8.5,F8.2)
WRITE(IWR,912) SET2(1),SET2(2)
912 FORMAT(2F8.0)

C DO 200 I = 1,50
WRITE(IWR,913)(KCON(I,J),J=1,6)
913 FORMAT(9F8.1)
WRITE(IWR,914)(COEF(I,J),J=1,6)
914 FORMAT(6F8.4)
200 CONTINUE

C DO 250 I=51,300
WRITE(IWR,913) KCON(I,1),KCON(I,2)
WRITE(IWR,914) COEF(I,1),COEF(I,2)
250 CONTINUE

CLOSE(IWR,IOSTAT=ICK)
IF(ICK.NE.0) WRITE(IOT,921)EE

921 FORMAT(' Trouble closing printer output file' )

STOP
END
# APPENDIX C

## SAMPLE OUTPUT FROM NTU53C COMPUTER INPUT ANALYZER PROGRAM

\[ R = 0.5 \quad NTU = 1.0 \]

<table>
<thead>
<tr>
<th>Value</th>
<th>0.0500</th>
<th>0.6667</th>
<th>1.2400</th>
<th>1.2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>300</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>200</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>100</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

| 250.0000  | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 225.0000  | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 200.0000  | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 175.0000  | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 150.0000  | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 125.0000  | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 100.0000  | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 75.0000   | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 50.0000   | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 25.0000   | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 0         | 0.5000 | 0.5000 | 0.5000 | 0.5000 |

\[ \text{with Column Labels: } 0, 6, 2, 4, 6, 0, 0, 0, 0, 0, 0, 0 \]
APPENDIX D
MODIFIED NTU53C PROGRAM USED TO RUN ON BATCH SYSTEM

//HESS JOB (2054.0267) 'NTU53C', CLASS=B
//"MAIN ORG=NPGVM1.2054P, SYSTEM=SY2
//EXEC FORTVCL, FARM.LKED= LIST, MAP
//FORT.SYSIN DD "
C
C THIS IS PROGRAM NTU53C
C
IT GENERATES AN INPUT FILE FOR THERMAL ANALYZER TO OBTAIN
1-5 EFFECTIVENESS-NTU RELATIONSHIP THAT IS NOT AVAILABLE IN
OPEN LITERATURE (3C MEANING TWO PARALLEL PASS AND THREE
COUNTERFLOW PASSES).
C
INTEGER Q, P
DIMENSION COEF(300,6), KCON(300,6), L1(8), L2(3), L3(6), SET2(2), FL4(4)
1, CHOT(22,22), CCLD(22,22), U(22,22), SURFT0(22,22), THOTIN(22,22), TCLD
2IN(22,22), TITLE(22,22), FNAME(22,22)
C
CHARACTER *25 TITLE
CHARACTER *25 FNAME
C
DO 70 0=1,21,2
P=0+1
READ(1,900) CHOT(0,1), CCLD(0,2), U(0,3), SURFT0(0,4), THOTIN(0,5), TCL
1DIN(0,6)
900 FORMAT(2F10.0,F10.5,3F10.0)
READ(1,918) TITLE(P,1), FNAME(P,2)
918 FORMAT(2A25)
C OPEN OUTPUT FILE
C
OPEN(2,FILE=FNAME(P,2), FORM='FORMATTED')
C
VALK1 = CHOT(0,1)
VALK2 = CCLD(0,2)
VALK3 = U(0,3)*SURFT0(0,4)/250.
TINIT = 125.
C
FRONT END
C
L1(1) = 300
L1(2) = 2
DO 10 1=3,8
10 L1(I) = 0
C
20 DO 20  I=1,3
   L2(I) = 0
C
   L3(1) = 300
   L3(2) = 50
   L3(3) = 2
   L3(5) = 4
   L3(6) = 6
C
   FL4(1) = .05
   FL4(2) = .66667
   FL4(3) = .8
   FL4(4) = TINIT
   L4 = 12
C
   CONSTANT TEMPERATURES
   SET2(1) = THOTIN(0.5)
   SET2(2) = TCLDIN(0;6)
C
   READY FOR INPUT SET 4
C
   NODE 1
   KCON(1,1) = 1004
   KCON(1,2) = 1014
   KCON(1,3) = 2004
   KCON(1,4) = 2014
   KCON(1,5) = 3004
   KCON(1,6) = 3015
   COEF(1,6) = VALK1
   DO 50  I = 1,5
   50  COEF(1,1) = VALK3
   NODES 2 TO 50
C
   DO 75  I = 2,50
   J = 101 - I
   K = 100 + I
   L = 201 - I
   N = I - 1
   M = 200 + I
   MM = 301 - I
   KCON(I,1) = 10*N + 5
   KCON(I,2) = 10*J + 4
   KCON(I,3) = 10*K + 4
   KCON(I,4) = 10*L + 4
   KCON(I,5) = 10*M + 4
KCON(I,6) = 10**MM + 4
COEF(I,1) = VALK1
DO 80 II = 2,6
COEF(I,II) = VALK3
80 CONTINUE
75 CONTINUE

