Design Mode Drum Attemperator Calculations
Using PEPSE

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ABSTRACT

This report demonstrates a method that uses basic PEPSE® modeling components and calculation features to analyze situations for which the code has no ad hoc components. The method is applied to a basic principles calculation of a boiler drum attemperator.

INTRODUCTION

The objective of this report is to illustrate a method of analysis. This method of analysis makes it possible to use PEPSE® to perform calculations that would not appear at first glance at the user's manual, Reference 1, to be within the code's capabilities. This illustration uses a specific modeling problem in order to demonstrate the method. The use of this particular problem should not be construed in any way as limiting the applicability of the method. The method is far broader in scope than this application. A brief description of the specific problem considered follows.

Commonly superheat temperature is controlled in fossil boilers by drum attemperators, Reference 2. Within such a device, superheated steam flows inside tubes that are immersed in the cooler drum water, and heat is transferred through the tube walls from the superheated steam to the drum water. The primary effect is that the superheated steam emerges from the tubes cooler than at the entrance. This cooler steam is then mixed with bypass steam. The relative amounts of steam flowing through and bypassing the attemperator tubes is controlled by valving to achieve a required superheat temperature.

A model of a drum-type fossil boiler attemperator has been developed for analysis by the PEPSE® code. This model calculates the steam-side outlet temperature, as it depends on the incoming fluid flow rates and states and on the internal heat transfer details. Thus, a mechanistic, "design-style" calculation is included. Such a model can be useful as a stand-alone tool to design or to analyze a proposed design of a drum attemperator, or it can be used in a broader sense in a boiler system model where the objective is to analyze the relationship between steam-flow split and superheat end-use temperature.

Proper modeling by PEPSE® required consideration of the regimes of heat transfer in the drum attemperator. Inside of the tubes heat is given up by flowing superheated steam. Outside of the tubes heat is absorbed by essentially stagnant saturated water. The existing design mode heat exchange components (either Class 1, feedwater heaters, or Class 2, heat exchangers) do not include this possibility. Therefore, it was not possible to use any of these models as-is. This report demonstrates a straightforward method of adapting the Type 20 heat exchnager component to perform the desired calculations. This demonstration highlights the versatility of the code in being able to provide a desired analysis even though the code does not include an ad hoc component, i.e., the exact details of the case to be analyzed were not anticipated when the code was written. The essential ingredients are the operational tools of the code and the ingenuity of the modeler.

Analysis - Problem Statement

The problem is to develop a method that will calculate the steam temperature exiting the tube side of a boiler drum attemperator. Figure 1 shows a schematic of this heat exchange device.

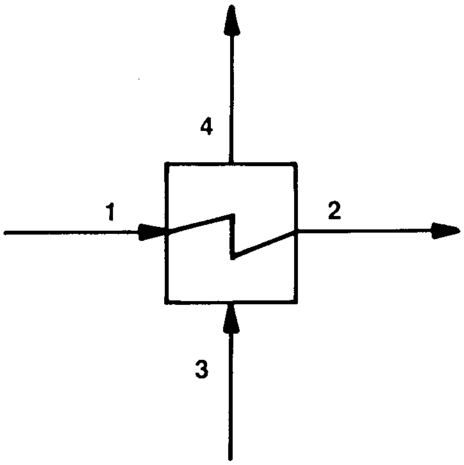

Figure 1. Drum Attemperator Schematic

In the schematic, steam eneters the tube side at 1 and exits at 2. The desired result of the analysis is the temperature at 2. The tubes are immersed in a large volume of water on the shell side. The schematic represents the shell side water entering at 3 and exiting at 4.

Analysis - Assumptions

The following assumptions apply to this analysis:

(1) The heat transfer process is at steady state.

(2) No work is done.

(3) No heat is lost or gained outside of the drum.

(4) Kinetic and potential energy changes are negligible.

(5) Flow inside of the tubes is single-phase steam.

(6) Heat transfer to the shell-side water occurs by pool boiling; thus, the bulk fluid is at saturation condition.

(7) Sufficient precision may be gained by calculating transport properties for the tube side at the entrance.

(8) Pressure changes, or their effect on heat transfer, are negligible.

(9) Because guessing/estimating is required at any step of solving the heat exchanger, PEPSE®'s iteration process is sufficient to stabilize these effects without iterating internal to the heat exchanger calculation itself.

Analysis - Method

The method of analysis employs basic equations of thermodynamics, fluid mechanics, and heat transfer. The PEPSE® component that makes this application possible is the Type 20 ("general") heat exchanger, which is consistent with Figure 1.

One available way to specify a Type 20 component is to input the rate of heat transfer to the tube-side flow by the PEPSE® variable BBHXGR (see Reference 1). By the first law of thermodynamics, the heat transfer rate and the exiting steam condition are related:

$$q = w_1 (h_2 - h_1) \quad , \tag{1}$$

where

q = heat transfer rate gained by steam, BBHXGR,
w_1 = steam flow rate through tubes,
h_1 = steam-entering enthalpy, and
h_2 = steam-exiting enthalpy.

Since the desired analysis result is temperature at 2, T_2, Equation (1) can be used to determine the desired value, given the entering conditions and a calculation for q, while benefiting from a simple steam table relationship:

$$h_2 = f (p, T_2) \quad , \tag{2}$$

where

p = pressure and
T = temperature.

