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High Pressure Humidification Columns: Design Equations, Algorithm, And Computer Code

Technical Report

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EXECUTIVE SUMMARY

This report describes the detailed development of a computer model used to simulate the humidification of an air stream in contact with a water stream in a countercurrent, packed tower, humidification column. The computer model is written in a FORTRAN programming language and has been developed as a user-model for the Advanced System for Process Engineering (ASPEN) simulator. This was done to utilize the powerful ASPEN flash algorithms as well as to provide ease of use when using ASPEN to model systems containing humidification columns. The model can easily be modified for stand-alone use by incorporating any standard algorithm for performing flash calculations. The model was primarily developed to analyze Humid Air Turbine (HAT) power cycles; however, it can be used for any application that involves a humidifier or saturator. The solution is based on a multiple stage model of a packed column which incorporates mass and energy balances, mass transfer and heat transfer rate expressions, the Lewis relation, and a thermodynamic equilibrium model for the air-water system.

The inlet air properties, inlet water properties and a measure of the mass transfer and heat transfer which occur in the column are the only required input parameters to the model. Several example problems are provided to illustrate the algorithm's ability to generate the temperature of the water, flow rate of the water, temperature of the air, flow rate of the air and humidity of the air as a function of height in the column. The algorithm can be used to model any high-pressure air humidification column operating at pressures up to 50 atm.

This report also provides a fundamental review of the principles involved with humidification for readers not familiar with these concepts. This discussion includes descriptions of various humidification processes, detailed derivations of the relevant expressions, and methods of incorporating these equations into a computer model for a humidification column.

I. INTRODUCTION

I.A. Example Application of High-Pressure Humidification

Consider a simple gas turbine power cycle as shown in Figure 1. Ambient air is compressed and then introduced into a combustion chamber along with a fuel such as natural gas or coal-derived gas. The hot, high pressure gas products from the combustion chamber enter a gas turbine, where power is generated via expansion. The amount of power produced from the gas turbine is a function of the temperature and mass flowrate of the entering gas. For example, a higher temperature and/or mass flowrate of the entering gas will result in more power being generated by the gas turbine. The exhaust stream from the gas turbine is typically very hot, with temperatures exceeding 700 K. In practice, the energy contained in this exhaust stream would be utilized to generate additional power. Several options exist for utilizing the energy contained in the gas turbine exhaust stream, such as the generation of steam which would then be expanded in a steam turbine. A relatively new option, however, is to use this energy to humidify air and generate power with a Humid Air Turbine (HAT).

Patent rights on the HAT power cycle are held by Fluor Daniel (Morton and Rao, 1989). High pressure gas humidification shows promise as a viable means of enhancing the efficiency of gas turbine power cycles using the HAT concept. In this cycle, the dry, high pressure air exiting the gas turbine compressor is contacted with high temperature water in a humidification column. This humidified air is then introduced into the gas turbine combustor. The energy required for humidification is supplied by the gas turbine exhaust stream. In comparison to the simple gas turbine cycle shown in Figure 1, the HAT cycle provides additional power by increasing the mass flowrate (added water vapor) through the gas turbine and improved efficiency by using the energy contained in the gas turbine exhaust stream for humidification.

I.B. Need for a High Pressure Humidification Model

To assess the technical and economic performance of processes that utilize humidifiers or saturators, accurately modelling the high pressure humidification column is important. This model must be capable of predicting the conditions, at pressures up to 50 atm (5 MN/m²), of the air and water streams exiting the humidifier, as well as basic performance information about the column. In addition, the model must be capable of predicting temperature and humidity profiles as a function of height throughout the column.

I.C. Previous Models for Humidification Columns

Parsons, Dotson, and Bechtel (1991) modelled the high pressure humidification of air in their study of regenerative, indirect-fired, coal-fueled gas turbines. Their humidification column was a single stage adiabatic flash drum. The gas cooled and became more humid in this column. The temperature/humidity path of the air followed an adiabatic saturation curve, therefore the effluent air stream exited at the wet bulb temperature of the incoming air, if it was saturated. Although simple to model, this approach cannot enhance the humidity of a high pressure air

Figure 1. Simplified Gas Turbine Power Cycle

stream to the degree possible in a countercurrent column (Morton and Rao, 1989). Furthermore, this model cannot be used for a countercurrent humidification column.

The governing expressions for the simultaneous mass and heat transfer processes occurring within a countercurrent humidification column have been presented by many authors, such as McCabe and Smith (1976), Kern (1950), Foust et al. (1980), and Mickley (1949). The nomenclature used in this report is based on that of McCabe and Smith (1976).

The model of McCabe and Smith (1976) is insufficient for our application because it only provides a solution for the effluent gas enthalpy, and not the temperature or humidity. Kern (1950) determined the properties of the exiting air stream by dividing the column into increments and solving the energy balance equations and the discrete form of the mass transfer and heat transfer equations. Foust et al. (1980) and Mickley (1949) presented a graphical solution which utilized the discrete form of the mass and heat transfer equations, the overall energy balance, the air-water saturation curve, and the Lewis Relation. Although these methods can be used to estimate the properties of the gas stream throughout an atmospheric humidification column, they would require significant modifications for high pressure countercurrent humidification columns such as that used in a HAT power cycle. For example, they would have to be presented in an efficient computer code rather than graphical form, the air-water equilibrium relationships would have to be predicted at various pressures rather than referring to a humidity chart, a technique for solving problems in which either the approach to wet bulb or the column characteristic was specified needs to be developed, modifications for columns in which equilibrium conditions are limiting rather than mass and heat transfer need to be incorporated, corrections for problems in which unrealistic approaches to wet bulb are specified need to be included, and methods for accounting for the change in the liquid flowrate must be made rather than assuming such changes are insignificant.

This need to develop a computer code to model the high pressure humidification column for analyzing the HAT power cycle was previously recognized by Morton and Rao (1989). In their proprietary model, based on the procedure similar to that described by Kern (1950), the column was divided into small sections. The governing mass and heat transfer equations and mass and energy balances were then solved for each column section. Rather than using the Lewis Relation, empirical correlations for mass and heat transfer coefficients were employed. The exiting air stream and entering water stream for each section were assigned as the entering air stream and exiting water stream for the section above. This procedure was continued from the bottom section to the top section of the column. The air exiting the top section corresponded to the air leaving the humidification column. This technique appears to be appropriate for the humidification model. In fact, several published predictions using this technique were matched using our technique.

Sivasubramanian and Boston (1990) also developed a proprietary mass and heat transfer-based approach that is applicable to high pressure staged separations. Their model is used in the RATEFRAC ASPEN model.

I.D. Need for a New Model

Process simulators typically require the inclusion of a separate program for processes that are governed by simultaneous mass and heat transfer. The only two models that are apparently capable of accomplishing this task are the proprietary algorithms of (1) Morton and Rao and (2) Sivasubramanian and Boston. The goal of this report, therefore, is to develop a high pressure countercurrent humidification column model which can be used as a stand-alone model or as a FORTRAN block in an ASPEN simulation of a power plant. This model will require a minimal amount of input data from the user, including the specification of the incoming water and air stream properties and a single measure of the size of the column (the approach to wet bulb or the column characteristic). The model will incorporate each of the modifications detailed in the previous section (I.C), thereby enabling it to be used for a wide variety of humidification problems.

II. HUMIDIFICATION PROCESSES

Many humidification processes can be illustrated on a humidity chart to show the temperature-humidity path of the air as it passes through the humidification column, See Figure 2. Point "A" is the entering gas at T_1 , H_1 . Points *E*, *P*, *Q*, *R* and *S* represent the temperature and humidity of the air as it exits various types of humidifiers. The processes which correspond to the paths shown in Figure 2 are the following:

- AE* adiabatic cooling and humidification.
- AP* cooling and dehumidification of gas.
- AQ* liquid cooling, gas humidification, and heating.
- AR* liquid cooling, gas humidification, and cooling.
- AS* liquid cooling, gas humidification, and cooling, but less humidification than adiabatic cooling

Although all processes increase relative or percent humidity, not all increase absolute humidity. This report considers only the following processes, *AE*, *AQ*, and *AR* because the power cycles to be analyzed are concerned with increasing air humidity. Although the *AS* process increases humidity, it was not considered in this study because the humidity enhancement is less than that attained in adiabatic humidification.

II.A. Adiabatic Gas Cooling and Humidification

In this simple process, curve *AE* of Figure 2, the water stream is not required for another column or process, therefore the column's function is primarily air humidification, not water cooling. The water can be recirculated without being heated or cooled and without makeup water being added to compensate for water lost to the effluent air. The makeup liquid enters at T_s , the steady state water temperature. This operation is illustrated in Figure 3.

Figure 2. Humidity Chart for Various Humidification Operations

**Humidified
Exit Air**

Water

**No Heating or Cooling
of the Recirculated Water**

**Packed
Column**

Pump

**Inlet
Air**

Make-Up Water

Figure 3. Adiabatic Cooling Apparatus

If enough contact occurs between vapor and liquid, the exiting gas and liquid will be in phase equilibrium. The temperature of the liquid reaches a steady state temperature T_s , which is also the adiabatic saturation temperature. The adiabatic saturation temperature is lower than the temperature of the incoming gas (unless the entering gas is saturated, in which case $T=T_s$; but there would be no useful purpose for such a "humidification" column since the air is already saturated). Therefore, the air is cooled and humidified in this process.

Figure 4 shows the temperature and humidity conditions in an adiabatic humidifier. Note that there is no temperature gradient in the liquid. The modelling section of this report will show that the effluent air approaches the saturation humidity only as the column becomes infinitely tall.

II.B. Liquid Cooling, Gas Humidification and Heating

In this column, a water stream is counter-currently contacted by air. The entering, warm liquid exits the column at a lower temperature. The liquid flow rate also decreases due to evaporation, although, in some cases, this change may be 1% or less. The air exits the column at a higher temperature and humidity, as shown by line AQ in Figure 2. The exiting water will be colder than the water entering the column. Therefore, the effluent water would require heating if it was to be recirculated as shown in Figure 5.

Liquid cooling, gas heating and humidification, AQ , has the potential to provide the air stream with the highest humidity of all processes shown in Figure 2. In this case, the temperature of the entering liquid, T_{xa} , is higher than the entering gas temperature, T_{yb} . The temperature requirements of the process are $T_{xa} > T_{yb} > T_{sb} > T_{db}$. Gas humidification and heating (AQ of Figure 2) always occur under these conditions.

II.C. Liquid Cooling, Gas Humidification and Cooling

The effluent air can exit a column at an elevated humidity and a lower temperature if: $T_{yb} > T_{xa} > T_{sb} > T_{db}$. The gas humidification and cooling occurs (AR of Figure 2) as the water cools in this column. Therefore the water would be heated if it were to be recirculated as shown in Figure 5.

Figure 6 illustrates the temperature profile at one point (with respect to column height) within a countercurrent column. Unlike the adiabatic humidification process, the gas at the interface can be much hotter than the bulk gas. Therefore the exiting gas can become saturated at T_s . Mass-transfer equations are no longer valid if this occurs since the mass transport is equilibrium limited. An overall energy balance must be satisfied with the assumption that the exiting gas is saturated.

Figure 4. Profiles at Several Positions Within an Adiabatic Humidification Column

Figure 5. Liquid Cooling, Gas Humidification, and Gas Heating (or Cooling) Apparatus

Figure 6. Profiles at One Position (Height) in a Countercurrent Column

III. SIMPLE MODEL OF A HUMIDIFICATION COLUMN

The simplest model for determining the effluent gas temperature and humidity for any of the processes described above involves only mass and energy balances over the entire column, See Figure 7. The details regarding this model are presented below to provide the reader with a thorough understanding of humidification theory. The computer model described in this report is based on the rigorous model described in Section IV. The main features of the simple humidification model are the following:

- Tower packing, diameter and height of the tower are not considered,
- Mass and heat transfer concepts are not considered, and
- The column can operate at elevated pressures.

The tower performance must be specified in terms of both of the following.

- The approach to wet bulb of the exiting water stream *must be specified*. In the limit the approach is 0° , and T_{wb} of the entering air.
- The exiting gas humidity or relative humidity must be specified. In the limit, the humid air exiting is completely saturated with water.

The danger associated with the use of such a simple model, which ignores the mass and heat rates of transfer between the water and air, include the following.

- The specified approach temperature to wet bulb (*ATWB*), 10°C for example, may be well below the realistic limit, 50°C for example, of the system. This realistic limit can only be determined using a rigorous model of the column.
- The specified relative or percent humidity will correspond to a unique *ATWB*, which is unlikely to coincide with the specified *ATWB*. The appropriate value of effluent humidity that corresponds to the specified *ATWB* can only be determined using a rigorous model.

The determination of the 6 unknowns for this problem requires the solution of six independent equations. The unknowns include: T_{ya} , H_a , H_{ya} , G_{xb} , T_{xb} , H_{xb} .

The three steps required to determine these values are described below.

Step 1. Solve for T_{xb}

$$T_{xb} = T_w \text{ Entering Air} + \text{Approach to Wet Bulb}$$

Figure 7. Column Representation Used in Mass and Energy Balance Model

$$T_{xb} = T_w + ATWB \quad \text{III-1}$$

- $ATWB$ is given
- Solve for T_w (a seventh unknown)

The equations needed to solve for the wet-bulb temperature are as follows:

$$T_w = T_{yb} + (H_b - H_w) \left(\frac{k_y}{h_y} \right) M_b \lambda_w \quad \text{III-2}$$

where

$$\frac{h_y}{M_b K_y} = C_s \left[\frac{k}{\rho_{air} D_v C_s} \right]^{2/3} \quad \text{III-3}$$

The procedure to solve for the wet bulb temperature is detailed below.

- A. P , H_b , H_{yb} , and T_{yb} are all specified.
- B. Guess T_w . An adequate first guess is *(Dew Point T of incoming gas at pressure P + the incoming gas temperature)/2*
- C. Solve for D_v at T_{yb} and P using correlations.
- D. Solve for K_{air} , Q_{air} , $C_{p \text{ H}_2\text{O vapor}}$, $C_{p \text{ air}}$ at T_{yb} and P using correlations.
- E. Solve

$$\left(\frac{h_y}{M_b k_y} \right) = C_s \left[\frac{k}{\rho D_v C_s} \right]^{2/3} \quad \text{III-4}$$

- F. Determine λ_w at T_w from tabular listings or correlations.
- G. Solve for H_w , the dew point composition in terms of humidity at P , T_w
- H. Solve for T_w

$$T_w = T_{yb} + (H_b - H_w) \left(\frac{M_b k_y}{h_y} \right) \lambda_w \quad \text{III-5}$$

- I. Does T_w (determined in step H) = T_w (determined in step B)? If not, change

guess on T_w and repeat.

If the Lewis Relation is used, one iterates on T_w as described above. If an energy balance is done, with T_s as the reference temperature,

$$G'_y H_{gas\ vap\ in} = G'_y H_{gas\ vap\ out} + H_{liq\ in} G_{x\ liq\ in} \quad \text{III-6}$$

$$C_s (T - T_s) + H \lambda_s = H_s \lambda_s + C_s (T_s - T_s) + \left(\frac{G_x}{G_y} \right) C_{p\ liq\ H_2O} (T_s - T_s) \quad \text{III-7}$$

$$C_s = C_{p\ gas} + C_{p\ H_2O\ vapor} H \quad \text{III-8}$$

where H_s = saturated humidity at T_s , and λ_s = latent heat at T_s .

This expression can also be written as:

$$\frac{H - H_s}{T - T_s} = - \frac{C_s}{\lambda_s} = \frac{-(C_{p\ air} + C_{p\ water\ vapor} H)}{\lambda_s} \quad \text{III-9}$$

The value of the steady-state water temperature, T_s , can be determined from this equation. The steps followed in the solution are similar to those above, except that one solves for H_s rather than T_w in step H.

$$H_s = \frac{(C_{p\ air} + C_{p\ water\ vapor} H) (T - T_s) + H \lambda_s}{\lambda_s} \quad \text{III-10}$$

If the guess for T_s is correct, the values of T_s and H_s will correspond to water at T_s and saturated humidity, H_s , at the same temperature. Therefore, determine if these parameters correspond to equilibrium conditions by performing a dew point calculation at T_s and P for the air/water system. The conversion between the molar dew point composition for the equilibrium vapor into a humidity is given by,

where $H_{s,eq}$ is calculated from an equation of state.

$$H_{s-eos} = \frac{M_{H_2O} Y_{H_2O}}{M_{air} (1 - Y_{H_2O})} \quad \text{III-11}$$

Does H_{s-eos} correspond to H_s determined from the energy balance? If so, T_s , H_s is the solution. If not, guess a new T_s until

$$\epsilon = \frac{H_{eos} - H_{s-energy}}{H_{s-energy}} < 0.0001 \quad \text{III-12}$$

$$T_w = T_{yb} + (H_b - H_w) \frac{\lambda_s}{C_s} \quad \text{III-13}$$

Where H_w is the saturated gas humidity at T_w and λ_s is the latent heat at T_w . One can now solve for T_{xb} using Equation III-1.

The Lewis Relation greatly simplifies the mathematics of this problem. Because the systems of interest are at pressures up to 50 atmospheres, the validity of the relation at these conditions must be established. The following expression

$$\frac{h_y}{M_b K_y} = C_s \left[\frac{k}{\rho D_v C_s} \right]^{\frac{2}{3}} \quad \text{III-14}$$

can be simplified to the following form for the air/water system, based on empirical results.

$$\frac{h_y}{C_s M_b K_y} = \left[\frac{k}{\rho D_v C_s} \right]^{\frac{2}{3}} = 1 \quad \text{III-15}$$

This relation, known as the Lewis Relation, should be valid in the pressure range of interest because at pressures between 1-50 atmospheres, k is pressure independent, ρD_v is pressure independent, and C_s is a weak function of pressure.

Step 2. Solve for H_{xb}

Definition of H_{xb} :

$$H_{xb} = C_l(T_{xb} - T_o) \quad (H_{xb}, T_{xb}) \quad \text{III-16}$$

Step 3. Now, there are four unknowns remaining

$$G_{xb}, H_a, T_{ya}, H_{ya}$$

The following four equations can be used to solve for these unknowns.

Water mass balance:

$$G_{xa} + G_y H_b - G_{xb} - G_y H_a = 0 \quad (G_{xb}, H_a) \quad \text{III-17}$$

Total energy balance:

$$G_{xa} H_{xa} + G_y H_{yb} - G_{xb} H_{xb} - G_y H_{ya} = 0 \quad (G_{xb}, H_{xb}, H_{ya}) \quad \text{III-18}$$

Definition of H_{ya} :

$$H_{ya} = H_a(\lambda_o + C_{pH_2O}(T_{ya} - T_o)) + C_{p, air}(T_{ya} - T_o) \quad (H_{ya}, H_a, T_{ya}) \quad \text{III-19}$$

Saturated gas exits if H_a from gas composition is saturated at T_{ya} , P . One may incorporate an "approach to saturation" in terms of percent humidity, for example:

$$H_a = 90\% H_a' \quad \text{III-20}$$

The algorithm for solving these equations is provided below.