NODE 51
KCON(51,1) = 3025
KCON(51,2) = 504
COEF(51,1) = VALK2
COEF(51,2) = VALK3

NODES 52 TO 300
DO 120 I = 52,300
K = I - I
IF(I.GT.100) GO TO 122
L = I - 50
M = 2*L - 1
J = I - M
GO TO 135
122 IF(I.GT.150) GO TO 124
J = I - 100
GO TO 135
124 IF(I.GT.200) GO TO 126
L = I - 150
M = 2*L - 1
N = M + 100
J = I - N
GO TO 135
126 IF(I.GT.250) GO TO 128
J = I - 200
GO TO 135
128 L = I - 250
M = 2*L - 1
N = M + 200
J = I - N
135 KCON(I,1) = 10**J + 4
KCON(I,2) = 10**K + 5
COEF(I,1) = VALK3
120 COEF(I,2) = VALK2

END OF DATA SETUP
NOW CREATE INPUT FOR ANALYZER

WRITE(2,919) TITLE(P,1)
919 FORMAT(1X,A25)
WRITE(2,908)(L1(I),I=1,8)
908 FORMAT(9I4)
   WRITE(2,908)(L(1),I=1,3)
   WRITE(2,908)(L(3),I=1,6)
   WRITE(2,911)FL4(1),FL4(2),L4,FL4(3),FL4(4)
911 FORMAT(F8.3,F8.5,I8,2F8.1)
   WRITE(2,912)SET2(1),SET2(2)
912 FORMAT(2F8.0)
C   DO 200 I = 1,50
   WRITE(2,913)(KCON(I,J),J=1,6)
913 FORMAT(9I8)
   WRITE(2,914)(COEF(I,J),J=1,6)
914 FORMAT(6F8.4)
200 CONTINUE

C   DO 250 I=51,300
   WRITE(2,913)KCON(I,1),KCON(I,2)
   WRITE(2,914)COEF(I,1),COEF(I,2)
250 CONTINUE

C   7 CONTINUE
   STOP
   END

//LKED.SYSLOD DD DISP=SHR,DSNAME=MSS.S2054.LOADLIB
//LKED.SYSIN DD *
   NAME NTU53C(R)
//
APPENDIX E
MASTER EXECUTION PROGRAM FOR NTU53C AND TVCOUNT

/HESS3OC JOB (2054, 0267), 'L E HESS', CLASS=P
*MAIN ORG=NPVMM1, 2054P, LINES=(5000, W)
*FORMAT PR DNAME= DEST= LOCAL
/EXEC FORTVG, PROG=NTU53C, LIB= 'MS_S2054, LOADLIB'
GO.TVSSIA DD DISP=(NEW PASS), DSN=&TVSSIA,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIB DD DISP=(NEW PASS), DSN=&TVSSIB,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIC DD DISP=(NEW PASS), DSN=&TVSSIC,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSID DD DISP=(NEW PASS), DSN=&TVSSID,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIE DD DISP=(NEW PASS), DSN=&TVSSIE,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIF DD DISP=(NEW PASS), DSN=&TVSSIF,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIG DD DISP=(NEW PASS), DSN=&TVSSIG,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIH DD DISP=(NEW PASS), DSN=&TVSSIH,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSII DD DISP=(NEW PASS), DSN=&TVSSII,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIJ DD DISP=(NEW PASS), DSN=&TVSSIJ,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIK DD DISP=(NEW PASS), DSN=&TVSSIK,
UNIT=SYSDA_SPACE=(CYL (2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
/GO.FT01F001 DD *
  250.  75.0  0.250000  15.  200.  100. 
NTU=0.05 R=0.30 COUNTER TVSSIA
  250.  75.0  1.250000  15.  200.  100. 
NTU=0.25 R=0.30 COUNTER TVSSIB
  250.  75.0  2.500000  15.  200.  100. 
NTU=0.50 R=0.30 COUNTER TVSSIC
   250. 75.0 3.75000 15. 200. 100.
NTU=0.75 R=0.30 COUNTER TVSSID
   250. 75.0 5.00000 15. 200. 100.
NTU=1.00 R=0.30 COUNTER TVSSIE
   250. 75.0 6.25000 15. 200. 100.
NTU=1.25 R=0.30 COUNTER TVSSF
   250. 75.0 7.50000 15. 200. 100.
NTU=1.50 R=0.30 COUNTER TVSSIG
   250. 75.0 10.00000 15. 200. 100.
NTU=2.00 R=0.30 COUNTER TVSSIH
   250. 75.0 12.50000 15. 200. 100.
NTU=2.50 R=0.30 COUNTER TVSSIJ
   250. 75.0 15.00000 15. 200. 100.
NTU=3.00 R=0.30 COUNTER TVSSIK
   250. 75.0 16.25000 15. 200. 100.

/ * STEP A EXEC FORTVG. PROG=TVSSIAC.LIB= 'MSS .S2054 .LOADLIB' 
GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
GO.FT03F001 DD DUMMY
GO.FT04F001 DD DISP=(OLD,DELETE).UNIT=SYSDA,DSN=&TVSSIA
GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
STEPB EXEC FORTVG. PROG=TVSSIAC.LIB= 'MSS .S2054 .LOADLIB'
   . FT01F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT02F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT09F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT10F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT03F001 DD DUMMY
   . FT04F001 DD DISP=(OLD,DELETE).UNIT=SYSDA,DSN=&TVSSIB
   . FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
STEPC EXEC FORTVG. PROG=TVSSIAC.LIB= 'MSS .S2054 .LOADLIB'
   . FT01F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT02F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT09F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT10F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT03F001 DD DUMMY
   . FT04F001 DD DISP=(OLD,DELETE).UNIT=SYSDA,DSN=&TVSSIC
   . FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
STEPD EXEC FORTVG. PROG=TVSSIAC.LIB= 'MSS .S2054 .LOADLIB'
   . FT01F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT02F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT09F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT10F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1))
   . FT03F001 DD DUMMY
   . FT04F001 DD DISP=(OLD,DELETE).UNIT=SYSDA,DSN=&TVSSID
   . FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//
APPENDIX F
MODIFIED NTU53P PROGRAM USED TO RUN ON BATCH SYSTEM