The heart of the problem is to determine the heat transfer rate and to feed the value into PEPSE®'s variable BBHXGR. PEPSE® will perform the necessary inversions of Equations (1) and (2) as part of its standard treatment of the Type 20 heat exchanger calculation. This can be done by inputing an initial estimate of BBHXGR for the component and adding a set of operations by which PEPSE® can modify BBHXGR based on a mechanistic calculation. By this approach, PEPSE® is able to adapt precisely to changing flow/thermal inputs to the drum and to heat exchange tube changes.

The heat transfer calculation is based on the "NTU-effectiveness" method as discussed in References 3 and 4.

Steam outlet temperature is

$$T_2 = T_1 - (T_1 - T_3) * [1 - \ell^{-UA/(wc)_1}] \quad , \qquad (3)$$

where

A = total tube external heat transfer area,
U = thermal conductance from tube to shell, and
wc = steam-side heat capacity (flow times specific heat).

Equation (3) is a simplification of the more general equation that accounts for inlet-to-outlet temperature variations on both tube and shell sides. The simplification occurs because boiling is assumed on the shell side, which means constant shell-side temperature and infinite shell-side heat capacity. Tube area is

$$A = N*L*\pi * \frac{D_o^{\,2}}{4} \quad , \qquad (4)$$

where

N = number of tubes,
L = length of tubes, and
D_o = outside diameter of tubes.

The thermal conductance between tube and shell sides based on tube outside area, Reference 4, is

$$U = \left[\frac{1}{h_i} \left(\frac{D_o}{D_i}\right) + R_i \left(\frac{D_o}{D_i}\right) + R_o + \frac{D_o \ln (D_o/D_i)}{2k_t} + \frac{1}{h_o}\right]^{-1} \quad , \qquad (5)$$

where

h_i = inside tube film heat transfer coefficient,
D_i = tube inside diameter,
R_i = tube inside fouling resistance,
R_0 = tube outside fouling resistance,
k_t = tube wall thermal conductivity, and
h_0 = outside tube film heat transfer coefficient.

In Equation (5) the first and last terms account for resistance to heat transfer through the interior and exterior heat transfer films. The second and third terms account for interior and exterior tube fouling, and the fourth term accounts for the heat transfer resistance of the tube wall itself.

Inside of the tubes the film coefficient is calculated by the Dittus-Boelter correlation

$$h_i = 0.023 * (\frac{k_b}{D_i}) * Re_i^{0.8} * Pr_i^{0.4} \quad , \tag{6}$$

where

k_b = inside bulk thermal conductivity,
Re_i = Reynolds number of flow inside of the tubes, and
Pr_i = Prandtl number inside of the tubes.

The Reynolds number is calculated

$$Re_i = (\frac{\rho VD}{\mu})_i \tag{7}$$

$$= \frac{4w_1}{N\pi D_i\mu_1} \quad , \tag{8}$$

where

ρ = steam density,
V = steam flow velocity in tubes, and
μ = steam viscosity.

Equation (8) for the internal Reynolds number depends on the assumption that using steam inlet conditions provides sufficient accuracy for the calculation. This is a reasonable assumption. If further sophistication were required, average values, inlet-to-exit, could be taken by using outlet values that were an iterate old in the calculation. This sophistication was regarded as unnecessary.

For pool boiling, Reference 3 gives a useful correlation, attributed to Rohsenow, which reduces to

$$\frac{1}{h_o} = \frac{0.013}{c_{pf}} \left(\frac{h_{fg}}{q/A}\right) \left[\left(\frac{q/A}{h_{fg}}\right) \frac{1}{\mu_f} \left(\frac{\sigma}{\rho_f - \rho_g}\right)^{1/2}\right]^{1/3} Pr_f \quad , \qquad (9)$$

where

c_{pf} = specific heat of saturated liquid,
h_{fg} = latent heat of vaporization,
q/A = heat transfer per unit surface area,
μ_f = viscosity of saturated liquid,
ρ_f = saturated liquid density, and
ρ_g = saturated vapor density.

In Equations (3) through (9) above, virtually all terms are available from PEPSE® steam table calls; and geometry and thermal conductivity inputs are available as basic information about the installation or design. Other needed information in the equations presented above can be calculated as indicated. Two notable exceptions appear in Equation (9). The (q/A) term can be calculated from the values of q for the previous iterate and from the geometry. The surface tension, σ, can be calculated from a simple linear fit of a curve from Reference 5

$$\sigma = -8.111 \times 10^{-6} * T_1 + 5.693 \times 10^{-3} \frac{\text{lbf}}{\text{ft}} \quad . \qquad (10)$$

As discussed earlier, these equations can be input to PEPSE® through the operations feature (see Reference 1). The user-supplied inputs, such as tube diameters, can be loaded via the set of operational variables.

Analysis Implementation

Figure 2 shows the PEPSE® schematic of a submodel of the drum attemperator.

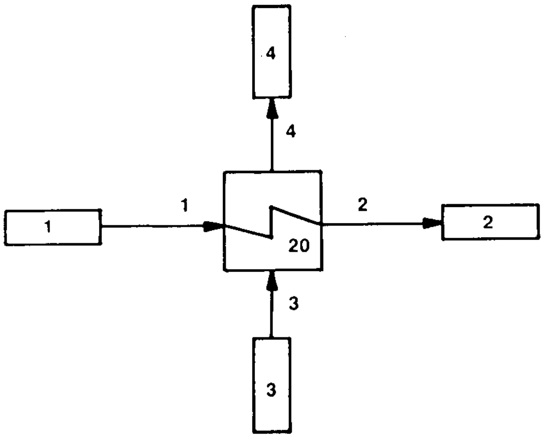

Figure 2. Drum Attemperator Submodel

The input data set for the submodel is presented in Table 1. The data set is liberally commented and is divided into sections to highlight the parts of the calculation.