- A. Guess G_{xb} ($=99\% G_{xa}$) ($=98\% G_{xb} \dots$) or set $G_{xb} = G_{xa}$
- ↑ B. Solve for H_a , water balance
- ↑ C. Solve for H_{ya} , energy balance
- ↑ D. Solve for T_{ya} , definition of H_{ya}
- ↑ E. Solve for H_a , saturation specification
- ↑ F. Does H_a (step B) = H_a (step E) → yes, solution reached
- ←←no← G. Iterate

If $G_{yb} \leq 0$, the problem cannot be solved; G_{xa} must be higher or the specified outlet air humidity must be lower.

IV. RIGOROUS MODEL OF A HUMIDIFICATION COLUMN

A more rigorous model of this process requires the derivation of governing equations for simultaneous mass transfer and heat transfer in a gas/liquid contact. Consider a small element of a gas warming and humidification and liquid cooling column as shown in Figure 8. Performing an energy balance on the volume of this element, s (cross sectional area)* dZ (change in height), yields

$$G_y' dH_y = d(G_x H_x). \quad \text{IV-1}$$

The rate of heat transfer from liquid to interface is

$$d(G_x H_x) = h_x(T_x - T_i)A_h dZ \quad \text{IV-2}$$

where T_x = Bulk liquid temperature,
 A_h = Heat transfer area/unit volume,
 h_x = Liquid side convective heat transfer coefficient, and
 T_i = Interfacial temperature.

The rate of heat transfer from interface to gas is

$$G_y' C_s dT_y = h_y(T_i - T_y)A_h dZ \quad \text{IV-3}$$

where C_s = Gas heat capacity,
 h_y = Gas-side convective heat transfer coefficient, and
 T_y = Bulk gas temperature.

The rate of mass transfer that occurs from the interface to the gas is

$$G_y' dH = k_y M_b (H_i - H)A_m dZ \quad \text{IV-4}$$

where M_b = gas molecular weight,
 H = Humidity, and
 A_m = "wetted" area for mass transfer.

Because G_x does not change much along the height of the element (this assumption will be relaxed in a later section to provide more precise results).

$$d(G_x H_x) = G_x dH_x = G_x C_p dT_x \quad \text{IV-5}$$

This expression can be substituted into Equation IV-1 to obtain

Figure 8. Differential Element for Rate-Limited Model

$$G_x C_p dT_x = h_x (T_x - T_i) A_h dZ. \quad \text{IV-6}$$

The rate of heat transfer from the liquid to the interface is

$$\frac{dT_x}{(T_x - T_i)} = \frac{h_x A_h}{G_x C_p} dZ. \quad \text{IV-7}$$

Equation IV-3 can be rearranged to yield heat transfer from interface to gas as

$$\frac{dT_y}{(T_i - T_y)} = \frac{h_y A_h}{C_s G_y'} dZ \quad \text{IV-8}$$

and equation IV-4 can be rearranged to yield mass transfer from interface to gas.

$$\frac{dH}{H_i - H} = \frac{k_y M_b A_m}{G_y'} dZ \quad \text{IV-9}$$

Since $G_y' dH_y = d(G_x H_x) = G_x C_p dT_x$, Equation IV-9 can be rearranged as follows.

$$\frac{dH_y}{dT_x} = \frac{G_x C_p}{G_y'} \quad \text{IV-10}$$

A more accurate derivation of dH_y/dT_x is presented later. Other expressions which will be used in the computer algorithm for the simulation of the humidification unit are presented below.

Combination of the mass transfer Equation IV-3 and the heat transfer interface to the Gas (Equation IV-2) yields:

$$G_y' (C_s dT_y + \lambda_o dH) = [\lambda_o k_y M_b (H_i - H) A_m + h_y (T_i - T_y) A_h] dZ \quad \text{IV-11}$$

where usually $A_m = A_h = A$.

Since $H_y = C_s (T - T_o) + H \lambda_o$ then:

$$dH_y \cong C_s dT_y + \lambda_o dH \quad (C_s \cong \text{constant}). \quad \text{IV-12}$$

Making this substitution yields an expression by combining mass transfer and gas-side heat transfer.

$$G_y dH_y = [\lambda_o K_y M_b (H_i - H) A + h_y (T_i - T_y) A] dZ \quad \text{IV-13}$$

If the following Lewis relation is valid for air/H₂O systems,

$$\frac{h_y}{M_b k_y} = C_s \quad \text{IV-14}$$

then h_y can be eliminated from Equation IV-13 and the equation can be simplified using the definition of gas enthalpy,

$$H_i = \lambda_o H_i + C_s (T_i - T_o) \quad \text{IV-15}$$

$$H_y = \lambda_o H_y + C_s (T_y - T_o) \quad \text{IV-16}$$

yielding for combined mass transfer and gas-side heat:

$$\frac{dH_y}{(H_i - H_y)} = \left[\frac{k_y M_b A}{G_y'} \right] dZ. \quad \text{IV-17}$$

Now, the liquid-side heat transfer and enthalpy balance yields:

$$G_y' dH_y - h_x (T_x - T_i) A dZ. \quad \text{IV-18}$$

These two expressions can be rearranged to yield:

$$\frac{(H_i - H_y)}{(T_i - T_y)} = - \frac{h_x}{k_y M_b} = - \frac{h_x C_s}{h_y}. \quad \text{IV-19}$$

Now, dividing Equation IV-4 by Equation IV-17 yields

$$\frac{dT_y / (T_i - T_y)}{dH_y / (H_i - H_y)} = \frac{h_y}{k_y M_b C_s} = 1 \quad (\text{Lewis Relation}) \quad \text{IV-20}$$

$$\frac{dT_y}{dH_y} = \frac{T_i - T_y}{H_i - H_y} \quad \text{IV-21}$$

IV.A. Adiabatic Humidification

For this case only, the following temperature constraints are required: $T_{xa} = T_{xb} = T_i = T_x = T_s$. The expression for heat transfer from the interface to gas is:

$$\frac{dT_y}{T_s - T_y} = \frac{H_{ya}}{C_s G'_s} dZ. \quad \text{IV-22}$$

Using an average C_s , integrate to obtain:

$$LN \frac{T_{yb} - T_s}{T_{ya} - T_s} = \frac{h_y A Z_t}{C_s G'_y} \left(\frac{S}{S} \right) = \frac{h_y A Z_t}{C_s M^1}, \quad V_t = S Z_t, \quad M' = S G'_y. \quad \text{IV-23}$$

The expression for mass transfer from interface to gas can be used to obtain an equivalent expression.

$$LN \frac{H_s - H_b}{H_s - H_a} = \frac{K_y M_b A Z_t}{G_y^1} = \frac{K_y M_b A V_t}{M^1} \quad \text{IV-24}$$

Now, by definition, the number of transfer units is

$$N_t = LN \frac{H_s - H_b}{H_s - H_a} \quad \text{IV-25}$$

therefore, the height of a transfer unit becomes

$$\frac{Z_t}{N_t} = H_t = \frac{\frac{Z_t}{K_y M_b A}}{G'_y} = \frac{G'_y}{K_y M_b A} = H_t \quad \text{IV-26}$$

or

$$N_t = LN \frac{T_{yb} - T_s}{T_{ya} - T_s} \quad \text{IV-27}$$

where,

$$H_t = \frac{G'_y C_s}{H_y A} \quad \text{IV-28}$$

IV.B. Countercurrent Flow Columns for Gas Heating or Cooling

Now consider a countercurrent cooling tower in which a hot dry air stream and warm water enter the column. Gas cooling or heating and humidification can occur along with liquid cooling. Figure 9 illustrates that this column will be modelled as a series of small, discrete sections where mass and heat transfer occur. The air exiting a lower section will enter the section above it as the water which exits the higher section flows into the one below.

The following set of equations represent the governing equations for each section of the column. The equations for heat transfer from the liquid to the interface are,

$$d(G_x H_x) = h_x (T_x - T_i) A dZ \quad \text{IV-29}$$

$$G_x C_x dT_x = h_x (T_x - T_i) A dZ. \quad \text{IV-30}$$

The rate of heat transfer from interface to gas is governed by

$$G_y C_y dT_y = h_y (T_i - T_y) A dZ. \quad \text{IV-31}$$

Mass transfer is governed by

$$G_y dH = k_y M_b (H_i - H) A dZ. \quad \text{IV-32}$$

Figure 9. Discrete Section Model of a Countercurrent Column

These expressions can be combined to yield,

$$\frac{dT_x}{T_x - T_1} = \frac{h_x A}{G_x C_1} dZ, \quad \text{IV-33}$$

$$\frac{dT_y}{T_1 - T_y} = \frac{h_y A}{C_s G_y'} dZ, \quad \text{IV-34}$$

and

$$\frac{dH}{H_1 - H} = \frac{k_y M_b A}{G_y'} dZ. \quad \text{IV-35}$$

The total enthalpy balance for the section is

$$dH_y = \frac{G_x}{G_y'} C_1 dT_x. \quad \text{IV-36}$$

The definition of gas enthalpy is

$$dH_y = C_p dT_y + \lambda_g dH \quad \text{IV-37}$$

These expressions can be further simplified if the following assumptions are made.

- Air/Water System
- Lewis Relation is valid
- $A_h = A_m$
- $dG_x \cong 0$

IV-38

IV-39

Expressions for countercurrent column design can now be derived which include:

$$\frac{dH_y}{H_1 - H_y} = \frac{k_y M_b A}{G_y'} dZ, \quad \text{IV-40}$$

$$G'_y dH_y = h_x (T_x - T_1) A dZ, \quad \text{IV-41}$$

$$\frac{H_1 - H_y}{T_1 - T_x} = \frac{H_x}{k_y M_b} = - \frac{h_x C_s}{H_y}, \quad \text{IV-42}$$

$$\frac{dT_y}{T_1 - T_y} = \frac{dH_y}{H_1 - H_y}, \quad \text{IV-43}$$

and

$$S Z_t = V_t. \quad \text{IV-44}$$

Expressions for the design of the cooling tower can also be derived as follows:

$$\int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H_1 - H_y} = \frac{K_y M_b A}{G'_y} \int_0^{Z_t} dZ = \frac{K_y M_b A}{G'_y} = \frac{K_y M_b A V_t}{M_y}, \quad \text{IV-45}$$

$$\int_{T_{xb}}^{T_{xa}} \frac{dT_y}{T_1 - T_y} = \frac{G'_y}{G_x C_1} \frac{K_y M_b A V_t}{C_1 M_x} = \frac{G'_y}{G_x C_1} \int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H_1 - H_y}, \quad \text{IV-46}$$

$$\int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H_1 - H_y} = \frac{K_y M_b A V_t}{M_y} = \frac{G_x C_1}{G'_y} \int_{T_{xb}}^{T_{xa}} \frac{dT_x}{H_1 - H_y}, \quad \text{IV-47}$$

$$\int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H_1 - H_y} = C_s \int_{T_{yb}}^{T_{ya}} \frac{dT_y}{H_1 - H_y} + \lambda_o \int_{H_b}^{H_a} \frac{dH}{H_1 - H_y}, \quad \text{IV-48}$$

and

$$\int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H_1 - H_y} = \int_{T_{yb}}^{T_{ya}} \frac{dT_y}{T_1 - T_y} = \int_{H_a}^{H_b} \frac{dH}{H_1 - H_y} \quad \text{IV-49}$$

The logic for solving these equations is presented below.

1. Assume that $G_{xb} \approx G_{xa}$.
2. Calculate H_{xb} .
3. Determine the value of the remaining unknowns, T_{xb} , H_a , T_{ya} , H_{ya} .
4. The following gas enthalpy-temperature diagram, Figure 10, illustrates the equilibrium (interface) conditions and operating line (energy balance) for the column.

There will be two general methods for specifying countercurrent problems. Either method requires the inlet water and air properties and flow rates. The column's capability to provide mass and heat transfer must then be specified as either (1) the Approach to Wet Bulb or (2) the column characteristic. Method (1) will require the computation of the characteristic, and method (2) will require the computation of the *ATWB*. If *ATWB* is specified, then T_{xb} can be calculated by adding *ATWB* to the wet bulb temperature of the entering air. Figure 10 can then be constructed for the specific column, thereby, yielding H_{ya} . If the characteristic is specified, one guesses on *ATWB*, constructs the diagram, and calculates the column characteristic as shown below.

$$CH' = \frac{k_y M_b a Z_t}{G_x CL} = \frac{k_y M_b a V_t}{M_x CL} = \int_{T_{xb}}^{T_{xa}} \frac{dT_x}{H_1 - H_y} \quad \text{IV-50}$$

Iteration on *ATWB*, and thereby T_{xa} , continues until the specified column characteristic is attained.

Now, H_a , T_{ya} remain as unknowns. The following expression is valid for the air/water system,

$$\int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H_1 - H_y} = \int_{T_{yb}}^{T_{ya}} \frac{dT_y}{T_1 - T_y} = \int_{T_{ya}}^{T_{yb}} \frac{dT_y}{T_y - T_1} \quad \text{IV-51}$$

5. One can now solve for T_{ya} . Assuming that the change in T_y is linear with respect to T_i (an assumption that can be verified in step 7), one can numerically integrate the enthalpy integral and integrate on T_{ya} until the temperature integral is equivalent to the enthalpy integral. This yields the exiting air temperature.

Figure 10. Equilibrium and Operating Lines for Humidification on the Enthalpy-Temperature Diagram

6. The definition of H_{ya} can now be used to solve for the last unknown, the effluent air humidity.

$$H_{ya} = C_s (T_{ya} - T_o) + H_a \lambda_o \quad \text{IV-52}$$

7. The following expression can be used to verify whether the size of the column; or this section of the column, was too large to justify the assumption used in Step 5.

$$\int_{T_{yb}}^{T_{ya}} \frac{dT_y}{T_i - T_y} = \int_{H_a}^{H_b} \frac{dH}{H_i - H} \quad \text{IV-53}$$

If these do not agree, the size of the column must be reduced in the manner prescribed in the next section of this report.

8. Finally, one must determine if the mass transfer of water into the air was equilibrium limited.

NOTE: In step 6, H_{ya} may be greater than the saturation humidity at the column pressure and the effluent gas temperature. If this occurs, the effluent properties must be solved by (1) guessing in effluent temperature, T_{ya} , (2) using an equation of state to solve for the saturated humidity H and (3) determining if T_{ya} and H satisfy the overall mass and energy balance.

V. DETAILS OF THE COMPUTER ALGORITHM

A large number of equations are associated with the humidification algorithm. Specific details for the algorithm are provided in this section. A block diagram outlining the step-wise calculational sequence for the algorithm is provided in Figure 11. Figure 8 provides a schematic showing all variables associated with a typical humidification column.

V.A. Logic Used to Solve the Entire Column

1. Specification of input data

The following stream data must be provided to the model: P , G_{xA} , T_{xA} , G_y' , T_{yB} , and H_{yB} . An equation of state is used to verify that the inlet water stream is a single liquid phase and the inlet air stream is a single gas phase. Similarly, the effluent streams are checked to verify that the exiting water is a single phase liquid and that the humidified air stream is either undersaturated or saturated, but not supersaturated. If these input streams are not in the correct phase, the

Figure 11. Block Diagram of the Algorithm

program is stopped and an error message is printed.

The column itself must be characterized in one of two ways: the approach temperature to wet bulb (ATWB) or approach to saturation temperature must be specified (the rating mode) or a value of the column characteristic must be specified (the design mode). The ATWB for the rating mode need not be input unless the user wishes to override the default value of 5.5 K. The column characteristic for the design mode is calculated according to the following equation.

$$CH = h_y a Z / (\dot{G}_y' c_p) = k_y M_b a Z / G_y' \quad V-1$$

A more commonly used column characteristic (Perry and Chilton, 1973), CH' , can alternatively be specified if desired.

$$CH' = k_y M_b a Z / G_x = (G_y' / G_x) CH = c_1 \int dT_x / (H_1 - H_y) \quad V-2$$

2. Generation of a high pressure humidity chart

Since the humidification column is operated at high pressures and humidity charts are valid only at atmospheric pressure, the model generates a tabular humidity diagram for the specified pressure. An equation of state is used to generate this table over a wide range of temperatures most likely to be encountered. These humidity values are determined at 1 K temperature increments. Interpolations from the table are performed using an exponential interpolation routine (rather than linear) to ensure a better representation of the saturation curve.

3. Determination of wet-bulb temperature of the entering air

The wet-bulb temperature, T_{wb} , of the entering air (temperature T_{yB} , humidity H_{yB}) is determined using the following expression:

$$T_{wb} = T_{yB} - \lambda_{Twb} (H_{wb} - H_{yB}) / c_p \quad V-3$$

where c_p is evaluated at the average temperature $(T_{wb} + T_{yB})/2$. Values of the latent heat of vaporization are interpolated from a tabular steam table listing. Saturated wet bulb humidities are determined from the table generated in Step 2.

4. Determination of T_{xB}

The temperature of the water exiting the column is determined by summing the approach to wet bulb and the wet bulb temperature of the air entering the column as follows.

$$T_{xB} = T_{wb} + ATWB \quad V-4$$

ATWB is either (a) the default value or specified by the user in the rating mode (it is increased only if it leads to an unrealistic solution), or (b) it is an adjustable parameter which is modified

until the specified column characteristic is attained in the design mode.

5. Division of the column into sections

The column is divided into segments with equivalent change in liquid temperature (not equal size or height). The temperatures at the top and bottom of the entire column are T_{xA} and T_{xB} , respectively. The temperatures at the top and bottom of each section are designated T_{xa} and T_{xb} , respectively. Therefore, for a column divided into N sections,

$$T_{xa} - T_{xb} = (T_{xA} - T_{xB})/N \quad \text{V-5}$$

6. Guess value of G_{xB}

The column must be solved from the bottom to the top. The exiting liquid flowrate, which is less than the entering water flowrate due to evaporation in the column, is initially estimated as a relatively high fraction of G_{xA} , such as $0.98 G_{xA}$.

7. Solve each section of the column

Using the procedure detailed in the next section of this report, the gas and liquid properties throughout the entire column are determined. If an enthalpy crossover occurs, Step 8 is implemented. If a crossover does not occur, the incoming water and exiting air from the last (top) section are used to determine, G_{xA} , T_{yB} , and H_{yB} , and Step 8 is skipped.

8. Enthalpy Crossover Occurs

For any section of the column, if the equilibrium and operating lines intersect, section-by-section computations are ceased and the ATWB is increased. If the ATWB was specified by the user, a message is printed indicating that the ATWB was unrealistic and had to be modified. The ATWB is then increased in 5.5 K increments until the enthalpy crossover disappears. If the column characteristic was specified, the ATWB guess is increased until the crossover disappears.

9. Comparison of calculated G_{xA} with input

G_{xA} , as calculated in either Step 7 or Step 8, must agree with the input value of G_{xA} .

10. G_{xB} modification

If the G_{xA} 's compared in Step 9 are not equal, G_{xB} is modified according to the following equation.

$$G_{xB}^{i+1} = G_{xB}^i + (G_{xA} - G_{xA}^i) \quad \text{V-6}$$

11. Problem specified by ATWB

If the model is being run in the rating mode and water flowrate convergence has been attained, the problem is solved. No more steps are performed.

12. Calculate Column Characteristic

If the water flowrate has converged and the model is being run in the design mode, the characteristic of the simulated column is calculated using either Equation V-1 or V-2.

13. Column Characteristic Convergence

The input column characteristic is compared with the calculated characteristic.

14. Column Characteristic Agreement

If agreement is attained between the actual and calculated column characteristics, the problem is solved. No more steps are performed.