//HESS1 JOB (2054, 0267), 'NTU53P', CLASS=B
//"MAIN ORG=NGVCM1.2054P,SYSTEM=SY2
//"EXEC FORTYCL,PARM.LKED= 'LIST,MAP'
C THIS IS PROGRAM NTU53P

IT GENERATES AN INPUT FILE FOR THERMAL ANALYZER TO OBTAIN
1.5 EFFECTIVENESS-NTU RELATIONSHIP THAT IS NOT AVAILABLE IN
OPEN LITERATURE (3P MEANING THREE PARALLEL PASSES AND TWO
COUNTERFLOW PASS).

INTEGER O,P
DIMENSION COEF(300,6),KCON(300,6),L1(8),L2(3),L3(6),SET2(2),FL4(4)
1 CHOT(22,22),CCLD(22,22),U(22,22),SURFTO(22,22),THOTIN(22,22),
2 TCLDIN(22,22),TITLE(22,22),FNAME(22,22)
C CHARACTER ^=25 TITLE
CHARACTER ^=25 FNAME
C
DO 7 O=1,21,2
P=O+1
READ(1,900) CHOT(O,1),CCLD(O,2),U(O,3),SURFTO(O,4),THOTIN(O,5),TCL
1 DIN(0,6)
900 FORMAT(2F10.0,F10.5,3F10.0)
READ(1,918) TITLE(P;1),FNAME(P,2)
918 FORMAT(2A25)
OPEN OUTPUT FILE
C
OPEN(2,FILE=FNAME(P,2),FORM='FORMATTED')
C
VALK1 = CHOT(0,1)
VALK2 = CCLD(O,2)
VALK3 = U(O,3)*SURFTO(O,4)/250.
TINIT = 125.
C
FRONT END
C
L1(1) = 300
L1(2) = 2
DO 10 I=3,8
10 L1(I) = 0
DO 20 I = 1, 3
20 L2(I) = 0
L3(1) = 300
L3(2) = 50
L3(3) = 6
L3(4) = 2
L3(5) = 4
L3(6) = 6
FL4(1) = .05
FL4(2) = .66667
FL4(3) = .8
FL4(4) = TINIT
L4 = 12

CONSTANT TEMPERATURES

SET2(1) = THOTIN(0, 5)
SET2(2) = TCLDIN(0, 6)

READY FOR INPUT SET 4

NODE 1
KCON(1, 1) = 514
KCON(1, 2) = 1504
KCON(1, 3) = 1514
KCON(1, 4) = 2004
KCON(1, 5) = 2014
KCON(1, 6) = 3015
COEF(1, 6) = VALK1
DO 50 I = 1, 5
50 COEF(1, I) = VALK3

NODES 2 TO 50
DO 75 I = 2, 50
J = I + 50
K = 151 - I
L = 150 + I
N = I - 1
M = 251 - I
MM = 250 + I
KCON(I, 1) = 10*N + 5
KCON(I, 2) = 10*I + 4
KCON(I, 3) = 10*K + 4
KCON(I, 4) = 10*L + 4
KCON(I, 5) = 10*M + 4
KCON(I, 6) = 10*MM + 4
COEF(I,1) = VALK1
DO 80 I1 = 2,6
COEF(I1) = VALK3
80 CONTINUE
75 CONTINUE

NODE 51
KCON(51,1) = 3025
KCON(51,2) = 14
COEF(51,1) = VALK2
COEF(51,2) = VALK3

NODGES 52 TO 300
DO 120 I = 52,300
K = I - 1
IF(I.GT.100) GO TO 122
J = I - 50
GO TO 135
122 IF(I.GT.150) GO TO 124
L = I - 100
M = 2*L - 1
N = M + 50
J = I - N
GO TO 135
124 IF(I.GT.200) GO TO 126
J = I - 150
GO TO 135
126 IF(I.GT.250) GO TO 128
L = I - 200
M = 2*L - 1
N = M + 150
J = I - N
GO TO 135
128 J = I - 250
135 KCON(I1) = 10*J + 4
KCON(I1) = 10*K + 5
COEF(I1) = VALK3
120 CONTINUE

END OF DATA SETUP
NOW CREATE INPUT FOR ANALYZER

WRITE(2,919) TITLE(P,1)
919 FORMAT(1X,A25)
WRITE(2,908)(L1(I),I=1,8)
908 FORMAT(914)
WRITE(2,908)(L2(I),I=1,3)
WRITE(2,908)(L3(I),I=1,6)
WRITE(2,911)(FL4(1),FL4(2),L4,FL4(3),FL4(4))
911 FORMAT(F8.3,F8.5,I8,F8.5,F8.2)
WRITE(2,912) SET2(1),SET2(2)
912 FORMAT(2F8.0)
C
DO 200 I = 1,50
WRITE(2,913)(KCON(I,J),J=1,6)
913 FORMAT(6F8.4)
DO 250 I=51,300
WRITE(2,913) KCON(I,1),KCON(I,2)
WRITE(2,914) COEF(I,1),COEF(I,2)
250 CONTINUE
C
7 CONTINUE
STOP
END
/*
//LKD.SYSLMOD DD DISP=SHR,DSNAME=MSS.S2054.LOADLIB
//LKD.SYSIN DD *
NAME NTU53P(R)
/*
//
APPENDIX G