The initial part of the data set contains the basic model description.

Debug output is activated on card 010200 to provide iterate-to-iterate demonstration of the progress of the heat transfer calculations.

A point to note in the base deck is the initial guess of the attemperator's heat transfer rate, -1.0e7 Btu/hr (the minus says heat is transferred from the tube-side steam).

Following the "end of base deck", the next data section, cards 87NNN0, loads values of constants and drum parameter inputs into PEPSE®'s operational variable storage spaces (OPVBs). For example, OPVB,2, entered on card 870020, contains the value of pi, 3.1714. These values contained in the OPVBs are then available for use in the operations that appear in the

Table 1

Drum Attemperator
Submodel Data Set

```
= DRUM ATTEMPERATOR SUBMODEL
*                    NDEBUG
010200  0  0  0  0  0  1
020002  NOPRNT
020004  NOPRNT
020021  NOPRNT
020022  NOPRNT
020023  NOPRNT
020024  NOPRNT
*  GEOMETRY
500010   1,U,   20,T
500020  20,T,    2,I
500030   3,U,   20,S
500040  20,D,    4,I
*  SOURCES AND SINKS
700010  33  1.4  2000.   1.E5
700020  32
700030  31  0.0  2000.   1.E6
700040  30
*  HEAT EXCHANGER
*                                     BBHXGR
700200  20  630.  0.  0.  0.  0.  0.  -1.E7  *  GUESS HEAT TRANSFER
*
*  END OF BASE DECK
*
*
*  SPECIAL CALCS FOR DRUM FOR MECHANISTIC MODEL
*
*  OPERATIONAL VARIABLES
*
*  CONSTANTS
870010  1.0       * ONE
870020  3.1714    * PI
870030  0.8       * EXPONENT IN DITTUS BOELTER
870040  4.0       * FOUR
870050  0.4       * EXPONENT IN DITTUS BOELTER
870060  0.023     * COEF IN DITTUS BOELTER
870070  0.5       * ONE HALF
870080  0.3333    * ONE THIRD
870090  0.013     * COEF IN POOL-BOILING CORRELATION
870100 -8.111E-6 * COEF IN SURFACE TENSION
870110  5.693E-3 * CONST IN SURF TENSION
870120  12.       * 12 IN/FT
* DRUM PARAMETER INPUTS
870200  30.       * NUMBER OF U-TUBES
870210  1.73      * DI, IN
870220  2.0       * DO, IN
870230  630.      * TUBE TOTAL AREA, SQ FT
870240  0.0       * RI, FOULING FACTOR
870250  0.0       * RO, FOULING FACTOR
870260  25.0      * TUBE WALL THERMAL COND
870270  1.0       * CLEANLINESS FACTOR
*
*  OPERATIONS
*
*  TUBE INSIDE (DITTUS-BOELTER) H.T. COEF -- OPVB,115
*
881000  PP,001,    CND,  HH,001,    OPVB,100  *  STEAM-IN THERMAL COND
881010  PP,001,    VIS,  HH,001,    OPVB,101  *  STEAM-IN VISC
881020  OPVB,4,    MUL,  WW,001,    OPVB,102  *  4*W
```