15. Column Characteristic Disagreement

If agreement is not attained, the value of ATWB is modified using Newton's method with a fixed slope until convergence of the column characteristic is attained.

V.B. Solution for a Section of the Column

Consider a discrete section of a humidification column, such as that shown in Figure 8. The properties of the incoming air and exiting water are known. The temperature of the incoming water is known, but its flowrate is not. Due to the lack of high pressure, high temperature, air/water mass and heat transfer coefficient correlations for packed towers, the Lewis Relation (McCabe and Smith, 1976) must be used.

$$h_y/(M_B k_y c_a) = N_{Le} = 1 \quad \text{V-7}$$

This expression is commonly used for atmospheric pressure humidification problems because the actual value of N_{Le} varies from 0.85 to 1.1 as temperature increases from 300 K to 800 K. The effect of pressure on the Lewis number can be estimated from the following expression (McCabe and Smith, 1976).

$$h_y/(M_B k_y c_a) = (N_{sc}/N_{Pr})^{2/3} = (k/\rho D_v c_a)^{2/3} \quad \text{V-8}$$

In the 1 to 50 atm. pressure range, the thermal conductivity and heat capacity of the humid air are very weak functions of pressure, density is proportional to pressure, and the diffusion coefficient is inversely proportional to pressure. Therefore, the pressure effect on the Lewis

number should be small, and the Lewis relation should be valid in the pressure range of interest. The use of the Lewis relation greatly simplifies the solution to the governing equations. More accurate solutions may be obtained if the actual values of the mass and heat transfer coefficients are experimentally determined and then the mass and heat transfer differential equations are solved numerically in a finite difference simulator.

The following step-wise procedure is used to determine the enthalpy, temperature and humidity of the exiting air and the flowrate of the entering water.

1. Determine the specific enthalpy of each inlet stream and the exiting water stream. Since the temperature of the water stream as it enters and exits each column section and the temperature and humidity of the incoming air stream are known, the specific enthalpy of each of these streams can be directly calculated.
2. Determine the humidity and enthalpy of saturated air as a function of temperature at the column pressure, represented by the equilibrium curve shown in Figure 10. This is accomplished by calling the table generated in Step 2 in Section V.A. of this report.
3. Establish the location of the operating line, illustrated in Figure 10. The change in liquid flowrate with respect to height for any section of a column can normally be ignored when determining this slope. A more accurate determination of the slope, which accounted for the change in liquid flowrate in each column section, can be obtained from the following energy balance.

$$G_y' dH_y = d(G_x H_x) \quad \text{V-9}$$

The resultant slope of the operating line becomes

$$dH_y/dT_x = c_l(G_x/G_y')(1 + (H_{xb}(G_{xa} - G_{xb})) / (G_{xb}(H_{xa} - H_{xb}))) \quad \text{V-10}$$

and can be reduced to the commonly used form

$$dH_y/dT_x = c_l(G_x/G_y'). \quad \text{V-11}$$

when the change in the liquid flowrate is ignored. The values for the parameters in the last term of Equation V-10 are established from the previous iteration. The operating line is then established because the coordinates of the point which corresponds to the bottom of the column, T_{xb} , H_{xb} , and the slope of the operating line are known. The temperature of the incoming water, T_{xa} , is known, therefore the enthalpy of the exiting air stream, H_{xa} , can be determined. Equation V-10 yields energy balance errors of 0.01 - 0.05%, while Equation V-11 results in errors at least an order of magnitude larger.

4. Determine the temperature of the interface, where the air is saturated. The slope of the tie line connecting a point on the operating line (T_x , H_y) to the conditions at the interface

at the same position in the column (T_i , H_i) is obtained by equating the heat flux on the liquid and gas sides of the interface and rearranging the result to yield

$$(H_i - H_y)/(T_i - T_y) = -h_x/(k_y M_b) = -h_x c_s/h_y. \quad V-12$$

Often, specific values of h_x and h_y are not known. In these cases, it is assumed that h_x is much greater than h_y , therefore the slope of the tie line is nearly vertical and

$$T_x = T_i. \quad V-13$$

5. Determine the value of the driving force integral and the characteristic of this section of the column. The equality of the following integrals (valid for the air/water system when the Lewis relation is used (McCabe and Smith, 1976)) is used to complete the problem.

$$(c_1 G_x / G_y) \int dT_x / (H_i - H_y) = \int dH_y / (H_i - H_y) = \int dT_y / (T_y - T_i) = \int dH_y / (H_i - H_y) \quad V-14$$

Either of the first two integrals of Equation V-14 is then determined numerically. When the column section is small enough to assume that the enthalpy profiles of the bulk gas and interfacial gas are linear with respect to each other, an analytical integration yields the following expression.

$$\int dH_y / (H_i - H_y) = \frac{(H_{y,s} - H_{y,b}) \ln((H_i - H_{y,s}) / (H_i - H_{y,b}))}{(H_i - H_{y,s}) - (H_i - H_{y,b})} = A \quad V-15$$

The enthalpy of the saturated vapor at the interface is compared to the enthalpy of the bulk vapor at the same position in the column. If at any time the enthalpy of the bulk gas is greater than or equal to the enthalpy of the saturated vapor, the computations are stopped and the ATWB is increased. This corresponds to the specification of an unreasonably small ATWB, resulting in a crossover or intersection of the equilibrium and operating lines.

6. Determine the 'characteristic' of this section of the column. CH is a dimensionless group which is equated to both of the following products (Perry and Chilton, 1973)

$$CH = h_y a Z / (G_y' c_s) = k_y M_b a Z / G_y'. \quad V-16$$

A more commonly used column characteristic (McCabe and Smith, 1976), CH' , can also be calculated

$$CH' = k_y M_b a Z / G_x = (G_y' / G_x) CH = c_1 \int dT_x / (H_i - H_y). \quad V-17$$

7. Determine the temperature of the exiting air. By definition, the enthalpy driving force integral has to be equal to the temperature driving force integral. Having established the

definite enthalpy integral, A , the upper bound, T_{ya} , of the temperature integral which satisfies Equation V-14 is determined. Analytical expressions result when the temperature of the bulk gas and the interfacial gas in this section of the column are assumed to be linear with respect to one another.

a. Gas Cooling

If the incoming water is colder than the incoming air, $T_{xa} < T_{yb}$, then

$$T_{ya} = T_{xa} + (T_{yb} - T_{xb}) \exp -fB \quad V-18$$

$$B = (1/f) \ln ((T_{ya} - T_{xb}) / (T_{ya} - T_{xa})) \quad V-19$$

$$f = 1-m \quad V-20$$

$$m = (T_{xa} - T_{xb}) / (T_{ya} - T_{yb}). \quad V-21$$

b. Isothermal Gas

If the incoming water is at the same temperature as the incoming air, $T_{xa} = T_{yb}$, then

$$T_{ya} = T_{xa}. \quad V-22$$

c. Gas Heating

If the incoming water is warmer than the incoming air, $T_{xa} > T_{yb}$, it is determined whether a temperature crossover occurs in the stage. This corresponds to a position in the stage where $T_x = T_y = T^*$. This occurs whenever the incoming water is warmer than the incoming air, but the effluent water is cooler than the incoming air.

c.1 Gas Heating With Crossover, $T_{xa} > T_{yb}$ and $T_{xb} < T_{yb}$.

Determine the Crossover Temperature, T^* , as follows

$$T^* = (T_{xb} - mT_{yb}) / (1-m). \quad V-23$$

T^* must satisfy the following expression to enable the improper integral obtained when integrating Equation V-14 to have a positive value.

$$T^* < ((T_{ya} + T_{yb}) / 2) \quad V-24$$

If this criterion is not satisfied, the range of liquid cooling which occurs

in the section is increased by specifying that a colder liquid is entering the stage. This corresponds to an increase in the actual size of this section of the column. The expression for the temperature of the effluent air under these conditions becomes

$$T_{ya} = T_{xa} - (T_{yb} - T_{xb}) \exp -fB. \quad V-25$$

c.2 Gas Heating Without Crossover, $T_{xa} > T_{yb}$ and $T_{xb} > T_{yb}$.

Under these conditions, the expression for the temperature of the effluent air is

$$T_{ya} = T_{xa} + (T_{yb} - T_{xb}) \exp -fB. \quad V-26$$

8. Determine the humidity of the exiting air. The enthalpy and temperature of the effluent air are now known, therefore, the humidity is determined by rearranging the definition of gas phase enthalpy

$$H_{ya} = c_s(T_{ya} - T_0) + H_{ya} \quad V-27$$

to obtain the following expression

$$H_{ya} = (H_{ya} - c_{p, \text{air}}(T_y - T_0)) / (c_{p, \text{H}_2\text{O}}(T_y - T_0) + \lambda_0). \quad V-28$$

9. Verify that the integrated solution is accurate. It is then substantiated that the section of the column is small enough to justify the assumptions concerning the nature of the profiles stated in Steps 5 and 7. This is accomplished by determining the value of the humidity driving force integral and comparing it to the enthalpy integral and temperature integral, which were previously equated. Again, an analytical solution is available if the profiles of the interfacial and bulk gas humidity are assumed to be linear.

$$\int dH_y / (H_i - H_y) = \frac{(H_{ya} - H_{yb}) \ln((H_{ia} - H_{ya}) / (H_{ib} - H_{yb}))}{(H_{ia} - H_{ya}) - (H_{ib} - H_{yb})} = C \quad V-29$$

If the integrals C and A agree to within 1 percent, the section of the column is considered to be small enough to enable the analytical expressions for the enthalpy, temperature, and humidity integrals to be used.

10. Determine if the air became supersaturated in this section of the column. Having established the humidity of the air, H_{ya} , at the temperature of the effluent air, T_{ya} , it is necessary to determine if the humidity is less than or equal to the saturation humidity at T_{ya} . If

$$H_{ya} \leq H^*_{T_{ya}} \quad V-30$$

then the solution for humidity based on the assumption of mass and heat transfer limited transport is correct, and proceed to Step 11. The solution for temperature and humidity is incorrect, however, if

$$H_{ya} > H^*_{Tya} \quad \text{V-31}$$

indicating that the transport of water into the air stream is equilibrium limited, not mass transfer limited. Under these conditions, the temperature and humidity of the effluent air stream are determined by assuming that the humidity, H_{ya} , corresponds to the saturation humidity at T_{ya} ,

$$H_{ya} = H^*_{Tya} \quad \text{V-32}$$

and that the temperature and humidity satisfy the mass and energy balances for this section of the column,

$$(G_x + H^*_{Tya} G_y') H_{xa} - G_x H_{xb} = G_y' (H_{ya} - H_{yb}). \quad \text{V-33}$$

Then proceed to (a) guess a temperature T_{ya} (or humidity H^*_{Tya}), such as the incorrect result obtained in Steps 7 (or 8), (b) solve Equation V-32 by referring to the table of temperature versus saturated humidity referred to in step 2, (c) rearrange Equation V-33 to solve for T_{ya} (or H^*_{Tya}), and check for convergence. Having established the temperature and saturated humidity that satisfy Equations V-32 and V-33, the relative size of the section of the column is estimated with Equations V-15, V-29, or the following.

$$\int dT_y / (T_i - T_y) = \frac{(T_{ya} - T_{yb}) \ln((T_{ia} - T_{ya}) / (T_{ia} - T_{yb}))}{(T_{ia} - T_{ya}) - (T_{ib} - T_{yb})} = D \quad \text{V-34}$$

These three integrals, A, C, D, typically agree to within 1 percent. Although Equations V-15, V-29, and V-34 are derived from Equation V-14, which is based on the mass and heat transfer expressions, they still provide an accurate result for the characteristic of this equilibrium-limited section of the column. Although the effluent air may be supersaturated due to round-off error, the degree of supersaturation is very small ($< 1\%$) when the column is divided into 50 sections or more.

If Equation V-31 was satisfied, Step 11 is skipped.

11. Determine the flowrate of the entering water. If the humidity of the effluent air is undersaturated, then a material balance on water is performed to determine the flowrate of the entering water stream.

$$G_{xa} = G_{xb} + G_y' (H_{ya} - H_{yb}) \quad \text{V-35}$$

12. The entering water stream and the exiting air stream are then assigned as the exiting water stream and the entering air stream for the next section (above) of the column, respectively. Since the column is divided into equal increments of change in liquid temperature, the temperature of the incoming liquid stream of the next section is also known. This information enables the procedures listed in Steps 1-11 to be repeated for each section of the column, starting at the bottom and ending at the top.

VI. EXAMPLE PROBLEMS

The input data and output results for two example air humidification problems are provided in Table 1. The first example illustrates a rating application where the exiting air is cooler and more humid than the entering air, i.e. gas cooling. The second example illustrates a design application where the specific column design parameters were used to calculate a column characteristic. This example illustrates an effluent air stream which is hotter and more humid than the incoming air stream, i.e. gas heating. Profiles of the gas temperature, gas humidity and liquid temperature throughout the column for these two examples are illustrated in Figures 12 and 13.

Note that the algorithm provides an exact material balance for the column. The error associated with the energy balance, 0.03%, is representative of all simulations. This error is associated with the assumption that the operating line is linear in each section of the column, although a very slight curvature does occur. Section V.B, Step 3 details the method employed to estimate the slope of the operating line. Simply estimating the slope as $c_1(G_x/G_y')$, which is commonly suggested, yields errors that are about an order of magnitude larger.

Figure 12. Humidity and Temperature Profiles for a Gas Cooling Problem

Figure 13. Humidity and Temperature Profiles for a Gas Heating Problem

Table 1. Input and Output Data for Humidification Examples		
	Gas Cooling (See Figure 12)	Gas Heating (See Figure 13)
Input Data		
Column Pressure, MN/m ²	1.386	1.386
Approach to Wet Bulb, K	22.2	---
Column Characteristic, CH	---	9.596
Entering Liquid Flowrate, kg/hr	6803.9	4309.1
Entering Liquid Temperature, K	422.0	411.5
Entering Dry Air Flowrate, kg/hr	6803.2	1308.2
Entering Air Temperature, K	444.3	322.0
Entering Air Humidity	0.0001	0.0
Column Sections	50	50
Output Results		
Approach to Wet Bulb, K	---	58.7
Column Characteristic, CH	0.578	---
Exiting Liquid Flowrate, kg/hr	6309.1	4054.7
Exiting Liquid Temperature, K	386.3	372.0
Exiting Dry Air Flowrate, kg/hr	6803.2	1308.2
Exiting Air Temperature, K	425.7	408.2
Exiting Air Humidity	0.07283	0.19449
Material Balance Error, % of total	0.0	0.0
Energy Balance Error, % of total	0.027	0.032

VI.A. Effect of Air Temperature on Column Performance

The effect of entering air temperature on column performance (i.e. exiting air humidity and temperature) was examined over a wide range of conditions. The column characteristic was kept constant in all runs, thereby, providing a comparison of results for the same column. The input data and results for these runs are provided in Table 2. The only input parameter that was varied from run to run was the entering air temperature to the column. As seen in Table 2, as the entering air temperature was varied from 294 K to 644 K, the exiting air humidity varied from 0.320 to 0.359, while the exiting air temperature remained relatively constant. Therefore, a doubling of the entering air temperature produced a 12% increase in exit air humidity, while having a negligible effect on the exiting air temperature. An enthalpy versus temperature diagram which illustrates the relationships of the humidity and temperature of the exiting air stream as a function of the temperature of the incoming air is presented in Figure 10.

Table 2. Effect of Entering Air Temperature on Column Performance								
Input Data								
Column Pressure, MN/m ²				1.386				
Column Characteristic, CH				2.0				
Entering Water Flowrate, kg/hr				6.803*10 ⁶				
Entering Water Temperature, K				460.9				
Entering Dry Air Flowrate, kg/hr				3.175*10 ⁶				
Entering Air Humidity				0.001				
Entering Air Temp., K	294.3	310.9	366.5	422.0	477.6	533.2	588.7	644.3
Output Data								
Exiting Air Temp., K	421.0	421.3	421.5	421.8	422.3	422.8	423.4	424.0
Exiting Air Humidity	0.320	0.323	0.326	0.330	0.336	0.342	0.351	0.359

VI.B. Effect of Energy Distribution on Column Performance

Several simulations were performed in which the total enthalpy of the entering air stream and water stream was held constant, but the temperatures of the individual streams were varied. The input data and results for these runs are provided in Table 3. As the temperature of the water entering the column was decreased for a given run, the temperature of the air entering the column was increased such that the total enthalpy of the two streams remained constant from run to run. These calculations were performed external to the model. As the inlet water temperature and inlet air temperature were varied from 463 K to 444 K and 509 K to 674 K, respectively, the exiting air humidity varied from 0.351 to 0.303. The exiting air temperature remained relatively constant for all runs. For a fixed quantity of energy entering the column, these results clearly indicate that the hottest, most humid air was obtained when the temperature of the water entering the column was as high as possible.

Table 3. Effect of Energy Distribution of Entering Streams on Column Performance					
Input Data					
Column Pressure, MN/m ²	1.386				
Column Characteristic, CH	2.0				
Entering Water Flowrate, kg/hr	6.803*10 ⁶				
Entering Dry Air Flowrate, kg/hr	3.175*10 ⁶				
Entering Air Humidity	0.001				
Entering Water Temp., K	463.7	460.9	455.4	449.8	444.3
Entering Air Temp., K	509.8	533.1	580.4	627.6	674.8
Output Data					
Exiting Air Temp., K	423.3	422.8	421.8	420.7	420.1
Exiting Air Humidity	0.351	0.342	0.328	0.315	0.303

VII. CONCLUSIONS

A robust algorithm has been developed for modelling a high pressure, countercurrent air humidification column. This model can be easily implemented in the simulation of any process which includes a high pressure, humidification column. The model is easy to use since the only required input data are the properties of the entering streams and a single parameter which describes the column's mass and heat transfer capabilities. The model generates profiles of temperature and humidity and is capable of adjusting the user-specified or default ATWB if it is unrealistic. The model also determines if the humidification of air is mass transfer limited or equilibrium limited. The material balance for the column is exact, and the energy balance is typically about 0.03% due to the nonlinearity of the operating line.

From parametric studies conducted with the model, it has been shown that the exiting air humidity increases with increased entering air temperature. It has also been shown that by varying the inlet temperatures of the water and air streams to the column, while maintaining a fixed total inlet enthalpy, the temperature and humidity of the exiting air stream increased as the inlet water temperature was increased.