MASTER EXECUTION PROGRAM FOR NTU53C AND TVCOUNT

/*MAIN ORG=NPGVM1 2054 P LINES=(5000, W)
FORMAT PB DDNAME=Dest=LOCAL
EXEC FOR TVSG, PROG=NTU53P, LIB='MSS.S2054, LOADLIB'
GO.TVSSIL DD DISP=(NEW, PASS), DSN=&TVSSIL,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIM DD DISP=(NEW, PASS), DSN=&TVSSIM,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIN DD DISP=(NEW, PASS), DSN=&TVSSIN,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIO DD DISP=(NEW, PASS), DSN=&TVSSIO,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIP DD DISP=(NEW, PASS), DSN=&TVSSIP,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIQ DD DISP=(NEW, PASS), DSN=&TVSSIQ,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIR DD DISP=(NEW, PASS), DSN=&TVSSIR,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIS DD DISP=(NEW, PASS), DSN=&TVSSIS,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIU DD DISP=(NEW, PASS), DSN=&TVSSIU,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.TVSSIV DD DISP=(NEW, PASS), DSN=&TVSSIV,
UNIT=SYSDA, SPACE=(CYL (2.2)),
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
GO.FT01001 DD *
250. 75.0 0.25000 15. 200. 100.
NTU=0.05 R=0.30 PARALLEL TVSSIL
250. 75.0 1.25000
NTU=0.25 R=0.30 PARALLEL TVSSIM
250. 75.0 2.50000
*/
THE EFFECTIVENESS OF HEAT EXCHANGERS WITH ONE SHELL PASS AND FIVE TUBE PASSES(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA L E HESS SEP 85
//GO: F008F001 DD UNIT=SYSDA, SPACE=CYL: {1,1,1}
//GO: F008F001 DD UNIT=SYSDA, SPACE=CYL: {1,1,1}
//GO: F008F001 DD UNIT=SYSDA, SPACE=CYL: {1,1,1}
//GO: F008F001 DD UNIT=SYSDA, SPACE=CYL: {1,1,1}

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Figure H.1 1-5:3P Effectiveness vs. $N_{tu}$ over Range of $R$ from 0.01 to 1.0
Figure H.2 1-5:3P Effectiveness vs. $N_{tu}$ over Range of $R$ from 0.01 to 0.5
Figure H.3  1-5:3P Effectiveness vs. $N_{tu}$ over Range of $R$ from 0.5 to 1.00
Figure I.1 1-5:3C Effectiveness vs. $N_{tu}$ over Range of $R$ from 0.01 to 1.0
Figure I.2 1-5:3C Effectiveness vs. \( N_{tu} \) over Range of \( R \) from 0.01 to 0.5
Figure I.3 1-5:3C Effectiveness vs. $N_{tu}$ over Range of $R$ from 0.5 to 1.00
APPENDIX J

EFFECTIVENESS COMPUTER GENERATED ANALYZER PROGRAM

**EFFECTIVENESS PROGRAM**

**LCM AUGUST 1985**

This program contains the 1.5 polynomial approximation coefficients. The effectiveness values are readily obtained by either of the 1.5 polynomial coefficients directly or by linear interpolation by entering the values for NTU and the type of heat exchanger (parallel or counter)

```
REAL NTU(E), R1, R2, COUNTER

WRITE (6, 10) NTU, R1, R2, COUNTER

10 FORMAT (6, 10)
```

```
READ (5, 20) EXCH
WRITE (6, 30) NTU

20 FORMAT (5, &20)

READ (5, 40)
WRITE (6, 50)

40 FORMAT (5, &60)

READ (5, 60)
WRITE (6, 60)

60 FORMAT (5, &60)
```

```
1.5 NTU = NTU = 0.99938 + 0.13879*NTU + 0.149081*NTU**2
```

```
IF NTU = 0.05 THEN NTU = F7.4)
```

```
ELSE IF NTU = 0.60 THEN NTU = F7.4)
```

```
WRITE (6, 60)
```

```
ELSE IF NTU = 0.60 THEN NTU = F7.4)
```
ENDIF
ENDIF
ENDIF
IF (R.GT.0.05) THEN
  IF (R.LE.0.10) THEN
    R1=0.05
    R2=0.10
    E1= 0.00079100+0.98831*NTU-0.49081*NTU**2+0.14654*NTU**3-0.025
    E2= 0.0108210+0.98622*NTU-0.50716*NTU**2+0.15773*NTU**3-0.028
  ELSE
    CALL INTERP (R,R1,R2,E1,E2,E)
    WRITE (6,60) E2
  ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.10) THEN
  IF (R.LE.0.15) THEN
    R1=0.10
    R2=0.15
    E1= 0.0108210+0.98622*NTU-0.50716*NTU**2+0.15773*NTU**3-0.028
    E2= 0.0125311+0.98238*NTU-0.52072*NTU**2+0.16779*NTU**3-0.030
  ELSE
    CALL INTERP (R,R1,R2,E1,E2,E)
    WRITE (6,60) E2
  ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.15) THEN
  IF (R.LE.0.20) THEN
    R1=0.15
    R2=0.20
    E1= 0.0125311+0.98238*NTU-0.52072*NTU**2+0.16779*NTU**3-0.030
    E2= 0.0142506+0.97866*NTU-0.53259*NTU**2+0.17545*NTU**3-0.032
  ELSE
    CALL INTERP (R,R1,R2,E1,E2,E)
    WRITE (6,60) E2
  ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.20) THEN
   IF (R.LE.0.25) THEN
      R1=0.20
      R2=0.25
      E1=0.00142506+0.97866*NTU-0.53259*NTU**2+0.17545*NTU**3-0.032
      E2=0.0013145+0.97670*NTU-0.54709*NTU**2+0.18482*NTU**3-0.035
      ELSE
         CALL INTERP (R,R1,R2,E1,E2,E)
         WRITE (6,60) E2
      ENDIF
   ENDIF
IF (R.EQ.0.25) THEN
   WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.25) THEN
   IF (R.LE.0.30) THEN
      R1=0.25
      R2=0.30
      E1=0.0013145+0.97670*NTU-0.54709*NTU**2+0.18482*NTU**3-0.035
      E2=0.00151081+0.97405*NTU-0.56166*NTU**2+0.19541*NTU**3-0.038
      ELSE
         CALL INTERP (R,R1,R2,E1,E2,E)
         WRITE (6,60) E2
      ENDIF
   ENDIF
IF (R.EQ.0.30) THEN
   WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.30) THEN
   IF (R.LE.0.35) THEN
      R1=0.30
      R2=0.35
      E1=0.00151081+0.97405*NTU-0.56166*NTU**2+0.19541*NTU**3-0.038
      E2=0.00174198+0.97091*NTU-0.57527*NTU**2+0.20542*NTU**3-0.040
      ELSE
         CALL INTERP (R,R1,R2,E1,E2,E)
         WRITE (6,60) E2
      ENDIF
   ENDIF
IF (R.EQ.0.35) THEN
   WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.35) THEN