Table 1
(Continued)

```
881030  OPVB,102,  DIV,  OPVB,20,   OPVB,103  *  4*W/N
881040  OPVB,103,  DIV,  OPVB,2,    OPVB,104  *  4*W/(N*PI)
881050  OPVB,104,  DIV,  OPVB,21,   OPVB,105  *  4*W/(N*PI*DI)
881060  OPVB,105,  MUL,  OPVB,12,   OPVB,106  *  CORRECT INCHES TO FEET
881070  OPVB,106,  DIV,  OPVB,101,  OPVB,107  *  IN-TUBE REYNOLDS NO.
881080  OPVB,107,  TO,   OPVB,3,    OPVB,108  *  RE TO 0.8 POWER
881090  PP,001,    PRA,  HH,001,    OPVB,109  *  STEAM-IN PRANDTL NO.
881100  OPVB,109,  TO,   OPVB,5,    OPVB,110  *  PR TO 0.4 POWER
881110  OPVB,100,  DIV,  OPVB,21,   OPVB,111
881120  OPVB,111,  MUL,  OPVB,12,   OPVB,112  *  KB/DI
*  MULTIPLY TERMS IN HI
881130  OPVB,6,    MUL,  OPVB,112,  OPVB,113
881140  OPVB,113,  MUL,  OPVB,108,  OPVB,114
881150  OPVB,114,  MUL,  OPVB,110,  OPVB,115  *  HI
881160  OPVB,1,    DIV,  OPVB,115,  OPVB,116  *  1.0/HI
*
*  TUBE OUTSIDE H.T. COEF, BASED ON POOL BOILING (ROHSENOW), USING
*  COLD-IN CONDITIONS -- OPVB,146
*
*  PROPERTIES - STEAM TABLE CALLS
*
881200  OPVB,50,   PHF,  PP,003,    OPVB,120  *  HF
881210  OPVB,50,   PHG,  PP,003,    OPVB,121  *  HG
881220  OPVB,121,  SUB,  OPVB,120,  OPVB,122  *  HG - HF
881230  PP,003,    PHV,  OPVB,120,  OPVB,123  *  VF
881240  PP,003,    PHV,  OPVB,121,  OPVB,124  *  VG
881250  OPVB,1,    DIV,  OPVB,123,  OPVB,125  *  RHO F
881260  OPVB,1,    DIV,  OPVB,124,  OPVB,126  *  RHO G
881270  OPVB,125,  SUB,  OPVB,126,  OPVB,127  *  RHO F - RHO G
881280  PP,003,    VIS,  OPVB,120,  OPVB,128  *  SAT LIQ VISC
881290  OPVB,50,   SAT,  PP,003,    OPVB,129  *  SAT T IN
881300  PP,003,    CPS,  OPVB,120,  OPVB,130  *  SAT LIQ CP
881310  PP,003,    PRA,  OPVB,120,  OPVB,131  *  SAT LIQ PRANDTL NO.
881320  OPVB,10,   MUL,  OPVB,129,  OPVB,132  *  TERM IN SURF TENSION
881330  OPVB,132,  ADD,  OPVB,11,   OPVB,133  *  SURFACE TENSION
*  TERMS IN HO EQN
881340  OPVB,1,    ABS,  BBHXGR,020,OPVB,134  *  ABS(Q)
881350  OPVB,134,  DIV,  OPVB,23,   OPVB,135  *  Q/A
881360  OPVB,135,  DIV,  OPVB,122,  OPVB,136  *  Q/A/HFG
881370  OPVB,9,    DIV,  OPVB,130,  OPVB,137  *
881380  OPVB,137,  DIV,  OPVB,136,  OPVB,138  *  FRONT TERM
881390  OPVB,136,  DIV,  OPVB,128,  OPVB,139  *  Q/A/HFG/VISC
881400  OPVB,133,  DIV,  OPVB,127,  OPVB,140  *  SIGMA, RHO TERM
881410  OPVB,140,  TO,   OPVB,7,    OPVB,141  *  SQUARE ROOT OF ....
881420  OPVB,139,  MUL,  OPVB,141,  OPVB,142  *  BRACKET
881430  OPVB,142,  TO,   OPVB,8,    OPVB,143
881440  OPVB,138,  MUL,  OPVB,143,  OPVB,144
881450  OPVB,144,  MUL,  OPVB,131,  OPVB,145  *  1./HO
881460  OPVB,1,    DIV,  OPVB,145,  OPVB,146  *  HO
*
*  NOW CALCULATE U, AND U-WEIGHTED TO CLEANLINESS FACTOR
*
*  FIRST THE TERMS IN U
881510  OPVB,22,   DIV,  OPVB,21,   OPVB,151  *  DO/DI
881520  OPVB,151,  DIV,  OPVB,115,  OPVB,152  *  (1./HI)*(DO/DI)
881530  OPVB,24,   MUL,  OPVB,151,  OPVB,153  *  RI*DO/DI
881540  OPVB,22,   LN,   OPVB,151,  OPVB,154  *  DO*LN(DO/DI)
881550  OPVB,7,    MUL,  OPVB,154,  OPVB,155  *  DO*LN(DO/DI)/2
881560  OPVB,155,  DIV,  OPVB,12,   OPVB,156  *  DO*LN(DO/DI)/2/12
881570  OPVB,156,  DIV,  OPVB,26,   OPVB,157  *  .../KT
```

Table 1

(Continued)

```
*  SUM THE TERMS
881580  OPVB,152,   ADD,   OPVB,153,   OPVB,158  *  FIRST TWO
881590  OPVB,158,   ADD,   OPVB,25,    OPVB,159  *  PLUS THIRD
881600  OPVB,159,   ADD,   OPVB,157,   OPVB,160  *  PLUS FOURTH
881610  OPVB,160,   ADD,   OPVB,145,   OPVB,161  *  PLUS FIFTH
881620  OPVB,1,     DIV,   OPVB,161,   OPVB,162  *  U
881630  OPVB,162,   MUL,   OPVB,27,    OPVB,163  *  U*CLEANLINESS FACTOR
*
*  CALC T STEAM OUT
*
*  FIRST NTU-EFFECTIVENESS METHOD APPL'N
*
881700  OPVB,163,   MUL,   OPVB,23,    OPVB,170  *  U*CL*A
881710  PP,001,     CPS,   HH,001,     OPVB,171  *  STEAM-IN CP
881720  OPVB,170,   DIV,   WW,001,     OPVB,172
881730  OPVB,172,   DIV,   OPVB,171,   OPVB,173  *  UA/W/CP
881740  OPVB,50,    SUB,   OPVB,173,   OPVB,174  * -UA/W/CP
881750  OPVB,1,     EXP,   OPVB,174,   OPVB,175  *  E(-UA/W/CP)
881760  OPVB,1,     SUB,   OPVB,175,   OPVB,176  *  1 - E(....)
881770  TT,001,     SUB,   TT,003,     OPVB,177  *  T1 - T3
881780  OPVB,177,   MUL,   OPVB,176,   OPVB,178
881790  TT,001,     SUB,   OPVB,178,   OPVB,179  *  T2
*  CALCULATE HEAT TRANSFER TO TUBE SIDE, BBHXQR
881800  PP,001,     PTH,   OPVB,179,   OPVB,180  *  H2
881810  OPVB,180,   SUB,   HH,001,     OPVB,181  *  DELTA H
881820  WW,001,     MUL,   OPVB,181,   BBHXQR,020
.
```

remainder of the data set. Operations access an individual value by referring to the index NNN in the card number 87NNN0.