VIII. NOMENCLATURE

a	area available for mass or heat transfer per volume packing
A	definite integral defined in Equation V-15
A	equivalent mass and heat transfer area
A_h	heat transfer area per volume packing
A_m	mass transfer area per volume packing
ATWB	approach to wet bulb
B	constant defined in Equation V-19
c_l	heat capacity of liquid water
$c_{p, \text{air}}$	heat capacity of dry air
$c_{p, \text{H}_2\text{O}}$	heat capacity of water vapor
c_a	heat capacity of humid air
C	definite integral defined in Equation V-29
CH	column characteristic
CH'	column characteristic
D	definite integral defined in Equation V-34
D_v	diffusivity
F	constant defined in Equation V-20
G_x	mass flux of water
G_{xa}	mass flux of water at top of section
G_{xA}	mass flux of water at top of column
G_{xA}^i	G_{xA} from previous iteration
G_{xb}	mass flux of water at bottom of section

G_{xB}	mass flux of water at bottom of column
G_{xB}^i	G_{xB} from previous iteration
G_{xB}^{i+1}	G_{xB} of current iteration
G_y	mass flux of dry air in column
h_x	liquid-side heat transfer coefficient
h_y	gas-side heat transfer coefficient
H_{Ty}^*	saturated gas humidity at temperature T_y
H_i	humidity at the interface
H_{ia}	humidity at the interface at the bottom of the section
H_{ib}	humidity at the interface at the top of the section
H_{wb}	saturation humidity at the wet bulb temperature
H_{ya}	bulk gas humidity at the top of the section
H_{yA}	bulk gas humidity at the top of the column
H_{yb}	bulk gas humidity at the bottom of the section
H_{yB}	bulk gas humidity at the bottom of the column
H_i	enthalpy of gas at the interface
H_{ia}	interfacial gas enthalpy at the top of the section
H_{ib}	interfacial gas enthalpy at the bottom of the section
H_x	liquid enthalpy
H_{xa}	liquid enthalpy at the top of the section
H_{xb}	liquid enthalpy at the bottom of the section
H_y	bulk gas enthalpy
H_{ya}	bulk gas enthalpy at the top of the section
H_{yb}	bulk gas enthalpy at the bottom of the section
k	thermal conductivity of the gas
k_y	gas-side mass transfer coefficient
M_B	molecular weight of air
m	constant defined by Equation V-21
N	number of sections in column
N_{Le}	Lewis number
N_{Pr}	Prandtl number
N_{Sc}	Schmidt number
P	column pressure
T^*	crossover temperature
T_0	reference temperature
T_i	interfacial temperature
T_{ia}	interfacial temperature at the top of the section
T_{ib}	interfacial temperature at the bottom of the section
T_{wb}	wet bulb temperature
T_x	liquid temperature
T_{xa}	liquid temperature at the top of the section
T_{xA}	liquid temperature at the top of the column
T_{xb}	liquid temperature at the bottom of the section
T_{xB}	liquid temperature at the bottom of the column

T_y	bulk gas temperature
T_{ya}	bulk gas temperature at the top of the section
T_{yA}	bulk gas temperature at the top of the column
T_{yb}	bulk gas temperature at the bottom of the section
T_{yB}	bulk gas temperature at the bottom of the column
Z	column height
ρ	gas density

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APPENDIX A

COMPUTER CODE:

FORTRAN BLOCK FOR ASPEN SIMULATION

C THIS PROGRAM CONTAINS A SATURATOR/HUMIDIFIER MODEL DEVELOPED
 C BY ROBERT ENICK, SCOTT KLARA, AND JOHN MARANO
 C
 C LAST REVISION: NOVEMBER 18, 1993 BY: SCOTT KLARA
 C
 C NOTES: (1) ALL UNITS MUST BE IN SI FOR ASPEN FLASH ROUTINE,
 C TEMPERATURE IS KELVIN,
 C PRESSURE IS N/SQM (Pa),
 C ENTHALPY IS J/KGMOLE
 C HEAT CAPACITY IS J/KGMOLE-K
 C (2) THE USER MUST COMPILE THIS PROGRAM FOR ASPEN
 C AS FOLLOWS: ASPCOMP FILENAME (W/O EXTENSION)
 C (3) THE AIR STREAM MUST BE THE FIRST INLET STREAM TO THE
 C USER BLOCK AND THE WATER STREAM MUST BE THE SECOND
 C INLET STREAM TO THE USER BLOCK IN THE ASPEN INPUT
 C (4) O2, N2, AND H2O SHOULD BE THE FIRST THREE COMPONENTS
 C IN THE ASPEN INPUT FILE COMPONENT LIST (IN THAT ORDER)
 C (5) THE PRESSURE USED FOR THE HUMIDIFIER WILL BE THE
 C PRESSURE OF THE INCOMING AIR STREAM
 C (6) THE PRESSURE OF THE INCOMING WATER STREAM MUST BE
 C EQUAL TO OR HIGHER THAN THE PRESSURE OF THE INCOMING
 C AIR STREAM, IF NOT, AN ERROR MESSAGE WILL BE PRINTED
 C IN THE USER OUTPUT FILE FROM THIS SUBROUTINE
 C (7) IT IS ASSUMED THAT THE INCOMING WATER STREAM IS PURE
 C WATER AND NO COMPONENTS OF THE AIR STREAM ARE SOLUBLE
 C IN THE WATER STREAM EXITING THE HUMIDIFIER
 C (8) IT IS ASSUMED THAT THE DRY AIR STREAM IS COMPRISED OF
 C O2 AND N2 ONLY
 C (9) PARAMETERS PASSED FROM ASPEN USER BLOCK:
 C INT(1) = 0, I/O IN PROGRAM UNITS (SI);
 C INT(1) = 1, I/O IN ENGLISH UNITS;
 C INT(2) = NUMBER OF STAGES TO BE USED;
 C INT(3) = 1, ITERATE TO MATCH SPEC COL CHARACTERISTIC;
 C INT(3) = 0, OFF;
 C REAL(1)= APPROACH TO WET BULB TEMP., IN DEG.K FOR
 C INT(1)=0 AND IN DEG.F FOR INT(1)=1
 C REAL(2)= SPECIFIED COLUMN CHARACTERISTIC.
 C (10) FOR EACH STAGE, THE FOLLOWING NOMENCLATURE IS USED.
 C FOR WATER FOR AIR
 C -----
 C HXIN = HXA HYIN = HYB
 C HXOUT = HXB HYOUT = HYA
 C TXIN = TXA TYIN = TYB


```

C      TXOUT = TXB      TYOUT = TYA
C      HUMIN  = HMB
C      HUMOUT = HMA
C
SUBROUTINE HUMBUG (NSIN, NINFI, SIN1, SIN2, SIN3, SIN4,
1      SINFI, NSOUT, NINFO, SOUT1, SOUT2, SOUT3,
2      SOUT4, SINFO, NSUBS, IDXSUB, ITYPE, NINT,
3      INT, NREAL, REAL, IDS, NPO, NBOPST, NIWORK,
4      IWORK, NWORK, WORK, NSIZE, SIZE, INTSIZ)
IMPLICIT REAL*8 (A-H,O-Z)
REAL*8 MWO2, MWN2, MWH2O
INTEGER COLPRN, TINT1, TINT2, TINT3, TINT4, TYINT1, TYINT2
COMMON /STWKWK/ NCPM,NCPCS,NCPNC,NTRIAL,IDUM3(2),TCALC,
1      PCALC,VCALC,QCALC,BETCAL,RDUM(21),RESLTS(1)
DIMENSION INDEX(1)
DIMENSION HUMINT(1000),HINT(1000),TINT(1000),ENTH(1000)
DIMENSION GXP(150),HXP(150),HIP(150),HYP(150),TXP(150),
1      ATWBP(150),TYP(150),HMIP(150),HMYP(150),
1      HMSP(150),ZHP(150),DGDH(150)
EQUIVALENCE (INDEX(1), RESLTS(1))
C      END COMMON /STWKWK/ 2-JUL-1983
COMMON /NCOMP/ NCC, NNCC, NC, NAC, NACC, NVCP, NVNCP, NVACC,
1      NVANCC, NASSAY, NCCASS, IDXWAT, NG
C      END COMMON /NCOMP/ 6-15-83
COMMON /STWORK/ NRETN, NIRETN, NHXF, NHYF, NWYF,
1      NSTW, KK1, KK2, KZ1, KZ2,
2      KA1, KA2, KRET, KRSC, MF,
3      MX, MX1, MX2, MY, MCS,
4      MNC, MHXF, MHYF, MWY, MRETN,
5      MIM, MIC, MIN, MPH, MIRETN,
6      MKBAS, MKPHAS, MTAPP, MKBASS, MTAPPS,
7      KEXT, KLNK, KFOUT, KFOUT1, KPHV,
8      KPHL, KLNGM, MF1, MFST, MSTOIL,
9      MSTOIS, HV, HL, HL1, HL2,
*      SV, SL, SL1, SL2, VV,
1      VL, VL1, VL2, XMWV, XMWL,
2      XMWL1, XMWL2, HCS, HNCS, SSALT,
3      VSALT, MSTOI, MLNKL, MLNKS, MLNKIN,
4      MZWK, MST, MIEXST, MIZWK, HSALT,
5      FSALT, RATIO
C      END COMMON /STWORK/ 09-18-89
COMMON /USER/ RMISS, IMISS, NGBAL, IPASS, IRESTR, ICONVG,
1      LMSG, LPMMSG, KFLAG, NHSTRY, NRPT, NTRMNL,
2      ISIZE

```

```

C  END COMMON /USER/ 09-07-81
  DIMENSION SIN1(1), SIN2(1), SIN3(1), SIN4(1), SOUT1(1),
1      SOUT2(1), SOUT3(1), SOUT4(1), IDXSUB(NSUBS),
2      ITYPE(NSUBS), INT(NINT), REAL(NREAL), IDS(2,13),
3      NBOPST(6,NPO), IWORK(NIWORK), WORK(NWORK),
4      SIZE(NSIZE), INTSIZ(NSIZE)

C
  COMMON /RPTGLB/ IREPFL, ISUB(10), IRGSUM, RSCALE
C  END COMMON /RPTGLB/ 04-10-84
C*****
C PETC COMMON STATEMENTS FOR SUBROUTINES
C*****
  COMMON /PETC1/ TINT, HINT, HUMINT, NPTS
  COMMON /PETC2/ AIRMW, TREF
  COMMON /PETC3/ COLPRN
C*****
C DEFINE VARIABLES FOR COMPONENT SEARCHES IN PACKED ARRAYS
C*****
  COMMON /FRMULA/ FRMULA(3,1)
  CHARACTER*4 FRMULA, O2(3), N2(3), WAT(3)
  DATA O2 /'O2 ',' ',' '/
  DATA N2 /'N2 ',' ',' '/
  DATA WAT /'H2O ',' ',' '/
C*****
C SPECIFY CONSTANTS
C*****
  PARAMETER (MWO2=31.999 , MWN2=28.013 , MWH2O=18.015)
  PARAMETER (IOUT=61)
C SET EXCESS WATER MOLAR FLOWRATE (KG-MOLES/SEC)
  EXCESS = SIN1(NCC+1)*100.
C CONVERT TREF (32 F) TO K AND HREF (1075.1 BTU/LB) TO J/KG
  TREF = (32.0+459.58)/1.8
  HREF = 1075.1*(2.20462/1.0)*(1.0/9.47831D-4)
C*****
C SET INDEX COUNTER VALUE FOR UNPACKING FLASH COMPOSITIONS
C*****
  MINO = MIM - 1
C*****
C OPEN DIAGNOSTIC OUTPUT FILE
C*****
  OPEN (IOUT,FILE='HUMBUG.TXT')
C*****
C RESET OUTPUT ASPEN STREAMS TO ZERO FOR RESTART RUNS
C*****

```

```

      IF(IRESTR.EQ.0.OR.IRESTR.EQ.1)THEN
        DO 10 I=1,NCC
          SOUT1(I) = 0.0
10      SOUT2(I) = 0.0
          IRESTR = 2
        ENDIF
C*****
C SET UNITS CONVERSION FACTORS FOR I/O
C*****
      IUNITS=INT(1)
      IF(IUNITS.EQ.1) THEN
        UCAP = 0.238846/1000.
        UDT = 1.8
        UTEMP=-459.67
        UMASS=2.20462
        UHEAT=9.47831E-4
        UENTH=UHEAT/UMASS
      ELSE
        UCAP = 1.0
        UDT = 1.0
        UTEMP= 0.0
        UHEAT= 1.0
        UMASS= 1.0
        UENTH= 1.0
      ENDIF
C*****
C CHECK PRESSURES OF INCOMING STREAMS AND STOP PROGRAM
C IF P(WATER).LT.P(AIR) AND PRINT OUT ERROR MESSAGE
C*****
      IF(SIN2(NCC+3).LT.SIN1(NCC+3))THEN
        IF(IPASS.EQ.4)WRITE(IOUT,103)
        GOTO 666
      ENDIF
C*****
C CHECK PHASES OF INCOMING STREAMS AND STOP PROGRAM
C IF AIR STREAM OR WATER STREAM ARE TWO PHASES OR THE WRONG SINGLE
PHASE
C*****
      IF(SIN1(NCC+5).NE.1.0.AND.SIN1(NCC+5).NE.0.0)THEN
        IF(IPASS.EQ.4)WRITE(IOUT,120)
        GOTO 666
      ENDIF
      IF(SIN1(NCC+5).EQ.0.0)THEN
        IF(IPASS.EQ.4)WRITE(IOUT,123)

```

```

      GOTO 666
    ENDIF
    IF(SIN2(NCC+6).NE.1.0.AND.SIN2(NCC+6).NE.0.0)THEN
      IF(IPASS.EQ.4)WRITE(IOUT,124)
      GOTO 666
    ENDIF
    IF(SIN2(NCC+6).EQ.0.0)THEN
      IF(IPASS.EQ.4)WRITE(IOUT,125)
      GOTO 666
    ENDIF
C*****
C DETERMINE THE BOILING POINT OF INCOMING WATER STREAM AT GIVEN
PRESSURE
C*****
      PRES=SIN1(NCC+3)*1.45038E-4
      CALL VAPINT (2, TEMP, PRES, HEATVAP)
      TBWAT=(TEMP+459.58)/1.8
C*****
C DEVELOP TABLE OF INTERFACIAL HUMIDITY AND ENTHALPY AS A FUNCTION
OF
C TEMPERATURE OVER A TEMPERATURE RANGE OF (TLOW + 1) TO TTOP
C*****
C
C CALCULATE MOLE FRACTIONS OF INCOMING AIR STREAM ON A "DRY" BASIS
C CALCULATE THE AVERAGE MW OF DRY AIR STREAM
C
      YO2A  = SIN1(1)/(SIN1(1)+SIN1(2))
      YN2A  = SIN1(2)/(SIN1(1)+SIN1(2))
      AIRMW = (YO2A*MWO2) + (YN2A*MWN2)
C
C CALCULATE WATER MOLE FRACTION AND HUMIDITY OF INCOMING AIR
STREAM
C
      YB  = SIN1(3)/SIN1(NCC+1)
      HUMYB = (MWH2O*YB)/(AIRMW*(1.0-YB))
C
C PERFORM WET BULB STEP 1 TO OBTAIN DEW POINT TEMPERATURE OF
INCOMING AIR
C
      DO 11 IJ=1, NCC+9
        WORK(IJ) = SIN1(IJ)
11  CONTINUE
      PRES = SIN1(NCC+3)
      V    = 1.0

```

```

KODE = 3
NPKODE = 2
GUESS = 311.00
MAXIT=100
TOL=1D-04
CALL FLASH (WORK, NSUBS, IDXSUB, ITYPE, NBOPST,
1 KODE, NPKODE, KPHSE, MAXIT, TOL,
2 PRES, V, GUESS, 4, 4, 0, 1, RESLTS(MRETN),
3 INDEX(MIRETN),LCFLAG)
IF(LCFLAG.NE.0)THEN
IF(IPASS.EQ.4)WRITE(IOUT,101)
ENDIF
TDP = TCALC

```

```

C
C CONSTRUCT TABLE FROM THE DEW POINT TEMPERATURE OF THE INCOMING
C AIR STREAM (TDP), OR 273 C, WHICHEVER IS HIGHER,
C TO THE HIGHER TEMPERATURE OF THE INCOMING AIR
C OR WATER STREAMS (TTOP) USING TEMPERATURE INCREMENTS OF TINCR
C

```

```

IF(SIN1(NCC+2).GT.SIN2(NCC+2))THEN
TTOP = SIN1(NCC+2)
ELSE
TTOP = SIN2(NCC+2)
ENDIF
TINCR = 1.0
IF(TDP.GT.273.0)THEN
TLOW = TDP
ELSE
TLOW = 273.15
ENDIF
NPTS = ((TTOP-TLOW)/TINCR) + 2
IF(IUNITS.EQ.1.AND.IPASS.EQ.4)
1 WRITE(IOUT,1130) NPTS,(TINCR*UDT),
1 ((TLOW)*UDT+UTEMP),(TTOP*UDT+UTEMP),
1 (SIN1(NCC+3)*(14.5038/1.0E5))
IF(IUNITS.EQ.0.AND.IPASS.EQ.4)
1 WRITE(IOUT,130) NPTS,TINCR,(TLOW),TTOP,SIN1(NCC+3)

```

```

C
DO 523 I=1,NPTS
IF(I.EQ.1)THEN
TEMP = TLOW
ELSE
TEMP = TEMP + TINCR
ENDIF

```

```

      IF(TEMP.GE.TBWAT)THEN
        HUMINT(I) = 1.0E30
        HINT(I)   = 1.0E30
        TINT(I)   = TEMP
        GOTO 716
      ENDIF
C
C ADD EXCESS WATER TO SATURATE THE INLET AIR STREAM
C WATER IS COMPONENT 3
C
      DO 522 II=1, NCC+9
        WORK(II) = SIN1(II)
522  CONTINUE
      WORK(3)    = SIN1(3)  + EXCESS
      WORK(NCC+1) = SIN1(NCC+1) + EXCESS
      PRES = SIN1(NCC+3)
      KODE = 2
      NPKODE = 2
      MAXIT=100
      TOL=1D-04
      CALL FLASH (WORK, NSUBS, IDXSUB, ITYPE, NBOPST,
1          KODE, NPKODE, KPHSE, MAXIT, TOL,
2          TEMP, PRES, GUESS, 4, 4, 0, 1,
3          RESLTS(MRETN),INDEX(MIRETN),LCFLAG)
      IF(LCFLAG.NE.0)THEN
        IF(IPASS.EQ.4)WRITE(IOUT,101)
      ENDIF
      IF(VCALC.EQ.1)THEN
        IF(IPASS.EQ.4)WRITE(IOUT,122)
        GOTO 666
      ENDIF
C
C FIND LOCATION OF "PACKED" WATER MOLE FRACTION FROM FLASH
CALCULATION
C
      KWAT = KIDVEC(WAT, FRMULA, 3, 1, 3, 1, NCC)
      DO 821 J=1,NCPM
        II = INDEX(MIN0+J)
        IF(II.EQ.KWAT)THEN
          YWAT = RESLTS(MY-1+J)
        ENDIF
821  CONTINUE
C
C CALCULATE INTERFACIAL HUMIDITY AND CS IN J/KG-K