IF (R.LE.0.40) THEN
  R1=0.35
  R2=0.40
  E1=0.00174198*0.87091*NTU-0.57527*NTU**2+0.20542*NTU**3-0.040
  E2=0.00184400*0.96879*NTU-0.59067*NTU**2+0.21718*NTU**3-0.044
  ELSE
    IF (R.EQ.0.40) THEN
      WRITE (6,60) E2
      CALL INTERP (R,R1,R2,E1,E2,E)
    ELSE
      WRITE (6,60) E
    ENDIF
  ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.40) THEN
  R1=0.40
  R2=0.45
  E1=0.00184400*0.96879*NTU-0.59067*NTU**2+0.21718*NTU**3-0.044
  E2=0.0023420*0.96459*NTU-0.60073*NTU**2+0.22416*NTU**3-0.046
  ELSE
    IF (R.EQ.0.45) THEN
      WRITE (6,60) E2
      CALL INTERP (R,R1,R2,E1,E2,E)
    ELSE
      WRITE (6,60) E
    ENDIF
  ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.45) THEN
  R1=0.45
  R2=0.50
  E1=0.0023420*0.96459*NTU-0.60073*NTU**2+0.22416*NTU**3-0.046
  E2=0.00230808+0.96140*NTU-0.61293*NTU**2+0.23322*NTU**3-0.048
  ELSE
    IF (R.EQ.0.50) THEN
      WRITE (6,60) E2
      CALL INTERP (R,R1,R2,E1,E2,E)
    ELSE
      WRITE (6,60) E
    ENDIF
  ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.50) THEN
  R1=0.50
  R2=0.55
  E1=0.00230808+0.96140*NTU-0.61293*NTU**2+0.23322*NTU**3-0.048
  ELSE
    IF (R.EQ.0.55) THEN
      WRITE (6,60) E
    ENDIF
  ENDIF
ENDIF
ENDIF
ENDIF
R2=0.55
E1=0.0230808+0.96140*NTU-0.61293*NTU**2+0.23322*NTU**3-0.048
 933*NTU**4+0.0042669*NTU**5
E2=0.0257953+0.95713*NTU-0.62234*NTU**2+0.23996*NTU**3-0.050
 762*NTU**4+0.0044499*NTU**5
IF(R.EQ.0.55) THEN
  WRITE (6,60) E2
  ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
  WRITE (6,60) E
ENDIF
ENDIF
IF (R.GT.0.55) THEN
  R1=0.55
  R2=0.60
  E1=0.0257953+0.95713*NTU-0.62234*NTU**2+0.23996*NTU**3-0.050
  762*NTU**4+0.0044499*NTU**5
  E2=0.0274755+0.95336*NTU-0.63230*NTU**2+0.24706*NTU**3-0.052
  681*NTU**4+0.0046391*NTU**5
  IF(R.EQ.0.60) THEN
    WRITE (6,60) E2
    ELSE
    CALL INTERP (R,R1,R2,E1,E2,E)
    WRITE (6,60) E
  ENDIF
ENDIF
ENDIF
IF (R.GT.0.60) THEN
  R1=0.60
  R2=0.65
  E1=0.0274755+0.95336*NTU-0.63230*NTU**2+0.24706*NTU**3-0.052
  681*NTU**4+0.0046391*NTU**5
  E2=0.0305249+0.94904*NTU-0.64122*NTU**2+0.25366*NTU**3-0.054
  530*NTU**4+0.0048293*NTU**5
  IF(R.EQ.0.65) THEN
    WRITE (6,60) E2
    ELSE
    CALL INTERP (R,R1,R2,E1,E2,E)
    WRITE (6,60) E
  ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.65) THEN
  R1=0.65
  R2=0.70
  E1=0.0305249+0.94903*NTU-0.64122*NTU**2+0.25366*NTU**3-0.054
* 530*NTU**4+0.0048293*NTU**5
  E2 = 0.03319573+0.94580*NTU-0.65184*NTU**2+0.26137*NTU**3-0.056
* 656*NTU**4+0.0050422*NTU**5
IF (R.EQ.0.70) THEN
  WRITE (6,60) E2
  ELSE
    CALL INTERP (R,R1,R2,E1,E2,E)
    WRITE (6,60) E
  ENDIF
ENDIF
ENDIF
IF (R.GT.0.70) THEN
  IF (R.LE.0.75) THEN
    R1 = 0.70
    R2 = 0.75
    E1 = 0.03319573+0.94580*NTU-0.65184*NTU**2+0.26137*NTU**3-0.056
    656*NTU**4+0.0050422*NTU**5
    E2 = 0.03339253+0.94193*NTU-0.66116*NTU**2+0.26833*NTU**3-0.058
    615*NTU**4+0.0052431*NTU**5
    IF (R.EQ.0.75) THEN
      WRITE (6,60) E2
      ELSE
        CALL INTERP (R,R1,R2,E1,E2,E)
        WRITE (6,60) E
      ENDIF
  ENDIF
ENDIF
IF (R.GT.0.75) THEN
  IF (R.LE.0.80) THEN
    R1 = 0.75
    R2 = 0.80
    E1 = 0.03339253+0.94193*NTU-0.66116*NTU**2+0.26833*NTU**3-0.058