The inputs of operations are also subdivided, with each section developing one of the terms in Equation (5) above. The result of these calculations, thermal conductance U stored in OPVB,162 by operation 162, card 881620, is ultimately used to calculate the steam outlet temperature (as dictated by Equation (3)) via operation 179, card 881790. Notice that a cleanliness factor has been included. This is a simple multiplier of the thermal conductance, U. A value of 1.0 corresponds to a clean condition, and values less than 1.0 represent dirty conditions (since they diminish the heat conductance).

The input values contained in Table 1 are reasonably typical for a mud drum attemperator. Therefore, the results of this analysis should be equally as representative.

Results and Discussion

The main result of interest for this analysis is the steam-side temperature at the exit of the heat exchanger. This information is given by Table 2, which is the PEPSE® Component Properties table. For this specific case, the value is 669°F.

Other information of additional interest is provided by Table 3, which is the PEPSE® Operation Set Values Calculated table at the start of the last iterate. This table shows the detailed makeup of the heat transfer calculations inside of the attemperator. It provides an opportunity to check (by hand) the values of transport properties and intermediate terms that contribute to the final result. For example, the results of operations 101 and 102 yield thermal conductivity and viscosity values that can be verified against standard reference values. Of special interest are the results of operation sets 145, 152, 157, and 162. These are, respectively, the outside, inside, and tube wall thermal resistance contributions to Equation (5). In this analysis, these are the only non-zero terms in

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 PEPSE CODE BY ENERGY INCORPORATED, IDAHO FALLS, ID.     VERSION 51L   CREATED 23 DEC 85      DATE 04/28/86.       PAGE   9
DRUM ATTEMPERATOR SUBMODEL
```

Table 2

Component Properties Results

```
                            CONNECTING
COMPONENT   COMPONENT        STREAM       PORT       FLUID      MASS                                   THERMO.                              SPECIFIC
 NUMBER    DESCRIPTION       NUMBER        ID          ID        FLOW     TEMPERATURE   PRESSURE     QUALITY   ENTHALPY      ENTROPY       VOLUME
                                                                (LBM/HR)      (F)        (PSI)       ( - )   (BTU/LBM)  (BTU/LBM-F)   (FT3/LBM)


    1     INPUT COMPONENT       1      U (OUTPUT)       0        100000.    786.695     2000.000    1.40000  1324.5930     1.44916     3.0046E-01

    2     OUTPUT COMPONENT      2      I (INPUT)        0        100000.    669.228     2000.000    1.13276  1200.1505     1.34378     2.2441E-01

    3     INFINITE SOURCE       3      U (OUTPUT)       0       1000000.    635.803     2000.000    0.00000   672.6775     0.86302     2.5603E-02

    4     INFINITE SINK         4      I (INPUT)        0       1000000.    635.803     2000.000    0.02672   685.1217     0.87438     2.9951E-02

   20     GEN. HT. EXCH.        1      T (INPUT)        0        100000.    786.695     2000.000    1.40000  1324.5930     1.44916     3.0046E-01
                                3      S (INPUT)        0       1000000.    635.803     2000.000    0.00000   672.6775     0.86302     2.5603E-02
                                2      T (OUTPUT)       0        100000.    669.228     2000.000    1.13276  1200.1505     1.34378     2.2441E-01
                                4      D (OUTPUT)       0       1000000.    635.803     2000.000    0.02672   685.1217     0.87438     2.9951E-02
```

Table 3

Operation Results

```
PEPSE CODE BY ENERGY INCORPORATED, IDAHO FALLS, ID.      VERSION 51L    CREATED 23 DEC 85       DATE 04/28/86.          PAGE   3
DRUM ATTEMPERATOR SUBMODEL


                                       OPERATION SET VALUES CALCULATED
                                        AT THE START OF ITERATION   6

         SET      VARIABLE (ID)         OPERATION       VARIABLE (ID)       =     VARIABLE (ID)
                      VALUE                                 VALUE                     VALUE

         100      PP      (    1)          CND          HH      (    1)     =     OPVB   ( 100)
                    2.00000E+03                          1.32459E+03               4.49121E-02

         101      PP      (    1)          VIS          HH      (    1)     =     OPVB   ( 101)
                    2.00000E+03                          1.32459E+03               6.20103E-02

         102      OPVB    (    4)          MUL          WW      (    1)     =     OPVB   ( 102)
                    4.00000E+00                          1.00000E+05               4.00000E+05

         103      OPVB    ( 102)           DIV          OPVB    (   20)     =     OPVB   ( 103)
                    4.00000E+05                          3.00000E+01               1.33333E+04

         104      OPVB    ( 103)           DIV          OPVB    (    2)     =     OPVB   ( 104)
                    1.33333E+04                          3.17140E+00               4.20424E+03

         105      OPVB    ( 104)           DIV          OPVB    (   21)     =     OPVB   ( 105)
                    4.20424E+03                          1.73000E+00               2.43020E+03

         106      OPVB    ( 105)           MUL          OPVB    (   12)     =     OPVB   ( 106)
                    2.43020E+03                          1.20000E+01               2.91624E+04

         107      OPVB    ( 106)           DIV          OPVB    ( 101)      =     OPVB   ( 107)
                    2.91624E+04                          6.20103E-02               4.70283E+05

         108      OPVB    ( 107)           TO           OPVB    (    3)     =     OPVB   ( 108)
                    4.70283E+05                          8.00000E-01               3.45054E+04