```

```

C      HUMID    = (MWH2O*YWAT)/(AIRMW*(1.0-YWAT))
      HUMINT(I) = HUMID
      CALL CPHEAT (TEMP, HUMID, CPAIR, CPWAT, CS)
C
C CALCULATE INTERFACIAL ENTHALPY
C
      HINT(I) = CS*(TEMP-TREF) + HUMINT(I)*HREF
      TINT(I) = TEMP
C
C OUTPUT SATURATION CURVE DATA AT PRINT TIME
C
716 IF(IUNITS.EQ.1.AND.IPASS.EQ.4)
      1   WRITE(IOUT,131)TINT(I)*UDT+UTEMP,HUMINT(I),
      1   HINT(I)*UENTH
      IF(IUNITS.EQ.0.AND.IPASS.EQ.4)
      1   WRITE(IOUT,131)TINT(I),HUMINT(I),HINT(I)
523 CONTINUE
C *****
C *** DETERMINE THE WET BULB TEMPERATURE FOR THE INCOMING AIR
STREAM ***
C
C APPROACH: (1) DETERMINE THE DEW POINT TEMPERATURE (TDP) OF THE
INCOMING
C      AIR STREAM WHICH WILL BE USED AS A LOWER LIMIT FOR
C      CONVERGENCE ON THE WET BULB TEMPERATURE (TWB), UNLESS
C      TDP IS LESS THAN 273 C, IN WHICH CASE 273 C IS THE LIMIT
C      (2) PERFORM A FLASH ON THE INCOMING AIR STREAM AND AN
C      ARBITRARY INCOMING WATER STREAM. THE WATER STREAM MUST
C      BE LARGE ENOUGH TO SATURATE THE AIR STREAM.
C      (3) ITERATE STEP 2 ON TWB UNTIL THE FOLLOWING EQUATION IS
C      SATISFIED: TWB = TYIN - HEATVAP/CS*(HUMWB-HUMB)
C *****
C ***** WARNING *****
C *** IF THE HUMIDITY OF THE ENTERING AIR IS 0.0000, THE DEW POINT WILL
***
C *** REFER TO THE TEMPERATURE AT WHICH THE AIR BEGINS TO LIQUIFY!
***
C *** THIS WILL NOT AFFECT THE SOLUTION ALGORITHM. REMEMBER WHAT
THESE ***
C *** EXTREMELY LOW TEMPERATURES MEAN, HOWEVER, WHEN THEY APPEAR.
***
C *****
C

```

```

C WRITE HEADER INFORMATION
C
C   IF(IPASS.EQ.4)WRITE(IOUT,104)
C
C INPUT A CONSTANT CP FOR LIQUID WATER IN J/KG-K AT ANY TEMPERATURE
C
C   CPLIQ = 4183.99538
C
C *****
C PERFORM WET BULB STEPS 2 & 3:
C CALCULATE SATURATION TEMPERATURE USING BOUNDED NEWTON'S
C METHOD; IF OUT OF RANGE, UPDATE USING HALF INTERVAL METHOD.
C *****
C
C   TYIN  = SIN1(NCC+2)
C   TLO   = TINT(1)
C   CALL INTERP (0, IPT, TLO, HI, HUMLO)
C   TEMP  = (TLO*1.8) - 459.58
C   CALL VAPINT (1, TEMP, PRES, HEATVAP)
C   HEATVAP = HEATVAP*(2.20462/1.0)*(1.0/9.47831D-4)
C   FLO    = (TYIN-TLO) - (HEATVAP/1020.)*(HUMLO-HUMYB)
C   IF(IPASS.EQ.4) WRITE(IOUT,105) 10000.*UDT+UTEMP,TLO*UDT+UTEMP,
C   &                                10000.*UDT
C   IF(TTOP.GT.TBWAT)THEN
C     THI = TBWAT
C   ELSE
C     THI = TTOP
C   ENDIF
C   CALL INTERP (0, IPT, THI, HI, HUMHI)
C   TEMP  = (THI*1.8) - 459.58
C   CALL VAPINT (1, TEMP, PRES, HEATVAP)
C   HEATVAP = HEATVAP*(2.20462/1.0)*(1.0/9.47831D-4)
C   FHI     = (TYIN-THI) - (HEATVAP/1020.)*(HUMHI-HUMYB)
C   IF(IPASS.EQ.4) WRITE(IOUT,105) TLO*UDT+UTEMP,THI*UDT+UTEMP,
C   &                                (THI-TLO)*UDT
C   TWBB  = 0.5*(TLO+THI)
C
C START ITERATION LOOP FOR WET BULB TEMPERATURE
C
C   TOLD = TLO
C   DO 12 I=3,100
C     CALL INTERP (0, IPT, TWBB, HI, HUMWB)
C     TDIFF = TWBB - TOLD
C     IF(IPASS.EQ.4) WRITE(IOUT,105) TOLD*UDT+UTEMP,TWBB*UDT+UTEMP,

```



```

&                                TDIFF*UDT
IF(DABS(TDIFF).LT. 0.01)GOTO 14
T  = (TWBB+TYIN-TREF)
HUM = 0.5*(HUMWB+HUMYB)
CALL CPHEAT (T, HUM, CPAIR, CPWAT, CS)
TEMP = (TWBB*1.8) - 459.58
CALL VAPINT (1, TEMP, PRES, HEATVAP)
HEATVAP = HEATVAP*(2.20462/1.0)*(1.0/9.47831D-4)
FWB = (TYIN-TWBB) - (HEATVAP/CS)*(HUMWB-HUMYB)
IF(FWB*FLO.GT.0.0)THEN
  TLO = TWBB
  FLO = FWB
ELSE
  THI = TWBB
  FHI = FWB
ENDIF
TOLD = TWBB
DHUMDT = (HUMINT(IPT+1)-HUMINT(IPT))/(TINT(IPT+1)
&      -TINT(IPT))
TWBB = TOLD + FWB/(1+HEATVAP*DHUMDT/CS)
IF(TWBB.LT.TLO .OR. TWBB.GT.THI) TWBB=0.5*(TLO+THI)
12 CONTINUE
14 CONTINUE
ICNT = I
C
C WRITE WET BULB TEMPERATURE RESULTS TO USER OUTPUT FILE ON RESULTS
PASS
C
IF(IPASS.EQ.4)THEN
  IF(IUNITS.EQ.0)THEN
    WRITE(IOUT,100) HUMWB,HUMYB,AIRMW,CS,TDP,TWBB,TDIFF,ICNT
  ELSE
    WRITE(IOUT,1100) HUMWB,HUMYB,AIRMW,CS*UCAP,TDP*UDT+UTEMP,
&      TWBB*UDT+UTEMP,TDIFF*UDT,ICNT
  ENDIF
ENDIF
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCC
C                                C
C START LOOPS FOR THE ENTIRE COLUMN AND THE                      C
C COLUMN INCREMENTS, STARTING AT THE BOTTOM OF COLUMN          C
C                                C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCC

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```

C
C WRITE HUMIDIFICATION HEADER TO PRINT FILE
C
  IF(IPASS.EQ.4)WRITE(IOUT,134)
C
C ICROSS IS THE FLAG FOR INTERNAL ENTHALPY CROSSOVER
C IF THERE IS A CROSSOVER, THE ATWB WILL BE INCREASED BY 2.777 DEGREES
K
C JMULT IS A MULTIPLIER FOR ADDING 2.777 DEGREES
C NO LONGER USED: KKKKK IS A FLAG FOR DOUBLING THE TEMP. INCREMENT
  WHEN A
C      'NO FEASIBLE SOLUTION' CROSSOVER OCCURS
C COLPRN IS THE PRINTER FLAG FOR THE WATER FLOW RATE CONVERGENCE
C
  COLTOL = 1.0D-7
  ICROSS = 0
  JMULT = 1
  KKKKK = 0
  IACOV = 0
  NAOPT = 0
  IAOPT = INT(3)
  ASPEC = REAL(2)
  IF(IAOPT.EQ.1) IACOV = 1
888 CONTINUE
  COLPRN = 0
  TYIN = SIN1(NCC+2)
  ADDWAT = 0.0
  GXA = SIN2(NCC+1)*MWH2O
  GYA = SIN1(NCC+1)*(1.0-YB)*AIRMW
  IF(ICROSS.EQ.1)THEN
    ATWB = REAL(1)/UDT + 2.777*JMULT
    IF(IPASS.EQ.4.AND.IUNITS.EQ.0) WRITE(IOUT,133) ATWB
    IF(IPASS.EQ.4.AND.IUNITS.EQ.1) WRITE(IOUT,1133) ATWB*UDT
    ICROSS = 0
    JMULT = JMULT + 1
  ELSEIF(NAOPT.GT.0)THEN
    ATWBO = ATWB
    ATWB = ATWBO - (ASUM-ASPEC)/(-1.0)
    WRITE(IOUT,*) ATWB
  ELSE
    ATWB = REAL(1)/UDT
    IF(IPASS.EQ.4.AND.IUNITS.EQ.0) WRITE(IOUT,132) ATWB
    IF(IPASS.EQ.4.AND.IUNITS.EQ.1) WRITE(IOUT,1132) ATWB*UDT
  ENDIF

```

```

IF(IAOPT.EQ.1)THEN
  NAOPT = NAOPT + 1
  IF(NAOPT.EQ.20) THEN
    IACOV=0
  ENDIF
ENDIF
NINCR = INT(2)
IF(NINCR.EQ.0) NINCR = (TXIN-TWBB-ATWB)/5./1.8 + 1
IF(NINCR.GT.150) NINCR = 150
C*****
C START LOOP FOR THE ENTIRE COLUMN, MAX OF 10 LOOPS
C TO CONVERGE ON USER INPUT OF GX
C*****
DO 622 NCOLUM = 1,100
  ADDWAT = 0.0
  IF(NCOLUM.EQ.1)THEN
    GXORIG = GXA
    GXORER = 100.0
  ELSE
    GXORER = DABS((GXORIG-GXA)/GXORIG)
    IF(GXORER.LE.COLTOL)THEN
      NCITS = NCOLUM+1
      IF(IACOV.EQ.1.AND.IAOPT.EQ.1) GOTO 625
      COLPRN = 1
      TINT1 = 0
      TINT2 = 0
      TINT3 = 0
      TINT4 = 0
      TYINT1 = 0
      TYINT2 = 0
    ENDIF
    IF(NCOLUM.EQ.50)THEN
      WRITE(IOUT,138)COLTOL,NCOLUM
    ENDIF
    GXA = GXORIG - (GXA-GXOUT)
    TYIN = TYYIN
  ENDIF
  NINCR2 = NINCR
C*****
C START LOOP FOR THE COLUMN INCREMENTS OR STAGES (NINCR)
C*****
DO 621 NIII=1,NINCR
C*****
C PROBLEM CLASSIFICATION

```

C STEP2 - Determination of TXOUT. Add approach to wet bulb.
 C KEEP ACCOUNT OF THE WATER LEAVING AND AIR ENTERING THE
 C BOTTOM, OR FIRST, STAGE. THEIR PROPERTIES WILL BE USED
 C IN THE COLUMN MATERIAL AND ENERGY BALANCES

C*****

```

      IF(NIII.EQ.1)THEN
        HUMIN  = HUMYB
        HUMYY  = HUMIN
        TXOUT  = TWBB + ATWB
        GXOUT  = GXA
        TYYIN  = TYIN
        TXXOUT = TXOUT
  
```

```

      ELSE
        HUMIN  = HUMOUT
        TXOUT  = TXIN
        TYIN   = TYOUT
  
```

```

      ENDIF
  
```

```

6666      IF(KKKKK.EQ.0)THEN
          TXIN  = ((SIN2(NCC+2)-TWBB-ATWB)/NINCR)*NIII +
1          (TWBB+ATWB)
  
```

```

      ELSE
        TXIN  = ((SIN2(NCC+2)-TWBB-ATWB)/NINCR)*(NIII+1)+
1        (TWBB+ATWB)
  
```

```

        KKKKK = 0
        NIII  = NIII + 1
  
```

```

      ENDIF
  
```

C*****

C CHECK FOR LIQUID HEATING

C*****

```

      IF(TXOUT.GE.TXIN)THEN
        IF(IPASS.EQ.4)WRITE(IOUT,121)
        GOTO 666
  
```

```

      ENDIF
  
```

C*****

C WRITE HEADER FOR STAGE NUMBER AND THE TYPE OF HUMIFICATION

C*****

```

      IF(IPASS.EQ.4.AND.COLPRN.EQ.1)THEN
        WRITE(IOUT,111) NIII
        IF(TYIN.GE.TXIN)THEN
          WRITE(IOUT,106)
        ENDIF
        IF((TYIN.LT.TXIN).AND.(TXOUT.LT.TYIN))THEN
          WRITE(IOUT,107)
        ENDIF
  
```

```

      IF((TYIN.LT.TXIN).AND.(TXOUT.GT.TYIN))THEN
        WRITE(IOUT,177)
      ENDIF
    ENDIF
  C*****
  C CALCULATION FOR INLET WATER STREAM ENTHALPY IN J/KG
  C*****
      HXIN = CPLIQ*(TXIN-TREF)
  C*****
  C CALCULATION FOR INLET AIR STREAM ENTHALPY IN J/KG
  C*****
      CALL CPHEAT (TYIN, HUMIN, CPAIR, CPWAT, CS)
      HYIN = CS*(TYIN-TREF) + HUMIN*HREF
      IF(NIII.EQ.1)THEN
        TYYIN = TYIN
        HYYIN = HYIN
      ENDIF
  C*****
  C DETERMINE WATER ENTHALPY AT BOTTOM OF COLUMN CONDITIONS AT
  TXOUT
  C IN J/KG. THIS ASSUMES THAT GX DOES NOT CHANGE SIGNIFICANTLY
  C THROUGHOUT THE STAGE
  C*****
      HXOUT = CPLIQ*(TXOUT-TREF)
      IF(NIII.EQ.1)THEN
        HXXOUT = HXOUT
      ENDIF
  C *****
  C STEP3 - CALCULATE SLOPE (GXGY) FOR TX, HY LINE
  C THIS EQN IS DERIVED BY ASSUMING THAT CHANGES
  C IN THE LIQUID FLOW RATE AND ENTHALPY
  C FROM THE PREVIOUS ITERATION AROUND THE COLUMN
  C CAN BE USED TO ESTIMATE THE DERIVATIVE dGx/dHx
  C *****
      GXGY = CPLIQ*GXA/GYA*(1. + DGDH(NIII))
  C *****
  C STEP4 AND STEP5
  C CALCULATE AREA OF STAGE USING A LOG MEAN APPROXIMATION
  C FOR THE ENTHALPY INTEGRAL
  C*****
      CALL INTERP (0, IPT, TXOUT, HI1, HUMI1)
      HY1 = HYIN
      DH1 = HI1 - HY1
      CALL INTERP (0, IPT, TXIN, HI2, HUMI2)

```

```

      HY2 = GXGY*(TXIN-TXOUT) + HYIN
C*****
C CHECK FOR ENTHALPY CROSSOVER AND HUMIDITY CROSSOVER
C ENTHALPY CROSSOVER IS IDENTICAL TO HUMIDITY CROSSOVER
C THEREFORE, ONLY ONE CHECK IS REQUIRED
C*****
      IF(HI2.LE.HY2)THEN
        ICROSS=1
        IF(IPASS.EQ.4)WRITE(IOUT,115)
        GOTO 888
      ENDIF
      DH2 = HI2 - HY2
      AREA = (HY2-HY1)*DLOG(DH2/DH1)/(DH2-DH1)
      HYOUT = HY2
C*****
C STEP6 - SOLVE FOR THE TYOUT THAT MATCHES THE AREA CALCULATED
      ABOVE
C   - CHECK FOR 'NO FEASIBLE SOLUTION' CROSSOVER, INCREASE TEMP
C   INCREMENT IF THIS OCCURS
C*****
      CALL TINTEG (0,ICONV,IDUM,IOUT,IUNITS,AREA,TXIN,TXOUT,TYIN,
&                TYOUT,KKKKK)
      IF(KKKKK.EQ.1)GOTO 6666
C*****
C STORE CONVERGENCE HISTORY FOR TINTEG
C*****
      IF(ICONV.EQ.-2.AND.COLPRN.EQ.1)TINT1=TINT1+1
      IF(ICONV.EQ.-1.AND.COLPRN.EQ.1)TINT2=TINT2+1
      IF(ICONV.EQ. 0.AND.COLPRN.EQ.1)TINT3=TINT3+1
      IF(ICONV.EQ. 1.AND.COLPRN.EQ.1)TINT4=TINT4+1
C*****
C STEP7 - SOLVE FOR EXIT AIR HUMIDITY BASED ON TYOUT AND HYOUT
      CALCULATED
C   ABOVE USING THIS EQUATION: HYOUT = CS(TYOUT-TREF) +
      HUMOUT*HREF
C*****
      CALL CPHEAT (TYOUT, 0.0, CPAIR, CPWAT, CS)
      HUMOUT = (HYOUT - CPAIR*(TYOUT-TREF))/(HREF + CPWAT*
&                (TYOUT-TREF))
C*****
C CALCULATE AREA OF STAGE USING A LOG MEAN APPROXIMATION
C FOR THE HUMIDITY INTEGRAL
C*****
      CALL INTERP (0, IPT, TXOUT, ENTHAL, HUMID)

```

```

HUMD1 = HUMID-HUMIN
CALL INTERP (0, IPT, TXIN, ENTHAL, HUMID)
HUMD2 = HUMID-HUMOUT
AREAH = (HUMOUT-HUMIN)*DLOG(HUMD2/HUMD1)/(HUMD2-HUMD1)
ARERR = (1.0 - AREAH/AREA)*100
C*****
C WRITE INFORMATION FOR AREA CALCULATION FOR EACH HUMIDIFIER STAGE
C*****
      IF(COLPRN.EQ.1.AND.IPASS.EQ.4)THEN
        WRITE(IOUT,110) AREA,AREAH,ARERR
      ENDIF
C*****
C STEP 8 - DETERMINE IF EXITING AIR STREAM FROM THE STAGE IS SATURATED
C
C IF THE EXITING GAS IS A VAPOR LIQUID MIXTURE, THIS SECTION
C OF THE COLUMN ACTS AS A SATURATOR, AND THE CORRECT COMPOSITION
C OF THE EXITING GAS IS THE SATURATED GAS WHICH SATISFIES THE MASS
C AND ENERGY BALANCE
C*****
      CALL INTERP (0, IPT, TYOUT, ENTHAL, HUMID)
      IF(HUMOUT.GT.HUMID)THEN
        IF(IPASS.EQ.4.AND.COLPRN.EQ.1)WRITE(IOUT,126)
C        IF(IPASS.EQ.4.AND.COLPRN.EQ.1)WRITE(IOUT,1104)
        TYOUT = TYOUT + 15.*(TYOUT-TYIN)
        CALL INTERP (0, IPT, TYOUT, ENTHAL, HUMOUT)
        FLO = 0.0
C*****
C CALCULATE SATURATION TEMPERATURE USING BOUNDED NEWTON'S
C METHOD; IF OUT OF RANGE, UPDATE USING HALF INTERVAL METHOD.
C*****
      DO 881 JS=1, 200
        TITER = TYOUT
        CALL CPHEAT (TITER, HUMOUT, CPAIR, CPWAT, CS)
        F = TITER-TREF-(HYIN-HUMOUT*HREF+(HUMOUT-HUMIN)*HXIN
&          +GXB*(HXIN-HXOUT)/GYA)/CS
        IF(F*FLO.EQ.0.0)THEN
          TLO = TYIN
          FLO = -F
          THI = TITER
          FHI = F
        ELSEIF(F*FLO.GT.0.0)THEN
          TLO = TITER
          FLO = F
        ELSE