    615*NTU**4+0.0052431*NTU**5
    E2 = 0.0363419+0.93822*NTU-0.67053*NTU**2+0.27531*NTU**3-0.060
    558*NTU**4+0.0054393*NTU**5
    IF (R.EQ.0.80) THEN
      WRITE (6,60) E2
      ELSE
        CALL INTERP (R,R1,R2,E1,E2,E)
        WRITE (6,60) E
      ENDIF
  ENDIF
ENDIF
IF (R.GT.0.80) THEN
  IF (R.LE.0.85) THEN
    R1 = 0.80
    R2 = 0.85
    E1 = 0.0363419+0.93822*NTU-0.67053*NTU**2+0.27531*NTU**3-0.060
    558*NTU**4+0.0054393*NTU**5
    E2 = 0.0382659+0.93407*NTU-0.67841*NTU**2+0.28109*NTU**3-0.062
* 088*NTU**4+0.0055850*NTU**5
IF(R.EQ.0.85) THEN
  WRITE (6,60) E2
ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
  WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.85) THEN
IF (R.LE.0.90) THEN
  R1=0.85
  R2=0.90
  E1= 00382659+0.93407*NTU-0.67841*NTU**2+0.28109*NTU**3-0.062
  051+NTU**4+0.005850*NTU**5
  E2= 00398221+0.93032*NTU-0.68748*NTU**2+0.28799*NTU**3-0.064
  051+NTU**4+0.005787*NTU**5
ENDIF
ENDIF
IF (R.EQ.0.90) THEN
  WRITE (6,60) E2
ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
  WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.90) THEN
IF (R.LE.0.95) THEN
  R1=0.90
  R2=0.95
  E1= 00398221+0.93052*NTU-0.68748*NTU**2+0.28799*NTU**3-0.064
  051+NTU**4+0.005787*NTU**5
  E2= 00426945+0.92609*NTU-0.69496*NTU**2+0.29381*NTU**3-0.065
  653+NTU**4+0.0059442*NTU**5
ENDIF
ENDIF
IF (R.EQ.0.95) THEN
  WRITE (6,60) E2
ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
  WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.95) THEN
IF (R.LE.1.00) THEN
  R1=0.95
  R2=1.00
  E1= 00426945+0.92609*NTU-0.69496*NTU**2+0.29381*NTU**3-0.065
  653+NTU**4+0.0059442*NTU**5
  E2= 00440670+0.92359*NTU-0.70365*NTU**2+0.30046*NTU**3-0.067
  514+NTU**4+0.0061309*NTU**5
ENDIF
ENDIF
IF (R.EQ.1.00) THEN
WRITE (6,60) E2
ELSE
   CALL INTERP (R,R1,R2,E1,E2,E)
   WRITE (6,60) E
ENDIF
ENDIF
ENDIF
ELSE IF (EXCH.EQ.'PARALLEL') THEN
IF (R.GE.0.01) THEN
   IF (R.LE.0.05) THEN
      R1=0.01
      R2=0.05
      E1= .00052233+0.89152*NTU-0.48055*NTU**2+0.13953*NTU**3-0.023
      243*NTU**4+0.0016989*NTU**5
      E2= .00081101+0.98817*NTU-0.49062*NTU**2+0.14604*NTU**3-0.024
      883*NTU**4+0.0018421*NTU**5
      IP(R.EQ.0.01) THEN
         WRITE (6,60) E1
      ELSE IF (R.EQ.0.05) THEN
         WRITE (6,60) E2
      ELSE
         CALL INTERP (R,R1,R2,E1,E2,E)
         WRITE (6,60) E
      ENDIF
   ENDIF
ENDIF
IF (R.GT.0.05) THEN
   IF (R.LE.0.10) THEN
      R1=0.05
      R2=0.10
      E1= .00081101+0.98817*NTU-0.49062*NTU**2+0.14604*NTU**3-0.024
      883*NTU**4+0.0018421*NTU**5
      E2= .00110555+0.98599*NTU-0.50718*NTU**2+0.15721*NTU**3-0.027
      865*NTU**4+0.0021337*NTU**5
      IF(R.EQ.0.10) THEN
         WRITE (6,60) E2
      ELSE
         CALL INTERP (R,R1,R2,E1,E2,E)
         WRITE (6,60) E
      ENDIF
   ENDIF
ENDIF
IF (R.GT.0.10) THEN
   IF (R.LE.0.15) THEN
      R1=0.10
      R2=0.15
      E1= .00110555+0.98599*NTU-0.50718*NTU**2+0.15721*NTU**3-0.027
      865*NTU**4+0.0021337*NTU**5
      E2= .00114518+0.98309*NTU-0.52246*NTU**2+0.16811*NTU**3-0.030
      968*NTU**4+0.0024604*NTU**5
IF(R.EQ.0.15) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.15) THEN
IF (R.LE.0.20) THEN
R1=0.15
R2=0.20