         109      PP      (    1)          PRA          HH      (    1)     =     OPVB   ( 109)
                    2.00000E+03                          1.32459E+03               1.12148E+00

         110      OPVB    ( 109)           TO           OPVB    (    5)     =     OPVB   ( 110)
                    1.12148E+00                          4.00000E-01               1.04693E+00

         111      OPVB    ( 100)           DIV          OPVB    (   21)     =     OPVB   ( 111)
                    4.49121E-02                          1.73000E+00               2.59608E-02

         112      OPVB    ( 111)           MUL          OPVB    (   12)     =     OPVB   ( 112)
                    2.59608E-02                          1.20000E+01               3.11529E-01

         113      OPVB    (    6)          MUL          OPVB    ( 112)      =     OPVB   ( 113)
                    2.30000E-02                          3.11529E-01               7.16517E-03

         114      OPVB    ( 113)           MUL          OPVB    ( 108)      =     OPVB   ( 114)
                    7.16517E-03                          3.45054E+04               2.47237E+02
```

Table 3
(Continued)

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 PEPSE CODE BY ENERGY INCORPORATED, IDAHO FALLS, ID.      VERSION 51L   CREATED 23 DEC 85       DATE 04/28/86.          PAGE   4
DRUM ATTEMPERATOR SUBMODEL



                                   OPERATION SET VALUES CALCULATED
                                    AT THE START OF ITERATION   6

           SET      VARIABLE (ID)         OPERATION       VARIABLE (ID)       =    VARIABLE (ID)
                        VALUE                                 VALUE                    VALUE

           115       OPVB  ( 114)            MUL            OPVB  ( 110)      =     OPVB  ( 115)
                      2.47237E+02                            1.04693E+00              2.58840E+02

           116       OPVB  (   1)            DIV            OPVB  ( 115)      =     OPVB  ( 116)
                      1.00000E+00                            2.58840E+02              3.86339E-03

           120       OPVB  (  50)            PHF            PP    (   3)      =     OPVB  ( 120)
                      0.00000E-01                            2.00000E+03              6.72677E+02

           121       OPVB  (  50)            PHG            PP    (   3)      =     OPVB  ( 121)
                      0.00000E-01                            2.00000E+03              1.13833E+03

           122       OPVB  ( 121)            SUB            OPVB  ( 120)      =     OPVB  ( 122)
                      1.13833E+03                            6.72677E+02              4.65654E+02

           123       PP    (   3)            PHV            OPVB  ( 120)      =     OPVB  ( 123)
                      2.00000E+03                            6.72677E+02              2.56029E-02

           124       PP    (   3)            PHV            OPVB  ( 121)      =     OPVB  ( 124)
                      2.00000E+03                            1.13833E+03              1.88306E-01

           125       OPVB  (   1)            DIV            OPVB  ( 123)      =     OPVB  ( 125)
                      1.00000E+00                            2.56029E-02              3.90580E+01

           126       OPVB  (   1)            DIV            OPVB  ( 124)      =     OPVB  ( 126)
                      1.00000E+00                            1.88306E-01              5.31050E+00

           127       OPVB  ( 125)            SUB            OPVB  ( 126)      =     OPVB  ( 127)
                      3.90580E+01                            5.31050E+00              3.37475E+01

           128       PP    (   3)            VIS            OPVB  ( 120)      =     OPVB  ( 128)
                      2.00000E+03                            6.72677E+02              1.76445E-01

           129       OPVB  (  50)            SAT            PP    (   3)      =     OPVB  ( 129)
                      0.00000E-01                            2.00000E+03              6.35803E+02

           130       PP    (   3)            CPS            OPVB  ( 120)      =     OPVB  ( 130)
                      2.00000E+03                            6.72677E+02              1.84125E+00

           131       PP    (   3)            PRA            OPVB  ( 120)      =     OPVB  ( 131)
                      2.00000E+03                            6.72677E+02              1.19508E+00

           132       OPVB  (  10)            MUL            OPVB  ( 129)      =     OPVB  ( 132)
                     -8.11100E-06                            6.35803E+02             -5.15700E-03
```

Table 3

(Continued)

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PEPSE CODE BY ENERGY INCORPORATED, IDAHO FALLS, ID.     VERSION 51L   CREATED 23 DEC 85      DATE 04/28/86.        PAGE   5
DRUM ATTEMPERATOR SUBMODEL


                                  OPERATION SET VALUES CALCULATED
                                   AT THE START OF ITERATION   6

       SET      VARIABLE (ID)        OPERATION       VARIABLE (ID)     =    VARIABLE (ID)
                   VALUE                                VALUE                  VALUE

       133      OPVB   ( 132)          ADD           OPVB   (  11)     =    OPVB   ( 133)
                 -5. 15700E-03                        5. 69300E-03            5. 36004E-04

       134      OPVB   (   1)          ABS           BBHXGR(  20)      =    OPVB   ( 134)
                  1. 00000E+00                       -1. 24443E+07            1. 24443E+07

       135      OPVB   ( 134)          DIV           OPVB   (  23)     =    OPVB   ( 135)
                  1. 24443E+07                        6. 30000E+02            1. 97528E+04

       136      OPVB   ( 135)          DIV           OPVB   ( 122)     =    OPVB   ( 136)
                  1. 97528E+04                        4. 65654E+02            4. 24194E+01

       137      OPVB   (   9)          DIV           OPVB   ( 130)     =    OPVB   ( 137)
                  1. 30000E-02                        1. 84125E+00            7. 06043E-03