```

```

        THI = TITER
        FHI = F
    ENDIF
    DHUMDT = (HUMINT(IPT+1)-HUMINT(IPT))/(TINT(IPT+1)
&          -TINT(IPT))
    TYOUT = TITER - F/(1-(HXIN-HREF)*DHUMDT/CS)
    IF(TYOUT.LT.TLO .OR. TYOUT.GT.TH1)
&      TYOUT = 0.5*(TLO+THI)
    CALL INTERP (0, IPT, TYOUT, HYOUT, HUMOUT)
    TDIFF = TYOUT-TITER
C      IF(COLPRN.EQ.1.AND.IPASS.EQ.4)
C      &      WRITE(IOUT,105) TITER*UDT+UTEMP, TYOUT*UDT+UTEMP,
C      &      TDIFF*UDT
        IF(DABS(F).LE.0.01)THEN
            IF(IPASS.EQ.4.AND.COLPRN.EQ.1)WRITE(IOUT,127)
            IF(COLPRN.EQ.1)TYINT1=TYINT1+1
C
C RECALCULATE AREA
C
        DH2 = HI2 - HYOUT
        AREA = (HY2-HY1)*DLOG(DH2/DH1)/(DH2-DH1)
        GOTO 882
    ENDIF
881    CONTINUE
        IF(IPASS.EQ.4.AND.COLPRN.EQ.1)WRITE(IOUT,128)
        IF(COLPRN.EQ.1)TYINT2=TYINT2+1
882    CONTINUE
    ENDIF
C*****
C STEP8 - Solve for GXB AND ADDWAT
C*****
        GXB = GXA
        GXA = GXA + GYA*(HUMOUT-HUMIN)
        ADDWAT = ADDWAT + ((GXA-GXB)/MWH2O)
C*****
C WRITE STREAM SUMMARY FOR EACH HUMIDIFIER STAGE
C*****
C*****
C INLET STREAM SUMMARY
C*****
        IF(IPASS.EQ.4.AND.COLPRN.EQ.1)THEN
            IF(IUNITS.EQ.0)THEN
                WRITE(IOUT,108) (GXA*3600.0), TXIN, HXIN
                WRITE(IOUT,109) (GYA*3600.0), TYIN, HYIN, HUMIN

```



```

ELSE
  WRITE(IOUT,1108) (GXA*3600.0)*UMASS, TXIN*UDT+UTEMP,
&    HXIN*UENTH
  WRITE(IOUT,1109) (GYA*3600.0)*UMASS, TYIN*UDT+UTEMP,
&    HYIN*UENTH, HUMIN
  ENDIF
ENDIF
C*****
C OUTLET STREAM SUMMARY
C*****
  IF(IPASS.EQ.4.AND.COLPRN.EQ.1)THEN
    IF(IUNITS.EQ.0)THEN
      WRITE(IOUT,112) (GXB*3600.0), TXOUT, HXOUT
      WRITE(IOUT,113) (GYA*3600.0), TYOUT, HYOUT, HUMOUT
    ELSE
      WRITE(IOUT,1112) (GXB*3600.0)*UMASS, TXOUT*UDT+UTEMP,
&    HXOUT*UENTH
      WRITE(IOUT,1113) (GYA*3600.0)*UMASS, TYOUT*UDT+UTEMP,
&    HYOUT*UENTH, HUMOUT
    ENDIF
  ENDIF
C*****
C MATERIAL AND ENERGY BALANCE FOR EACH HUMIDIFIER STAGE
C*****
  HIN = GXA*HXIN*3600.0 + GYA*HYIN*3600.0
  HOUT = GXB*HXOUT*3600.0 + GYA*HYOUT*3600.0
  ERR = (DABS((HIN-HOUT)/HIN))*100.0
  WTIN = GXA + GYA*HUMIN
  WTOUT= GXB + GYA*HUMOUT
  WERR = (DABS((WTIN-WTOUT)/WTIN))*100.0
  HCIN = GXA*HXIN*3600.0 + GYA*HYYIN*3600.0
  HCOU= GXOUT*HXXOUT*3600.0 + GYA*HYOUT*3600.0
  ERRC = (DABS((HCIN-HCOU)/HCIN))*100.0
  WTCIN= GXA + GYA*HUMYY
  WTCOUT=GXOUT + GYA*HUMOUT
  WERRC= (DABS((WTCIN-WTCOUT)/WTCIN))*100.0
  IF(IPASS.EQ.4.AND.COLPRN.EQ.1)THEN
    IF(IUNITS.EQ.0) THEN
      WRITE(IOUT,114) HIN,HOUT,ERR,HCIN,HCOU,ERRC,WERR,WERRC
    ELSE
      WRITE(IOUT,1114) HIN*UHEAT, HOUT*UHEAT, ERR,
1      HCIN*UHEAT,HCOU*UHEAT,ERRC,WERR,WERRC
    ENDIF
  ENDIF

```

```

C*****
C SAVE COLUMN PROFILE INFORMATION
C*****
  IF(NIII.EQ.1)THEN
    GXP(1) = GXB
    HXP(1) = HXOUT
    HIP(1) = HI1
    HYP(1) = HYIN
    TXP(1) = TXOUT
    ATWBP(1) = ATWB
    TYP(1) = TYIN
    HMIP(1) = HUMI1
    HMYP(1) = HUMIN
    CALL INTERP (0, IPT, TYIN, ENTHAL, HMSP(1) )
    ZHP(1) = 0.0
    ASUM = 0.0
  ENDIF
  NIII1=NIII+1
  GXP(NIII1) = GXA
  HXP(NIII1) = HXIN
  HIP(NIII1) = HI2
  HYP(NIII1) = HYOUT
  TXP(NIII1) = TXIN
  CALL INTERP (2, IPT, TAPP, HYOUT, HUMID )
  ATWBP(NIII1) = TXIN-TAPP
  TYP(NIII1) = TYOUT
  HMIP(NIII1) = HUMI2
  HMYP(NIII1) = HUMOUT
  CALL INTERP (0, IPT, TYOUT, ENTHAL, HMSP(NIII1) )
  ASUM = ASUM + AREA
  ZHP(NIII1) = ASUM
  DGDH(NIII) = (HXOUT/GXB)*(GXA-GXB)/(HXIN-HXOUT)
C
C END STAGE DO LOOP
C
  IF(NIII.EQ.NINCR2)GO TO 624
621 CONTINUE
624 CONTINUE
  IF(COLPRN.EQ.1)GOTO 623
622 CONTINUE
623 CONTINUE
C
C CHECK CONVERGENCE OF COLUMN CHARACTERISTIC
C

```

```

625 IF(IAOPT.EQ.1.AND.IACOV.EQ.1)THEN
      IF(DABS(ASUM-ASPEC).LE.0.01*ASPEC) IACOV=0
      GOTO 888
ENDIF
C*****
C PRINT CONVERGENCE SUMMARY
C*****
      IF(IPASS.EQ.4)THEN
        WRITE(IOUT,137)COLTOL,NCITS
        WRITE(IOUT,145)TINT1,TINT2,TINT3,TINT4,TYINT1,TYINT2
      ENDIF
C ICROSS = 0
C*****
C PRINT COLUMN CHARACTERISTIC
C*****
      IF(IPASS.EQ.4)THEN
        WRITE(IOUT,146)
        WRITE(IOUT,147) (GXORIG/GYA),ASUM
        WRITE(IOUT,148) ASUM*(GYA/GXORIG)
        WRITE(IOUT,149)
      ENDIF
C*****
C PRINT TOWER PROFILES
C*****
      IF(IPASS.EQ.4)THEN
        IF(IUNITS.EQ.0)THEN
          WRITE(IOUT,139)
        ELSE
          WRITE(IOUT,140)
        ENDIF
        DO 854 I=NINCR2+1,1,-1
          IF(IUNITS.EQ.0)THEN
            WRITE(IOUT,141) ZHP(I)/ASUM,(GXP(I)*3600.0),
&                          HXP(I),HIP(I),HYP(I),TXP(I)
          ELSE
            WRITE(IOUT,141) ZHP(I)/ASUM,(GXP(I)*3600.0*UMASS),
&                          (HXP(I)*UENTH),(HIP(I)*UENTH),
&                          (HYP(I)*UENTH),(TXP(I)*UDT+UTEMP)
          ENDIF
854 CONTINUE
        IF(IUNITS.EQ.0)THEN
          WRITE(IOUT,142)
        ELSE
          WRITE(IOUT,143)

```

```

ENDIF
DO 855 I=NINCR2+1,1,-1
  IF(IUNITS.EQ.0)THEN
    WRITE(IOUT,144) ZHP(I)/ASUM,ATWBP(I),TYP(I),HMIP(I),
&      HMYIP(I),HMSP(I)
  ELSE
    WRITE(IOUT,144) ZHP(I)/ASUM,(ATWBP(I)*UDT),
&      (TYP(I)*UDT+UTEMP),
&      HMIP(I),HMYIP(I),HMSP(I)
  ENDIF
855  CONTINUE
ENDIF
C*****
C COMPUTE RESULTING PRODUCT STREAMS TO SEND BACK TO ASPEN
C*****
C
C FOR OUTLET AIR STREAM
C
  DO 64 IJ=1, NCC+9
    WORK(IJ) = SIN1(IJ)
64  CONTINUE
    WORK(3) = SIN1(3) + ADDWAT
    WORK(NCC+1) = SIN1(NCC+1) + ADDWAT
    TEMP = TYOUT
    PRES = SIN1(NCC+3)
    KODE = 2
    NPKODE = 2
    MAXIT=100
    TOL=1D-04
    CALL FLASH (WORK, NSUBS, IDXSUB, ITYPE, NBOPST,
1      KODE, NPKODE, KPHSE, MAXIT, TOL,
2      TEMP, PRES, GUESS, 4, 4, 0, 1,
3      RESLTS(MRETN),INDEX(MIRETN),LCFLAG)
    IF(LCFLAG.NE.0)THEN
      IF(IPASS.EQ.4)WRITE(IOUT,101)
    ENDIF
    EXTRA = 0.0
    IF(VCALC.LT.1.0)THEN
      EXTRA = (SIN1(NCC+1)+ADDWAT)*(1.0-VCALC)
      ERRLIQ = (EXTRA/ADDWAT)*100.0
      IF(IPASS.EQ.4)WRITE(IOUT,117) VCALC,ERRLIQ
    ENDIF
    SOUT1(NCC+1) = SIN1(NCC+1) + ADDWAT - EXTRA
    DO 211 I=1,NCPM

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      II = INDEX(MIN0+I)
      SOUT1(II) = RESLTS(MY-1+I)*SOUT1(NCC+1)
211 CONTINUE
      SOUT1(NCC+2) = TCALC
      SOUT1(NCC+3) = PCALC
      SOUT1(NCC+4) = HV/XMWV
      SOUT1(NCC+5) = 1.00D0
      SOUT1(NCC+6) = 0.00D0
      SOUT1(NCC+7) = SV/XMWV
      SOUT1(NCC+8) = XMWV/VV
      SOUT1(NCC+9) = XMWV
C
C FOR OUTLET WATER STREAM
C
      DO 62 IJ=1, NCC+9
        WORK(IJ) = SIN2(IJ)
62 CONTINUE
      WORK(3) = GXOUT/MWH2O + EXTRA
      WORK(NCC+1) = GXOUT/MWH2O + EXTRA
      TEMP = TXXOUT
      PRES = SIN1(NCC+3)
      KODE = 2
      NPKODE = 2
      MAXIT=100
      TOL=1D-04
      CALL FLASH (WORK, NSUBS, IDXSUB, ITYPE, NBOPST,
1          KODE, NPKODE, KPHSE, MAXIT, TOL,
2          TEMP, PRES, GUESS, 4, 4, 0, 1,
3          RESLTS(MRETN),INDEX(MIRETN),LCFLAG)
      IF(LCFLAG.NE.0)THEN
        IF(IPASS.EQ.4)WRITE(IOUT,101)
      ENDIF
      IF(VCALC.GT.0.0)THEN
        IF(IPASS.EQ.4)WRITE(IOUT,116) VCALC
      ENDIF
      SOUT2(NCC+1) = GXOUT/MWH2O + EXTRA
      DO 210 I=1,NCPM
        II = INDEX(MIN0+I)
        SOUT2(II) = RESLTS(MX-1+I)*SOUT2(NCC+1)
210 CONTINUE
      SOUT2(NCC+2) = TCALC
      SOUT2(NCC+3) = PCALC
      SOUT2(NCC+4) = HL/XMWL
      SOUT2(NCC+5) = 0.00D0

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SOUT2(NCC+6) = 1.00D0
SOUT2(NCC+7) = SL/XMWL
SOUT2(NCC+8) = XMWL/VL
SOUT2(NCC+9) = XMWL
C*****
C WRITE OUTLET STREAM SUMMARY FOR ASPEN STREAMS
C*****
      IF(IPASS.EQ.4)THEN
        WRITE(IOUT,118)
        DO 212 I=1,NCC+9
          WRITE(IOUT,119)SOUT1(I),SOUT2(I)
212    CONTINUE
      ENDIF
C*****
C CLOSE USER OUTPUT PRINT FILE
C*****
      CLOSE (IOUT)
C*****
C FORMAT STATEMENTS
C*****
100  FORMAT(/,'HUMIDITY - WET BULB = ',F20.5,' KG H2O/KG DRY AIR',/,
1    'HUMIDITY - YB      = ',F20.5,' KG H2O/KG DRY AIR',/,
1    'MW OF DRY-AIR      = ',F20.5,/,
1    'CS                  = ',F20.5,' J/KG-K',/,
1    'DEW POINT TEMP.    = ',F20.5,' K',/,
1    'WET BULB TEMP.     = ',F20.5,' K',/,
1    'DELTA TEMP.        = ',F20.5,' K',/,
1    'ICNT                = ',9X,I5)
1100 FORMAT(/,'HUMIDITY - WET BULB = ',F20.5,' LB H2O/LB DRY AIR',/,
1    'HUMIDITY - YB      = ',F20.5,' LB H2O/LB DRY AIR',/,
1    'MW OF DRY-AIR      = ',F20.5,/,
1    'CS                  = ',F20.5,' BTU/LB-F',/,
1    'DEW POINT TEMP.    = ',F20.5,' F',/,
1    'WET BULB TEMP.     = ',F20.5,' F',/,
1    'DELTA TEMP.        = ',F20.5,' F',/,
1    'ICNT                = ',9X,I5)
101  FORMAT(1X,'*** LCFLAG NE 0, FLASH CONVERGENCE ERROR ***')
102  FORMAT(1X,'*** KER NE 0, ENTHALPY MODEL ERROR ***')
103  FORMAT(1X,'*** ERROR ***',/, 'THE PRESSURE OF INCOMING WATER
1    STREAM IS LOWER THAN THE PRESSURE OF THE INCOMING AIR STREAM')
104  FORMAT(/,78('*'),/,
1    '***',20X,'WET BULB TEMPERATURE CONVERGENCE',20X,'***',/,
1    78('*'),/,
1    4X,'TITER',9X,'TWB',9X,'TDIFF',/,