E1=0.98309*NTU-0.52246*NTU**2+0.16811*NTU**3-0.030
* 968*NTU**4+0.0024604*NTU**5
E2=0.97914*NTU-0.53367*NTU**2+0.17485*NTU**3-0.032
* 43*NTU**4+0.0025741*NTU**5
IF(R.EQ.0.20) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.20) THEN
IF (R.LE.0.25) THEN
R1=0.20
R2=0.25
E1=0.97914*NTU-0.53367*NTU**2+0.17485*NTU**3-0.032
* 43*NTU**4+0.0025741*NTU**5
E2=0.97701*NTU-0.54864*NTU**2+0.18464*NTU**3-0.034
* 902*NTU**4+0.0027929*NTU**5
IF(R.EQ.0.25) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
ENDIF
IF (R.GT.0.25) THEN
IF (R.LE.0.30) THEN
R1=0.25
R2=0.30
E1=0.97701*NTU-0.54864*NTU**2+0.18464*NTU**3-0.034
* 902*NTU**4+0.0027929*NTU**5
E2=0.97558*NTU-0.56664*NTU**2+0.19807*NTU**3-0.038
* 885*NTU**4+0.0032195*NTU**5
IF(R.EQ.0.30) THEN
WRITE (6,60) E2
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
  WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.30) THEN
  IF (R.LE.0.35) THEN
    R1=0.30
    R2=0.35
    E1= 0.0143113+0.97558*NTU-0.56664*NTU**2+0.19807*NTU**3-0.038
    885*NTU**4+0.0032195*NTU**5
    E2= 0.0169053+0.97206*NTU-0.57958*NTU**2+0.20740*NTU**3-0.041
    850*NTU**4+0.0034854*NTU**5
    IF(R.EQ.0.35) THEN
      WRITE (6,60) E2
    ELSE
      CALL INTERP (R,R1,R2,E1,E2,E)
      WRITE (6,60) E
    ENDIF
  ENDIF
ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
  WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.35) THEN
  IF (R.LE.0.40) THEN
    R1=0.35
    R2=0.40
    E1= 0.0169053+0.97206*NTU-0.57958*NTU**2+0.20740*NTU**3-0.041
    500*NTU**4+0.0034854*NTU**5
    E2= 0.0176316+0.96998*NTU-0.59515*NTU**2+0.21912*NTU**3-0.045
    854*NTU**4+0.0038805*NTU**5
    IF(R.EQ.0.40) THEN
      WRITE (6,60) E2
    ELSE
      CALL INTERP (R,R1,R2,E1,E2,E)
      WRITE (6,60) E
    ENDIF
  ENDIF
ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
  WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.40) THEN
  IF (R.LE.0.45) THEN
    R1=0.40
    R2=0.45
    E1= 0.0176316+0.96998*NTU-0.59515*NTU**2+0.21912*NTU**3-0.045
    854*NTU**4+0.0038805*NTU**5
    E2= 0.0210897+0.96559*NTU-0.60498*NTU**2+0.22583*NTU**3-0.046
    805*NTU**4+0.0040487*NTU**5
    IF(R.EQ.0.45) THEN
      WRITE (6,60) E2
    ELSE
      CALL INTERP (R,R1,R2,E1,E2,E)
    ENDIF
  ENDIF
ELSE
  CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.45) THEN
IF (R.LE.0.50) THEN
R1=0.45
R2=0.50
E1= 0.00210897+0.96559*NTU-0.60498*NTU**2+0.22583*NTU**3-0.046
* 805*NTU**4+0.040487*NTU**5
E2= 0.00230583+0.96163*NTU-0.61546*NTU**2+0.23327*NTU**3-0.048
* 857*NTU**4+0.042594*NTU**5
IF(R.EQ.0.50) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.50) THEN
IF (R.LE.0.55) THEN
R1=0.50
R2=0.55
E1= 0.00230583+0.96163*NTU-0.61546*NTU**2+0.23327*NTU**3-0.048
* 857*NTU**4+0.042594*NTU**5
E2= 0.00259035+0.95726*NTU-0.62480*NTU**2+0.23985*NTU**3-0.050
* 625*NTU**4+0.044354*NTU**5
IF(R.EQ.0.55) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.55) THEN
IF (R.LE.0.60) THEN
R1=0.55
R2=0.60
E1= 0.00259035+0.95726*NTU-0.62480*NTU**2+0.23985*NTU**3-0.050
* 625*NTU**4+0.044354*NTU**5
E2= 0.00277374+0.95331*NTU-0.63434*NTU**2+0.24638*NTU**3-0.052
* 303*NTU**4+0.045925*NTU**5
IF(R.EQ.0.60) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF

ENDIF
ENDIF
IF (R.GT.0.60) THEN
IF (R.LE.0.65) THEN
R1=0.60
R2=0.65
E1= 0.0277374*0.95531*NTU-0.63434*NTU**2+0.24638*NTU**3-0.052
* 303*NTU**4+0.0045925*NTU**5
E2= 0.0291448*0.95025*NTU-0.64574*NTU**2+0.25460*NTU**3-0.054
* 593*NTU**4+0.0048260*NTU**5
IF(R.EQ.0.65) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
IF (R.GT.0.65) THEN
IF (R.LE.0.70) THEN
R1=0.65
R2=0.70
E1= 0.0291148*0.95025*NTU-0.64574*NTU**2+0.25460*NTU**3-0.054
* 593*NTU**4+0.0048260*NTU**5
E2= 0.0325394*0.94575*NTU-0.65400*NTU**2+0.26039*NTU**3-0.056
* 1053*NTU**4+0.0049575*NTU**5
IF(R.EQ.0.70) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
IF (R.GT.0.70) THEN
IF (R.LE.0.75) THEN
R1=0.70
R2=0.75
E1= 0.0322294*0.94575*NTU-0.65400*NTU**2+0.26039*NTU**3-0.056
* 1053*NTU**4+0.0049575*NTU**5
E2= 0.0338351*0.94231*NTU-0.66425*NTU**2+0.26788*NTU**3-0.058
* 110*NTU**4+0.0051617*NTU**5
IF(R.EQ.0.75) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.75) THEN
  IF (R.LE.0.80) THEN
    R1 = 0.75
    R2 = 0.80
    E1 = 0.0362305 + 0.984231*NTU - 0.66425*NTU**2 + 0.26788*NTU**3 - 0.058
    * 110*NTU**4 + 0.0051617*NTU**5
    E2 = 0.0362305 + 0.984231*NTU - 0.67369*NTU**2 + 0.27495*NTU**3 - 0.060
    * 079*NTU**4 + 0.0053606*NTU**5
    IF (R.EQ.0.80) THEN
      WRITE (6,60) E2
      ELSE
        CALL INTERP (R,R1,R2,E1,E2,E)
      ENDIF
    ENDIF
  ENDIF
ENDIF
IF (R.GT.0.80) THEN
  IF (R.LE.0.85) THEN
    R1 = 0.80
    R2 = 0.85
    E1 = 0.0362305 + 0.93852*NTU - 0.67369*NTU**2 + 0.27495*NTU**3 - 0.060
    * 079*NTU**4 + 0.0053606*NTU**5
    E2 = 0.0382374 + 0.93414*NTU - 0.68130*NTU**2 + 0.28045*NTU**3 - 0.061
    * 487*NTU**4 + 0.0054884*NTU**5
    IF (R.EQ.0.85) THEN
      WRITE (6,60) E2
      ELSE
        CALL INTERP (R,R1,R2,E1,E2,E)
      ENDIF
    ENDIF
  ENDIF
ENDIF
IF (R.GT.0.85) THEN
  IF (R.LE.0.90) THEN
    R1 = 0.85
    R2 = 0.90
    E1 = 0.0382374 + 0.93414*NTU - 0.68130*NTU**2 + 0.28045*NTU**3 - 0.061
    * 487*NTU**4 + 0.0054884*NTU**5
    E2 = 0.0391805 + 0.93133*NTU - 0.69231*NTU**2 + 0.28893*NTU**3 - 0.063
    * 953*NTU**4 + 0.0057472*NTU**5
    IF (R.EQ.0.90) THEN
      WRITE (6,60) E2
      ELSE
        CALL INTERP (R,R1,R2,E1,E2,E)
      ENDIF
    ENDIF
  ENDIF
ENDIF
ENDIF
IF (R.GT.0.90) THEN
  IF (R.LE.0.95) THEN
    ENDIF
ENDIF
ENDIF
ENDIF
R1=0.90
R2=0.95
E1= 0.00391805+0.93133*NTU-0.69231*NTU**2+0.28893*NTU**3-0.063
* 953*NTU**4+0.0057472*NTU**5
* 756*NTU**4+0.0059298*NTU**5
IF(R.EQ.0.95) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
IF (R.GT.0.95) THEN
R1=0.95
R2=1.00
E1= 0.00418844+0.92722*NTU-0.70050*NTU**2+0.29533*NTU**3-0.065
* 754*NTU**4+0.0059298*NTU**5
* 92385*NTU**4+0.0061690*NTU**5
IF(R.EQ.1.00) THEN
WRITE (6,60) E2
ELSE
CALL INTERP (R,R1,R2,E1,E2,E)
WRITE (6,60) E
ENDIF
ENDIF
ENDIF
STOP
END
SUBROUTINE INTERP (R,R1,R2,E1,E2,E)
E=0.0
E=(E1-E2)*(R-R2)/(R1-R2)+E2
RETURN
END
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