       138      OPVB   ( 137)          DIV           OPVB   ( 136)     =    OPVB   ( 138)
                  7. 06043E-03                        4. 24194E+01            1. 66443E-04

       139      OPVB   ( 136)          DIV           OPVB   ( 128)     =    OPVB   ( 139)
                  4. 24194E+01                        1. 76445E-01            2. 40412E+02

       140      OPVB   ( 133)          DIV           OPVB   ( 127)     =    OPVB   ( 140)
                  5. 36004E-04                        3. 37475E+01            1. 58829E-05

       141      OPVB   ( 140)          TO            OPVB   (   7)     =    OPVB   ( 141)
                  1. 58828E-05                        5. 00000E-01            3. 98532E-03

       142      OPVB   ( 139)          MUL           OPVB   ( 141)     =    OPVB   ( 142)
                  2. 40412E+02                        3. 98532E-03            9. 58119E-01

       143      OPVB   ( 142)          TO            OPVB   (   8)     =    OPVB   ( 143)
                  9. 58119E-01                        3. 33300E-01            9. 85842E-01

       144      OPVB   ( 138)          MUL           OPVB   ( 143)     =    OPVB   ( 144)
                  1. 66443E-04                        9. 85842E-01            1. 64087E-04

       145      OPVB   ( 144)          MUL           OPVB   ( 131)     =    OPVB   ( 145)
                  1. 64087E-04                        1. 19508E+00            1. 96097E-04

       146      OPVB   (   1)          DIV           OPVB   ( 145)     =    OPVB   ( 146)
                  1. 00000E+00                        1. 96097E-04            5. 09952E+03

       151      OPVB   (  22)          DIV           OPVB   (  21)     =    OPVB   ( 151)
                  2. 00000E+00                        1. 73000E+00            1. 15607E+00
```

Table 3
(Continued)

```
                          OPERATION SET VALUES CALCULATED
                           AT THE START OF ITERATION   6

SET     VARIABLE (ID)        OPERATION        VARIABLE (ID)      =     VARIABLE (ID)
           VALUE                                 VALUE                    VALUE

152     OPVB   ( 151)           DIV           OPVB   ( 115)      =     OPVB   ( 152)
         1.15607E+00                           2.58840E+02              4.46635E-03

153     OPVB   (  24)           MUL           OPVB   ( 151)      =     OPVB   ( 153)
         0.00000E-01                           1.15607E+00              0.00000E-01

154     OPVB   (  22)           LN            OPVB   ( 151)      =     OPVB   ( 154)
         2.00000E+00                           1.15607E+00              2.90052E-01

155     OPVB   (   7)           MUL           OPVB   ( 154)      =     OPVB   ( 155)
         5.00000E-01                           2.90052E-01              1.45026E-01

156     OPVB   ( 155)           DIV           OPVB   (  12)      =     OPVB   ( 156)
         1.45026E-01                           1.20000E+01              1.20855E-02

157     OPVB   ( 156)           DIV           OPVB   (  26)      =     OPVB   ( 157)
         1.20855E-02                           2.50000E+01              4.83419E-04

158     OPVB   ( 152)           ADD           OPVB   ( 153)      =     OPVB   ( 158)
         4.46635E-03                           0.00000E-01              4.46635E-03

159     OPVB   ( 158)           ADD           OPVB   (  25)      =     OPVB   ( 159)
         4.46635E-03                           0.00000E-01              4.46635E-03

160     OPVB   ( 159)           ADD           OPVB   ( 157)      =     OPVB   ( 160)
         4.46635E-03                           4.83419E-04              4.94977E-03

161     OPVB   ( 160)           ADD           OPVB   ( 145)      =     OPVB   ( 161)
         4.94977E-03                           1.96097E-04              5.14587E-03

162     OPVB   (   1)           DIV           OPVB   ( 161)      =     OPVB   ( 162)
         1.00000E+00                           5.14587E-03              1.94331E+02

163     OPVB   ( 162)           MUL           OPVB   (  27)      =     OPVB   ( 163)
         1.94331E+02                           1.00000E+00              1.94331E+02

170     OPVB   ( 163)           MUL           OPVB   (  23)      =     OPVB   ( 170)
         1.94331E+02                           6.30000E+02              1.22428E+05

171     PP     (   1)           CPS           HH     (   1)      =     OPVB   ( 171)
         2.00000E+03                           1.32459E+03              9.12256E-01