```

```

1      4X,'-----',9X,'---',9X,'-----')
1104  FORMAT(/,1X,'*****',/,
1      1X,'SATURATION TEMPERATURE CONVERGENCE',/,
1      1X,'*****',/,
1      4X,'TITER',8X,'TYOUT',8X,'TDIFF',/,
1      4X,'-----',8X,'-----',8X,'-----')
105  FORMAT(1X,F10.5,3X,F10.5,3X,F10.5)
106  FORMAT (/,'GAS COOLING AND HUMIDIFICATION PROBLEM',/)
107  FORMAT (/,'GAS HEATING AND HUMIDIFICATION PROBLEM',/,
1      '    WITH TEMPERATURE CROSSOVER',/)
177  FORMAT (/,'GAS HEATING AND HUMIDIFICATION PROBLEM',/,
1      '    WITHOUT TEMPERATURE CROSSOVER',/)
108  FORMAT (/,'INLET STREAM SUMMARY',/,
1      '-----',/,
1      'WATER INLET FLOW (GXA) =',E12.5,' KG/HR',/,
&      'TEMPERATURE      (TXIN) =',F12.5,' K',/,
&      'ENTHALPY         (HXIN) =',E12.5,' J/KG',/)
1108  FORMAT (/,'INLET STREAM SUMMARY',/,
1      '-----',/,
1      'WATER INLET FLOW (GXA) =',E12.5,' LB/HR',/,
&      'TEMPERATURE      (TXIN) =',F12.5,' F',/,
&      'ENTHALPY         (HXIN) =',E12.5,' BTU/LB',/)
109  FORMAT ('AIR FLOWRATE      (GYB) =',E12.5,' KG DRY-AIR/HR',/,
&      'TEMPERATURE      (TYIN) =',F12.5,' K',/,
&      'ENTHALPY         (HYIN) =',E12.5,' J/KG DRY-AIR',/,
&      'HUMIDITY         (HUMIN) =',F12.5,' KG H2O/KG DRY-AIR',/)
1109  FORMAT ('AIR FLOWRATE      (GYB) =',E12.5,' LB DRY-AIR/HR',/,
&      'TEMPERATURE      (TYIN) =',F12.5,' F',/,
&      'ENTHALPY         (HYIN) =',E12.5,' BTU/LB DRY-AIR',/,
&      'HUMIDITY         (HUMIN) =',F12.5,' LB H2O/LB DRY-AIR',/)
110  FORMAT (3X,'AREA-H',5X,'AREA-HUM',4X,'ERROR',/,
1      3X,'-----',5X,'-----',4X,'-----',/,
1      F10.5,2X,F10.5,F9.2)
111  FORMAT (/,60('*'),/,
1      '****',19X,'STAGE NUMBER ',I3,19X,'****',/,
1      60('*'))
112  FORMAT ('OUTLET STREAM SUMMARY',/,
1      '-----',/,
1      'WATER OUTLET FLOW (GXB) =',E12.5,' KG/HR',/,
&      'TEMPERATURE      (TXOUT) =',F12.5,' K',/,
&      'ENTHALPY         (HXOUT) =',E12.5,' J/KG',/)
1112  FORMAT ('OUTLET STREAM SUMMARY',/,
1      '-----',/,
1      'WATER OUTLET FLOW (GXB)  =',E12.5,' LB/HR',/,

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& 'TEMPERATURE (TXOUT) =',F12.5,' F',/,
& 'ENTHALPY (HXOUT) =',E12.5,' BTU/LB',/)
113 FORMAT ('AIR FLOWRATE (GYA) =',E12.5,' KG DRY-AIR/HR',/,
& 'TEMPERATURE (TYOUT) =',F12.5,' K',/,
& 'ENTHALPY (HYOUT) =',E12.5,' J/KG DRY-AIR',/,
& 'HUMIDITY (HUMOUT) =',F12.5,' KG H2O/KG DRY-AIR')
1113 FORMAT ('AIR FLOWRATE (GYA) =',E12.5,' LB DRY-AIR/HR',/,
& 'TEMPERATURE (TYOUT) =',F12.5,' ',/,
& 'ENTHALPY (HYOUT) =',E12.5,' BTU/LB DRY-AIR',/,
& 'HUMIDITY (HUMOUT) =',F12.5,' LB H2O/LB DRY-AIR')
114 FORMAT (/,'WATER AND ENERGY BALANCE FOR THIS STAGE',/,
1 '-----',/,
1 'TOTAL ENERGY IN =', 1P, E12.5, ' J/HR', /,
& 'TOTAL ENERGY OUT =', E12.5, ' J/HR', /,
& 'PERCENT ERROR = ', 0P, F8.3, ' %', //,
1 'CUM . ENERGY IN =', 1P, E12.5, ' J/HR', /,
1 'CUM . ENERGY OUT =', E12.5, ' J/HR', /,
1 'CUM . PERC. ERROR= ', 0P, F8.3, ' %', //,
1 'WATER MASS BALANCE ERROR=', 0P, F12.9, ' %',/,
1 'CUM . MASS BALANCE ERROR=', 0P, F12.9, ' %',/)
1114 FORMAT (/,'WATER AND ENERGY BALANCE FOR THIS STAGE',/,
1 '-----',/,
1 'TOTAL ENERGY IN =', 1P, E12.5, ' BTU/HR', /,
& 'TOTAL ENERGY OUT =', E12.5, ' BTU/HR', /,
& 'PERCENT ERROR = ', 0P, F8.3, ' %', //,
1 'CUM . ENERGY IN =', 1P, E12.5, ' BTU/HR', /,
1 'CUM . ENERGY OUT =', E12.5, ' BTU/HR', /,
1 'CUM . PERC. ERROR= ', 0P, F8.3, ' %', //,
1 'WATER MASS BALANCE ERROR=', 0P, F12.9, ' %',/,
1 'CUM . MASS BALANCE ERROR=', 0P, F12.9, ' %',/)
115 FORMAT (//,'***** INTERNAL CROSSOVER (GX TOO HIGH/GY TOO LOW)',
& 'APPROACH TOO SMALL) *****',/,
& '***** THE ATWB WILL BE AUTOMATICALLY INCREASED',
& ' AND THE PROBLEM WILL BE STARTED OVER *****',/)
116 FORMAT (//,'***** WARNING - OUTLET WATER STREAM CONTAINS 2',
1 ' PHASES *****',/,
1 ' VCALC =',F10.5)
117 FORMAT (//,'***** WARNING - OUTLET AIR STREAM CONTAINS 2',
1 ' PHASES *****',/,
1 ' VCALC =',F10.5,/,
1 ' LIQUID % DIFFERENCE =',F10.5)
118 FORMAT (//,'*** ASPEN OUTLET STREAM SUMMARY ***',/,
1 '-----',/,
1 9X,'AIR',20X,'WATER',/,

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1      9X,'---',20X,'-----')
119  FORMAT (F20.10,5X,F20.10)
120  FORMAT (/,'***** ERROR - PROGRAM TERMINATED *****',/,
1      /,'***** INCOMING AIR STREAM CONTAINS 2 PHASES *****')
121  FORMAT (/,'***** LIQUID HEATING SPECIFIED - RUN TERMINATED *****')
122  FORMAT (/,'***** INSUFFICIENT EXCESS WATER - RUN TERMINATED *****')
123  FORMAT (/,'***** ERROR - PROGRAM TERMINATED *****',/,
1      /,'***** INCOMING AIR STREAM IS LIQUID PHASE *****')
124  FORMAT (/,'***** ERROR - PROGRAM TERMINATED *****',/,
1      /,'***** INCOMING WATER STREAM CONTAINS 2 PHASES *****')
125  FORMAT (/,'***** ERROR - PROGRAM TERMINATED *****',/,
1      /,'***** INCOMING WATER STREAM IS VAPOR PHASE *****')
126  FORMAT (/,'AIR SATURATED IN THIS STAGE, RECOMPUTE TYOUT')
127  FORMAT (6X,'TYOUT: CONVERGED')
128  FORMAT (6X,'TYOUT: NOT CONVERGED')
129  FORMAT(1X,F10.5,3X,F10.5,3X,F10.5,3X,F10.5,3X,F10.5)
130  FORMAT(78('*'),/,
1      '*****',16X,'INTERFACIAL ENTHALPY AND HUMIDITY CURVE',16X,'*****',/,
1      78('*'),/,
1      1X,'NUMBER OF POINTS      =',I8,/,
1      1X,'TEMPERATURE INCREMENT  =',F8.2,' K',/,
1      1X,'LOW TEMPERATURE        =',F8.2,' K',/,
1      1X,'HIGH TEMPERATURE       =',F8.2,' K',/,
1      1X,'PRESSURE               =',F20.2,' N/M2',/,
1      1X,'TEMP (K)',17X,'HUMIDITY',9X,'ENTHALPY (J/KG)',/,
1      1X,'-----',17X,'-----',9X,'-----')
1130 FORMAT(78('*'),/,
1      '*****',16X,'INTERFACIAL ENTHALPY AND HUMIDITY CURVE',17X,'*****',/,
1      78('*'),/,
1      1X,'NUMBER OF POINTS      =',I8,/,
1      1X,'TEMPERATURE INCREMENT  =',F8.2,' F',/,
1      1X,'LOW TEMPERATURE        =',F8.2,' F',/,
1      1X,'HIGH TEMPERATURE       =',F8.2,' F',/,
1      1X,'PRESSURE               =',F8.2,' PSIA',/,
1      1X,'TEMP (F)',17X,'HUMIDITY',7X,'ENTHALPY (BTU/LB)',/,
1      1X,'-----',17X,'-----',7X,'-----')
131  FORMAT(1X,F8.2,5X,F20.6,5X,F13.2)
132  FORMAT(/,'APPROACH TO WET BULB =',F8.2,' K')
1132 FORMAT(/,'APPROACH TO WET BULB =',F8.2,' F')
133  FORMAT(/,'ADJUSTED APPROACH TO WET BULB =',F8.2,' K')
1133 FORMAT(/,'ADJUSTED APPROACH TO WET BULB =',F8.2,' F')
134  FORMAT(/,78('*'),/,
1      '*****',19X,'BEGIN HUMIDIFICATION CALCULATIONS',20X,'*****',/,
1      78('*'))

```

```

137 FORMAT(/,
1    78('*'),/,
1    '****',26X,'CONVERGENCE HISTORY',27X,'****',/,
1    78('*'),//,
1    'THE INLET WATER FLOW RATE HAS CONVERGED',/,
1    '  TOLERANCE = ',E10.5,/,
1    '  ITERATIONS = ',I10)
138 FORMAT(/,
1    'THE INLET WATER FLOW RATE HAS NOT CONVERGED  **',/,
1    '  TOLERANCE = ',E10.5,/,
1    '  ITERATIONS = ',I10)
139 FORMAT(/,78('*'),/,
&    '****',28X,'COLUMN PROFILES',29X,'****',/,
&    78('*'),//,
&    2X,'Z',6X,'G (KG/HR)',4X,'HX (J/KG)',3X,'HI (J/KG)',
&    3X,'HY (J/KG)',4X,'TX (K)',/,
&    2X,'-',6X,'-----',4X,'-----',3X,'-----',
&    3X,'-----',4X,'-----')
140 FORMAT(/,78('*'),/,
&    '****',28X,'COLUMN PROFILES',29X,'****',/,
&    78('*'),//,
&    2X,'Z',6X,'G (LB/HR)',4X,'HX (BTU/LB)',3X,
&    'HI (BTU/LB)',3X,'HY (BTU/LB)',4X,'TX (F)',/,
&    2X,'-',6X,'-----',4X,'-----',3X,
&    '-----',3X,'-----',4X,'-----')
141 FORMAT(F5.3,4(2X,E12.5),2X,F7.1)
142 FORMAT(/,78('*'),/,
&    '****',28X,'COLUMN PROFILES',29X,'****',/,
&    78('*'),//,
&    2X,'Z',
&    6X,'TAPPR',4X,'TY (K)',7X,'HUMI',10X,'HUMID',
&    8X,'HUMSAT',/,
&    2X,'-',
&    6X,'-----',4X,'-----',7X,'-----',10X,'-----',
&    8X,'-----')
143 FORMAT(/,78('*'),/,
&    '****',28X,'COLUMN PROFILES',29X,'****',/,
&    78('*'),//,
&    2X,'Z',
&    6X,'TAPPR',4X,'TY (F)',7X,'HUMI',10X,'HUMID',
&    8X,'HUMSAT',/,
&    2X,'-',
&    6X,'-----',4X,'-----',7X,'-----',10X,'-----',
&    8X,'-----')

```

```

144 FORMAT(F5.3,2X,F7.1,2X,F7.1,3(2X,F12.5))
145 FORMAT(/,'TINTEG CONVERGENCE SUMMARY',/,
1      ' INPUT TEMP LIMIT ERRORS      =',I4,/,
1      ' MAXIMUM ITERATIONS EXCEEDED =',I4,/,
1      ' NO FEASIBLE SOLUTION          =',I4,/,
1      ' CONVERGED                      =',I4,/,
1      'SATURATED TYOUT CONVERGENCE SUMMARY',/,
1      ' CONVERGED                      =',I4,/,
1      ' NOT CONVERGED                  =',I4)
146 FORMAT(/,78('*'),/,
1      '****',25X,'COLUMN CHARACTERISTICS',25X,'****',/,
1      178('*'))
147 FORMAT(/,
1      'L/G RATIO                      =',F20.5,/,
1      ' ACCORDING TO PERRYS HANDBOOK, L/G FOR MECHANICAL DRAFT',/,
1      ' COOLING TOWERS SHOULD BE BETWEEN 0.75 - 1.50 AND',/,
1      ' THE SECOND COLUMN CHARACTERISTIC LISTED BELOW SHOULD',/,
1      ' BE BETWEEN 0.50 - 2.50',/,
1      'COLUMN CHARACTERISTIC =',F20.5,/,
1      'THIS COLUMN CHARACTERISTIC IS EQUAL TO THE FOLLOWING',/,
1      ' (Ky*Mb*Am*ZT)/Gy or (Ky*Mb*Am*VT)/My',/,
1      ' (hy*Ah*ZT)/(Cs*Gy) or (hy*Ah*VT)/(Cs*My)',/,
1      'or')
148 FORMAT(/,
1      'COLUMN CHARACTERISTIC =',F20.5,/,
1      'THIS COLUMN CHARACTERISTIC IS EQUAL TO THE FOLLOWING',/,
1      ' (Ky*Mb*Am*ZT)/Gx, (Ky*Mb*Am*VT)/Mx, IF CI IS ABOUT UNITY')
149 FORMAT(/,
1      ' where: Ky = gas mass transfer coefficient (lb-mol/ft2-h)',/,
1      ' Mb = dry-air molecular weight (lb/lb mol)',/,
1      ' Am = transfer area for mass transfer (ft2/ft3)',/,
1      ' ZT = total column height (ft)',/,
1      ' Gy = dry-air flux (lb/ft2-h)',/,
1      ' hy = gas heat transfer coefficient (Btu/ft2-h-F)',/,
1      ' Ah = transfer area for heat transfer (ft2/ft3)',/,
1      ' Cs = humid heat (Btu/lb-F)',/,
1      ' hx = liquid heat transfer coefficient (Btu/ft2-h-F)',
1      '/',
1      ' Ci = specific heat of liquid (Btu/lb-F)',/,
1      ' Gx = liquid mass flux (lb/ft2-h)',/,
1      ' VT = total contact volume (ft3)',/,
1      ' My = dry-air flowrate (lb/h)',/,
1      ' Mx = liquid mass flowrate (lb/h)',/)

```

C

C PROGRAM STOPPED BECAUSE OF ERROR
 C SET OUTLET STREAMS EQUAL TO INLET STREAMS SO THAT ASPEN CAN
 C CONTINUE CALCULATIONS

C
 C

RETURN

666 DO 65 IJI=1, NCC+9

SOUT1(IJI) = SIN1(IJI)

SOUT2(IJI) = SIN2(IJI)

65 CONTINUE

SOUT1(3) = SIN1(3) + 0.05

SOUT1(NCC+1) = SIN1(NCC+1) + 0.05

SOUT2(3) = SIN2(3) - 0.05

SOUT2(NCC+1) = SIN2(NCC+1) - 0.05

RETURN

END

C*****

SUBROUTINE TINTEG (IDS, ICSV, NIT, IO, IU, A, TXA, TXB, TYB,
 1 TYA, KKKKK)

C*****

C This subroutine evaluates the integral of $dTy/(Ty-TI)$ between the
 C limits TyA and TyB, and solves for TyA given the area, A; and TxA,
 C TxB, and TyB. This integral appears in gas humidification problems
 C where:

C

C TXA = Inlet temperature of liquid;

C TXB = Outlet temperature of liquid;

C TYB = Inlet temperature of gas;

C TYA = Outlet temperature of humidified gas;

C TI = Gas/Liquid interface temperature.

C

C The interface temperature is assumed to be a linear function of Ty
 C with slope $m(TyA)$ equal to $(TxA-TxB)/(TyA-TyB)$, and intercept
 C $TxB-m*TyB$. There are three solutions to the above integral. If Ty
 C does not equal TI within the interval TyA to TyB, the solution is:

C

C $F1(TyA) = F2(TyA)$ Eq.1

C

C However, if $m = 1$, the degenerative solution is found:

C

C $F1(TyA) = 1$ Eq.2

C

C If TyA equals TyB within the interval TyA to TyB, the integral is an
 C improper integral, and a different solution is obtained:

```

C
C          F1(TyA) = -F2(TyA)          Eq.3
C
C In the above:    F1 = (TyA-TxA)/(TyB-TxB)
C                  F2 = exp[(m(TyA)-1)*Area]
C
C Which solution is valid depends on the type of problem being solved,
C ie. gas cooling/liquid cooling, gas cooling/liquid heating, gas
C heating/liquid cooling, or gas heating/liquid subcooling. Limiting
C solutions exist for TxA = TxB, TxA = TyB, or TxB = TyB. The above
C equations may have one, two or no real roots.
C
C The integer parameters in the argument list are:
C
C     IDS - controls how direct substitution is applied to solve
C           Eqs.1 and 2; if = 1: calculate F2, solve for TyA
C           using F1, iterate; if = 2: calculate F1, solve for
C           TyA using F2, iterate; if = 0: an algorithm picks the
C           scheme to find the feasible solution (if any).
C     ICNV - if = 1, iteration has converged to a solution, if = 0,
C           no solution found, if = -1, ran out of iterations
C           before solution was found, and if = -2, error found
C           in input data.
C     NIT  - number of iterations performed.
C     IO   - number for output device.
C     IU   - temperature print units, if = 0 Kelvin, if = 1, deg.F
C
C Coding and testing completed 01/06/93 by J.J. Marano/BRSC.
C Updated 02/05/93 to find feasible solutions (IJM).
C
C

```

```

C     IMPLICIT REAL*8 (A-H,O-Z)
C     REAL*8 M
C     COMMON /PETC3/ COLPRN
C     INTEGER COLPRN
C     PARAMETER (NMAX=100, ATOL=0.01)

```

```

C*****

```

```

C SET UNITS

```

```

C*****

```

```

C     IF(IU.EQ.0)THEN
C         UTEMP = 0.0
C         UDT   = 1.0
C     ELSE
C         UTEMP = -459.67

```

```

    UDT = 1.8
ENDIF
C
JDS = IDS
ICNV = 1
N = 0
SIGN = 1.0
TNEW = TYB
DTX = TXA - TXB
DTB = TYB - TXB
C
IF(DTB.NE.0)THEN
    AO = -DTX/DTB
ELSE
    AO = 1.E10
ENDIF
C IF(COLPRN.EQ.1)WRITE(IO,1)IDS, TYB, A, TXA, TXB
C *****
C Problem Classification
C *****
    IF(TYB.GT.TXA)THEN
        TLO = TXA
        THI = TYB
        IF(TXA.GT.TXB)THEN
C *****
C Gas cooling/liquid cooling
C *****
            IF(JDS.EQ.0)THEN
                IF((TYB-TXA).GE.DTB*DEXP((DTX/(TXA-TYB)-1.)*A))THEN
                    JDS = 1
                ELSE
                    JDS = 2
                ENDIF
            ENDIF
            IF(JDS.EQ.1)THEN
                T = TXA
            ELSE
                T = TYB
            ENDIF
        ELSE
C *****
C Gas cooling/liquid heating
C *****
            IF(JDS.EQ.0)THEN

```

```

        JDS = 1
        IF(A.LT.AO)JDS=2
    ENDIF
C*****
C Initialization
C*****
        IF(JDS.EQ.1)THEN
            T = TXA + DTB*DEXP(-A)
        ELSE
            T = TYB
        ENDIF
C*****
C Check for input temperature limit error
C*****
        IF(TXB.GT.TYB)THEN
            ICNV =-2
            GOTO 100
C*****
C Check for TXB equal to TYB
C*****
        ELSEIF(TXB.EQ.TYB)THEN
            IF(IDS.EQ.0)THEN
                JDS = 2
                IF(COLPRN.EQ.1)THEN
C                    WRITE(IO,2)JDS,TLO*UDT+UTEMP,THI*UDT+UTEMP,AO
C                    WRITE(IO,5)N,TNEW*UDT+UTEMP,100000.,100000.
                ENDIF
                GOTO 100
            ENDIF
        ENDIF
        ELSEIF
        ENDIF
        ELSEIF(TYB.LT.TXA)THEN
            TLO = TYB
            THI = TXA
            IF(TYB.GT.TXB)THEN
C*****
C Gas heating/liquid subcooling
C*****
                IF(JDS.EQ.0)JDS = 2
                SIGN =-1.0
                ELSEIF(TYB.LT.TXB)THEN
C*****
C Gas heating/"normal" liquid cooling
C*****

```

```

        IF(JDS.EQ.0)THEN
            JDS = 1
            IF(A.LT.AO)JDS = 2
        ENDIF
C*****
C Check for input temperature limit error
C*****
        IF(TXB.GT.TXA)THEN
            ICNV =-2
            GOTO 100
        ENDIF
    ELSE
C*****
C Gas heating/TXB equal to TYB
C*****
        IF(JDS.EQ.0)THEN
            JDS = 2
            IF(COLPRN.EQ.1)THEN
C                WRITE (IO,2) JDS, TLO*UDT+UTEMP, THI*UDT+UTEMP, AO
C                WRITE (IO,5) N, TNEW*UDT+UTEMP, 100000., 100000.
            ENDIF
            GOTO 100
        ENDIF
    END IF
C*****
C Initialization
C*****
        IF (JDS.EQ.1) THEN
            T = TXA + SIGN*DTB*DEXP(-A)
        ELSE
            T = TYB
        ENDIF
C
    ELSE
C*****
C Gas isothermal/liquid cooling; check for input temperature
C limit error
C*****
        IF(TXB.GT.TXA)THEN
            ICNV =-2
        ELSE
            IF(COLPRN.EQ.1)THEN
C                WRITE(IO,2) JDS, TNEW*UDT+UTEMP, TNEW*UDT+UTEMP, AO
C                WRITE(IO,5) N, TNEW*UDT+UTEMP, 100000., 100000.
            ENDIF
        ENDIF
    END IF