172     OPVB   ( 170)           DIV           WW     (   1)      =     OPVB   ( 172)
         1.22428E+05                           1.00000E+05              1.22428E+00
```

Table 3

(Continued)

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PEPSE CODE BY ENERGY INCORPORATED, IDAHO FALLS, ID.     VERSION 51L   CREATED 23 DEC 85      DATE 04/28/86.        PAGE   7
DRUM ATTEMPERATOR SUBMODEL



                                   OPERATION SET VALUES CALCULATED
                                    AT THE START OF ITERATION    6

  SET      VARIABLE (ID)          OPERATION         VARIABLE (ID)      =     VARIABLE (ID)
               VALUE                                    VALUE                    VALUE

  173       OPVB   ( 172)            DIV             OPVB   ( 171)     =      OPVB   ( 173)
             1. 22428E+00                             8. 12256E-01             1. 50726E+00

  174       OPVB   (  50)            SUB             OPVB   ( 173)     =      OPVB   ( 174)
             0. 00000E-01                             1. 50726E+00            -1. 50726E+00

  175       OPVB   (   1)            EXP             OPVB   ( 174)     =      OPVB   ( 175)
             1. 00000E+00                            -1. 50726E+00             2. 21515E-01

  176       OPVB   (   1)            SUB             OPVB   ( 175)     =      OPVB   ( 176)
             1. 00000E+00                             2. 21515E-01             7. 78485E-01

  177       TT     (   1)            SUB             TT     (   3)     =      OPVB   ( 177)
             7. 86695E+02                             6. 35803E+02             1. 50892E+02

  178       OPVB   ( 177)            MUL             OPVB   ( 176)     =      OPVB   ( 178)
             1. 50892E+02                             7. 78485E-01             1. 17467E+02

  179       TT     (   1)            SUB             OPVB   ( 178)     =      OPVB   ( 179)
             7. 86695E+02                             1. 17467E+02             6. 69229E+02

  180       PP     (   1)            PTH             OPVB   ( 179)     =      OPVB   ( 180)
             2. 00000E+03                             6. 69228E+02             1. 20015E+03

  181       OPVB   ( 180)            SUB             HH     (   1)     =      OPVB   ( 181)
             1. 20015E+03                             1. 32459E+03            -1. 24443E+02

  182       WW     (   1)            MUL             OPVB   ( 181)     =      BBHXGR(  20)
             1. 00000E+05                            -1. 24443E+02            -1. 24443E+07
```

Equation (5). We are neglecting internal and external fouling. The largest (dominant) resistance in the U equation occurs at the steam side of the tubes. It is important to recognize this fact because any change within the system that impacts this term, e.g., steam flow rate, will have a significant impact on the heat transfer rate and consequently on the attemperated steam temperature. Thus, it would not be safe to do a single analysis for this exit temperature and to extrapolate to some other steam flow rate. Note that it is tempting to extrapolate in order to calculate steam flow split ratio for a desired value of mixed, attemperated steam temperature. Instead, the safe approach would be to expand the model to include the flow split, the bypass steam flow, and the remixed steam and cooled steam. Potentially by PEPSE®'s control feature the needed flow split could be determined. This is well within the code's capability, and it is left as an exercise for the interested reader.

Since the calculated pool-boiling-side heat resistance contributes infinitesimally to the calculated overall resistance, it is important to verify that this is the proper type of correlation to be using. The analyst needs to be sure that the shell-side water is at saturation condition and that cooling of the steam is causing boiling of some of the water. If, instead, the water is subcooled and only water heatup is occurring, the shell-side thermal resistance will be dramatically larger than this correlation has calculated. Furthermore, Equation (3) is based on the assumption of constant temperature on the shell side, which would no longer be true. An alternative correlation for film resistance and an alternative form of the NTU-effectiveness equation would be needed for this case.

In this submodel analysis, the reason for activating the debug print (card 010200 of the input set, Table 1) has been to track the behavior of the heat transfer calculations. As discussed in the Analysis Method section, Equation (9), the appearance of heat transfer rate in the h_0 correlation causes the solution to be iterative. As a consequence, overall thermal conductance, U, Equation (5), may change from iterate to iterate. In order to obtain a valid solution, the change of U with iterations must approach zero. It is important to assure this behavior via the debug printout because PEPSE®'s standard mass and energy convergence criteria will not detect effects of U disturbances. The component is always energy balanced, and there is nothing in the model to cause mass flow disturbances. In effect, PEPSE®'s criteria regard the solution as being converged at all iterates. In the particular model at hand, the shell-side resistance, h_0, contributes very little to the overall resistance. Thus, after a very few iterates, h_0 variations from iterate to iterate are of little consequence to the calculated system behavior.

Concluding Remarks

This analysis of a drum attemperator has shown a method of problem solving that enables the user to obtain calculations tailored to his application. While the approach is general, this specific case has analyzed the steam temperature exiting the heat exchanger. The calculation considers the details and mechanisms of heat transfer that occur between the steam and water sides. Because PEPSE® contains no ad hoc model for this particular problem, it was necessary to use a general heat exchange (performance-mode) component combined with PEPSE®'s equation-writing tools (operations) to represent the mechanics. The end result is a user-developed design mode drum attemperator model.

The model is useful as developed to do sensitivity studies and to do design studies of the effects of materials, numbers of tubes, flow rate, cleanliness, and any other parameters contained in the drum's description. Additionally, the drum attemperator could be merged into a larger system model to do system impact studies, such as flow split effects.

As is true of any analysis, care in setting up the equations and technical review of the results are required to validate the method. In the present case, this means being certain that the equations and the correlations are within their range of derivation. In addition, the user needs to be sure that the method has converged in PEPSE®. This is necessary because PEPSE® has not been coded to check convergence of this type of user-designed calculation. This external examination of convergence may require iterate-to-iterate printing of the results by PEPSE®'s debug utility.

References

1. W. C. Kettenacker et al., "PEPSE® Manual, Volume I, User Input Description", Energy Incorporated, Idaho Falls, Idaho, 1985.

2. Anon., "Steam, Its Generation and Use", The Babcock and Wilcox Company, New York, Thirty-Ninth Edition, Third Printing, 1978.

3. J. P. Holman, "Heat Transfer", McGraw-Hill, Inc., New York, 1976.

4. W. C. Kettenacker et al., "PEPSE® Manual, Volume II, Engineering Model Description", Energy Incorporated, Idaho Falls, Idaho, 1985.

5. E. Schmidt, "Properties of Water and Steam in SI-Units", Springer-Verlag, New York, 1969.