```



```

        ENDIF
    ENDIF
    GOTO 100
C
    END IF
C    IF(COLPRN.EQ.1)WRITE(IO,2)JDS,TLO*UDT+UTEMP,THI*UDT+UTEMP,AO
C
C    Perform iterations on F1 and F2 using direct substitution.
C
    NTEN = 1
    TOLD = TLO - 1.0
    DO 10 N = 1, NMAX
        IF (JDS.EQ.1) THEN
C
C        Calculate F2 with old T, solve F1 for TNEW.
C
            TNEW = TXA + SIGN*DTB*DEXP((DTX/(T-TYB)-1.)*A)
            ELSE
C
C        Calculate F1 with old T, solve F2 for TNEW.
C
            TNEW = TYB + DTX/(1.+DLOG(SIGN*(T-TXA)/DTB)/A)
            END IF
C
            DTY = TNEW - TYB
            IF (DTX.EQ.0 .AND. DTY.EQ.0) THEN
                M = 1.0
            ELSE
                IF (DTY.EQ.0) DTY = 1.E-10
                M = DTX/DTY
            END IF
C
            IF(COLPRN.EQ.1)WRITE(IO,5)N,TNEW*UDT+UTEMP,T*UDT+UTEMP,M
C*****
C    Check temperature limits
C*****
        IF(TNEW.LT.TLO)THEN
            TNEW = THI
            ICNV = 0
            GOTO 100
        ELSEIF(TNEW.GT.THI)THEN
            TNEW = TLO
            ICNV = 0
            GOTO 100
        ENDIF
    
```

```

C*****
C Check for convergence
C*****
      IF ( ABS(TNEW-T).LE.ATOL ) GO TO 100
C
C Check for cycling after every tenth iteration; reverse
C iteration scheme if necessary.
C
      IF ( N/10.EQ.NTEN .AND. (TNEW-T)/(T-TOLD).LT. 0.0 ) THEN
        IF (IDS.EQ.0) THEN
          IF (JDS.EQ.1) THEN
            JDS = 2
          ELSE
            JDS = 1
          END IF
        END IF
      END IF
C      IF(COLPRN.EQ.1)WRITE( IO, 6 ) JDS
C
C Update temperature guess.
C
      T = 0.5*(T+TNEW)
      ELSE
        TOLD = T
        T = TNEW
      END IF
      IF (N.EQ.10*NTEN) NTEN = NTEN + 1
C
10 CONTINUE
      ICNV =-1
      N = NMAX
C
100 NIT = N
      TYA = TNEW
      IF(ICNV.EQ.-2.AND.COLPRN.EQ.1)WRITE(IO,101)
      IF(ICNV.EQ.-1.AND.COLPRN.EQ.1)WRITE(IO,102)
      IF(ICNV.EQ.0)THEN
        TYA = (TXA+TYB)/2.0
C
C REMOVE THIS IF YOU DESIRE TO STACK YOUR STAGES IF CROSSOVER
C OCCURS AND NO FEASIBLE SOLUTION IS FOUND, OTHERWISE TYA
C WILL BE DETERMINED AS SHOWN ABOVE.
C      KKKKK = 1
      IF(COLPRN.EQ.1)WRITE(IO,103)
      ENDIF

```

```

      IF(ICNV.EQ.1.AND.COLPRN.EQ.1)WRITE(IO,104)
C*****
C  FORMAT STATEMENTS
C*****
      1 FORMAT (//'*** SOLVING FOR THE OUTLET GAS TEMPERATURE ***',/,
        &'TINTEG: IDS =', I3,' TYB =', F8.3, 16X,
        &' AREA =', F8.4,
        &' /, 'TINTEG: ', ' TXA =', F8.3,' TXB =', F8.3 )
      2 FORMAT ('TINTEG: JDS =', I3,' TLO =', F8.3,' THI =', F8.3,
        &' AM1 =', F8.4 )
      5 FORMAT ('TINTEG: ITER =', I3,' TNEW =', F8.3,' TOLD =', F8.3,
        &' M =', F8.4 )
      6 FORMAT ('TINTEG: JDS =', I3 )
     101 FORMAT ('TINTEG: INPUT TEMP LIMIT ERROR',/)
     102 FORMAT ('TINTEG: MAX ITERATIONS EXCEEDED',/)
     103 FORMAT ('TINTEG: NO FEASIBLE SOLUTION FOUND',/,
       1 ' AVERAGE TEMPERATURE WILL BE USED',/)
     104 FORMAT ('TINTEG: CONVERGED',/)
      RETURN
      END
C*****
      SUBROUTINE INTERP (INT, IPT, TS, HI, HUMID)
C*****
C
C  INT = 0 :
C  Given a temperature, this subroutine performs a table look up
C  for interfacial enthalpy and humidity for the air/water system.
C
C  INT = 1 :
C  Given a humidity, look up temperature and enthalpy.
C
C  INT = 2 :
C  Given an enthalpy, look up temperature.
C
C  Linear interpolation for T vs. H, and 1/T vs. ln(Hum).
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /PETC1/ TINT, HINT, HUMINT, NPTS
      DIMENSION TINT(1000),HINT(1000),HUMINT(1000)
      PARAMETER (IOUT=61)
C
C  TS known, find HI AND HUMID
C
      IF (INT.EQ.0) THEN

```

```

IF (TS.LT.TINT(1) ) THEN
  WRITE ( IOUT, 10 ) TS
10  FORMAT ( '***** TEMPERATURE ',
    &      1P, E12.5, ' IS OUTSIDE RANGE OF DATA *****' )
  HI   = HINT(1)
  HUMID = HUMINT(1)
  IPT  = 1
  GO TO 99
ELSEIF (TS.GT.TINT(NPTS) ) THEN
  WRITE ( IOUT, 10 ) TS
  HI   = HINT(NPTS)
  HUMID = HUMINT(NPTS)
  IPT  = NPTS-1
  GO TO 99
ENDIF
C
DO 15 N = 1, NPTS-1
  IF (TS.GE.TINT(N) .AND. TS.LE.TINT(N+1)) GO TO 20
15 CONTINUE
C
20 F   = (TS - TINT(N) )/( TINT(N+1) - TINT(N) )
  HI   = (1.-F)*HINT(N)  + F*HINT(N+1)
C
  F   = (1./TS - 1./TINT(N) )/( 1./TINT(N+1) - 1./TINT(N) )
  HUMID = (1.-F)*DLOG(HUMINT(N)) + F*DLOG(HUMINT(N+1))
  HUMID = DEXP(HUMID)
  IPT  = N
C
C HUMID known, find HI AND TS
C
  ELSEIF (INT.EQ.1) THEN
    IF (HUMID.LT.HUMINT(1) ) THEN
      WRITE ( IOUT, 30 ) HUMID
30  FORMAT ( '***** HUMIDITY ',
        &      1P, E12.5, ' IS OUTSIDE RANGE OF DATA *****' )
      HI   = HINT(1)
      TS   = TINT(1)
      IPT  = 1
      GO TO 99
    ELSEIF (HUMID.GT.HUMINT(NPTS) ) THEN
      WRITE ( IOUT, 30 ) HUMID
      HI   = HINT(NPTS)
      TS   = TINT(NPTS)
      IPT  = NPTS-1

```

```

      GO TO 99
    ENDIF
  C
    DO 35 N = 1, NPTS-1
      IF (HUMID.GE.HUMINT(N) .AND. HUMID.LE.HUMINT(N+1)) GO TO 40
35  CONTINUE
  C
40  F  = DLOG(HUMID/HUMINT(N))/DLOG(HUMINT(N+1)/HUMINT(N))
      TS = (1.-F)/TINT(N) + F/TINT(N+1)
      TS = 1./TS
  C
      F = (TS - TINT(N))/(TINT(N+1) - TINT(N))
      HI = (1.-F)*HINT(N) + F*HINT(N+1)
      IPT = N
  C
  C HI known, find TS
  C
      ELSEIF (INT.EQ.2) THEN
        IF (HI.LT.HINT(1)) THEN
          WRITE ( IOUT, 50 ) HI
50  FORMAT ( '***** ENTHALPY ',
          &      1P, E12.5, ' IS OUTSIDE RANGE OF DATA *****' )
          TS = TINT(1)
          GO TO 99
        ELSEIF (HI.GT.HINT(NPTS)) THEN
          WRITE ( IOUT, 50 ) HI
          TS = TINT(NPTS)
          GO TO 99
        ENDIF
  C
    DO 55 N = 1, NPTS-1
      IF (HI.GE.HINT(N) .AND. HI.LE.HINT(N+1)) GO TO 60
55  CONTINUE
  C
60  F  = (HI - HINT(N))/(HINT(N+1) - HINT(N))
      TS = (1.-F)*TINT(N) + F*TINT(N+1)
  C
      END IF
  CC
99  RETURN
    END
  C*****
    SUBROUTINE CPHEAT (TEMP, HUMID, CPAIR, CPWAT, CS)
  C*****

```

```

C
C  GIVEN A TEMPERATURE, THIS SUBROUTINE CALCULATES THE HEAT
CAPACITY
C  FOR DRY AIR AND WATER VAPOR. GIVEN A TEMPERATURE AND HUMIDITY,
THIS
C  SUBROUTINE ALSO CALCULATES CS.
C  CORRELATIONS FOR AIR AND WATER VAPOR CP FROM "BASIC PRINCIPLES
AND
C  CALCULATIONS IN CHEMICAL ENGINEERING", HIMMELBLAU,
C  THIRD EDITION, PG. 495-497
C
  IMPLICIT REAL*8 (A-H,O-Z)
  REAL*8 MWH2O
  COMMON /PETC2/ AIRMW, TREF
  CPAIR = 0.D0
  CPWAT = 0.D0
  CS    = 0.D0
  T = (TEMP + TREF)/2.0
C
C  DRY AIR CP IN J/KG-K
C
  CPAIR = 6.713 + 0.04697E-2*T + 0.1147E-5*T*T - 0.4696E-9*T*T*T
  CPAIR = (CPAIR*1.0E3)/(0.239*AIRMW)
C
C  WATER VAPOR CP IN J/KG-K
C
  CPWAT = 6.970 + 0.3464E-2*T - 0.0483E-5*T*T
  CPWAT = (CPWAT*1.0E3)/(0.239*18.015)
C
C  CALCULATE CS IN J/KG-K
C
  CS = CPAIR + CPWAT*HUMID
  RETURN
  END
C*****
  SUBROUTINE VAPINT (INT, TEMP, PRES, HEATVAP)
C*****
C
C  THIS SUBROUTINE INTERPOLATES THE HEAT OF VAPORIZATION FOR WATER
C  AS A FUNCTION OF TEMPERATURE AND PRESSURE
C  IF INT=1, GIVEN A TEMPERATURE, THE SUBROUTINE RETURNS THE
CORRESPONDING
C  HEAT OF VAPORIZATION
C  IF INT=2, GIVEN A PRESSURE, THE SUBROUTINE RETURNS THE

```

CORRESPONDING

C BOILING POINT FOR WATER

C

IMPLICIT REAL*8 (A-H,O-Z)

DIMENSION TV(190),HV(190),PV(190)

PARAMETER (IOUT=61)

C*****

C HEAT OF VAPORIZATION DATA FOR WATER/STEAM TAKEN FROM SMITH &
VAN NESS

C STEAM TABLES,

C TV = TEMPERATURE IN F

C HV = HEAT OF VAPORIZATION IN BTU/LB

C PV = PRESSURE IN PSI

C NPTS = TOTAL NUMBER OF DATA POINTS IN ARRAYS

C*****

DATA NPTS /190/

DATA TV / 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56,

1 58, 60, 62, 64, 66, 68, 70, 72, 74, 76, 78, 80, 82,
2 84, 86, 88, 90, 92, 94, 96, 98, 100, 102, 104, 106, 108,
3 110, 112, 114, 116, 118, 120, 122, 124, 126, 128, 130, 132, 134,
4 136, 138, 140, 142, 144, 146, 148, 150, 152, 154, 156, 158, 160,
5 162, 164, 166, 168, 170, 172, 174, 176, 178, 180, 182, 184, 186,
6 188, 190, 192, 194, 196, 198, 200, 202, 204, 206, 208, 210, 212,
7 215, 220, 225, 230, 235, 240, 245, 250, 255, 260, 265, 270, 275,
8 280, 285, 290, 295, 300, 305, 310, 315, 320, 325, 330, 335, 340,
9 345, 350, 355, 360, 365, 370, 375, 380, 385, 390, 395, 400, 405,
1 410, 415, 420, 425, 430, 435, 440, 445, 450, 455, 460, 465, 470,
2 475, 480, 485, 490, 495, 500, 505, 510, 515, 520, 525, 530, 535,
3 540, 545, 550, 555, 560, 565, 570, 575, 580, 585, 590, 595, 600,
4 605, 610, 615, 620, 625, 630, 635, 640, 645, 650, 655, 660, 665,
5 670, 675, 680, 685, 690, 695, 700, 705 /

DATA HV / 1075.1, 1074.0, 1072.9, 1071.7, 1070.5, 1069.3, 1068.2,

1 1067.1, 1065.9, 1064.8, 1063.6, 1062.5, 1061.4, 1060.2,
2 1059.1, 1057.9, 1056.8, 1055.7, 1054.5, 1053.4, 1052.3,
3 1051.2, 1050.1, 1048.9, 1047.8, 1046.6, 1045.5, 1044.4,
4 1043.2, 1042.1, 1040.9, 1039.8, 1038.7, 1037.5, 1036.4,
5 1035.2, 1034.1, 1033.0, 1032.0, 1030.9, 1029.7, 1028.6,
6 1027.5, 1026.4, 1025.3, 1024.1, 1023.0, 1021.8, 1020.7,
7 1019.5, 1018.3, 1017.2, 1016.0, 1014.9, 1013.7, 1012.5,
8 1011.3, 1010.2, 1009.0, 1007.8, 1006.7, 1005.5, 1004.4,
9 1003.2, 1002.0, 1000.8, 999.7, 998.5, 997.3, 996.1,
1 995.0, 993.8, 992.6, 991.4, 990.2, 989.0, 987.8,
2 986.6, 985.3, 984.1, 982.8, 981.5, 980.3, 979.0,
3 977.8, 976.6, 975.3, 974.1, 972.8, 971.5, 970.3,

4 968.3, 965.2, 961.9, 958.7, 955.3, 952.1, 948.7,
5 945.3, 942.0, 938.6, 935.3, 931.8, 928.2, 924.6,
6 921.0, 917.4, 913.7, 910.1, 906.3, 902.6, 898.8,
7 895.0, 891.1, 887.1, 883.2, 879.2, 875.1, 871.0,
8 866.8, 862.5, 858.2, 853.8, 849.4, 844.9, 840.4,
9 835.7, 831.0, 826.2, 821.4, 816.6, 811.7, 806.7,
1 801.6, 796.5, 791.2, 785.9, 780.4, 774.9, 769.3,
2 763.6, 757.8, 751.9, 745.9, 739.8, 733.6, 727.3,
3 720.8, 714.2, 707.5, 700.6, 693.6, 686.5, 679.2,
4 671.9, 664.4, 656.7, 648.9, 640.9, 632.6, 624.1,
5 615.4, 606.5, 597.4, 588.1, 578.6, 568.8, 558.7,
6 548.4, 537.7, 526.6, 515.3, 503.7, 491.5, 478.8,
7 465.5, 452.0, 437.6, 422.7, 407.0, 390.5, 372.1,
8 353.3, 332.8, 310.0, 284.5, 254.9, 219.1, 171.7,
9 77.6 /

DATA PV / 0.0886,0.0961,0.1041,0.1126,0.1217,0.1315,0.1420,
1 0.1532,0.1652,0.1780,0.1918,0.2063,0.2219,0.2384,
2 0.2561,0.2749,0.2949,0.3162,0.3388,0.3628,0.3883,
3 0.4153,0.4440,0.4744,0.5067,0.5409,0.5772,0.6153,
4 0.6555,0.6980,0.7429,0.7902,0.8403,0.8930,0.9487,
5 1.0072,1.0689,1.1338,1.2020,1.2740,1.3500,1.4290,
6 1.5120,1.6000,1.6920,1.7880,1.8890,1.9950,2.1050,
7 2.2210,2.3430,2.4700,2.6030,2.7420,2.8870,3.0390,
8 3.1980,3.3630,3.5360,3.7160,3.9040,4.1000,4.3050,
9 4.5180,4.7390,4.9700,5.2100,5.4600,5.7200,5.9900,
1 6.2720,6.5650,6.8690,7.1840,7.5100,7.8490,8.2010,
2 8.5660,8.9440,9.3360,9.7440,10.168,10.605,11.057,
3 11.525,12.010,12.512,13.031,13.568,14.123,14.696,
4 15.591,17.188,18.915,20.780,22.800,24.970,27.310,
5 29.820,32.530,35.430,38.540,41.850,45.400,49.200,
6 53.250,57.550,62.130,67.010,72.180,77.680,83.500,
7 89.650,96.160,103.03,110.31,117.99,126.10,134.62,
8 143.58,153.01,162.93,173.33,184.23,195.70,207.71,
9 220.29,233.47,247.25,261.67,276.72,292.44,308.82,
1 325.91,343.71,362.27,381.59,401.70,422.61,444.35,
2 466.97,490.43,514.70,539.90,566.12,593.28,621.44,
3 650.59,680.80,712.19,744.55,777.96,812.68,848.37,
4 885.20,923.45,962.80,1003.6,1045.6,1088.8,1133.4,
5 1179.3,1226.7,1275.7,1326.1,1378.1,1431.5,1486.5,
6 1543.2,1601.5,1661.6,1723.4,1787.0,1852.4,1919.8,
7 1989.0,2060.3,2133.5,2208.8,2286.4,2366.2,2448.0,
8 2532.4,2619.2,2708.4,2800.4,2895.0,2992.7,3094.1,
9 3199.1 /

C*****

C FOR INT=1, GIVEN A TEMPERATURE, FIND THE CORRESPONDING HEAT OF
C VAPORIZATION

C*****

```

IF(INT.EQ.1)THEN
  IF (TEMP.LT.TV(1)) THEN
    WRITE (IOUT, 10) TEMP
    HEATVAP = HV(1)
    GOTO 99
  ENDIF
  IF (TEMP.GT.TV(NPTS)) THEN
    WRITE (IOUT, 10) TEMP
    HEATVAP = HV(NPTS)
    GOTO 99
  ENDIF
  DO 15 N=1,NPTS-1
    IF (TEMP.GE.TV(N) .AND. TEMP.LE.TV(N+1)) GO TO 20
  15 CONTINUE
  20 F = (TEMP - TV(N))/(TV(N+1) - TV(N))
    HEATVAP = (1.-F)*HV(N) + F*HV(N+1)
    GOTO 99
ENDIF

```

C*****

C FOR INT=2, GIVEN A PRESSURE, FIND THE CORRESPONDING BOILING POINT
C TEMPERATURE FOR WATER

C*****

```

IF(INT.EQ.2)THEN
  IF (PRES.LT.PV(1)) THEN
    WRITE (IOUT, 11) PRES
    TEMP = TV(1)
    GOTO 99
  ENDIF
  IF (PRES.GT.PV(NPTS)) THEN
    WRITE (IOUT, 11) PRES
    TEMP = TV(NPTS)
    GOTO 99
  ENDIF
  DO 16 N=1,NPTS-1
    IF (PRES.GE.PV(N) .AND. PRES.LE.PV(N+1)) GO TO 21
  16 CONTINUE
  21 F = (PRES - PV(N))/(PV(N+1) - PV(N))
    TEMP = (1.-F)*TV(N) + F*TV(N+1)
    GOTO 99
ENDIF

```

C*****

AIM

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Centimeter

Inches

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2 of 2

C FORMAT STATEMENTS

C*****

```
10 FORMAT ('***** TEMPERATURE IS OUTSIDE RANGE OF DATA *****',  
1 /,'***** IN SUBROUTINE VAPINT *****',  
1 /,'***** TEMP = ',F10.5,' *****')  
11 FORMAT ('***** PRESSURE IS OUTSIDE RANGE OF DATA *****',  
1 /,'***** IN SUBROUTINE VAPINT *****',  
1 /,'***** PRES = ',F10.5,' *****')  
99 RETURN  
END
```

DATE

FILMED

8/17/94

END