DIRECT CONTACT HEAT EXCHANGER PERFORMANCE

INCOMPLETE
DRAFT

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I. ANALYSIS OF EXPERIMENTAL DATA ON EG&G'S DCHE FOR ELECTRICITY PRODUCTION

Although the final performance result of a DCHE is the cost of the net electricity produced, the best performance cannot be achieved without optimizing the components of the system as well as the whole system. Thus collection and analysis of data on the internal performance of the column assists in optimizing the operation of the particular column as well as in suggesting ways for improving the operation and design of future columns.

In a geothermal system, column performance is determined first by the throughput and secondly by the efficiency of heat transfer. The maximum throughput is determined by the flooding velocity or the velocity at which the thermodynamic efficiency of the column seriously deteriorates.

A calculational procedure and program has been prepared as described later for determining plate efficiencies, entrainment, temperature profile, and thermodynamic efficiency for a given steady state set of data. This provides one operating condition for estimating entrainment and plate efficiencies. Since plate efficiencies and entrainment are an intimate part of the calculations, they must be estimated by empirical equations. Consequently, the entire collection of data for all the steady state runs must be ^{solved?} solved iteratively to determine the entrainment and plate efficiency as a function of process conditions.

Considerable insight in column operation can be obtained by determining the temperature profile during operation. Thus, on-line data analysis will assist the test operations.

A. Theory

Understanding of column behavior and analysis of data requires adequate description of the internal behavior of the column, specifically of each individual tray.

In this column, the counterflowing working and geothermal fluids are contacted as shown in figure 1 with the result that, in the general case:

- (1) contacting is crossflow so that it behaves between countercurrent and parallel, and the outflowing streams may not be thermally homogeneous
- (2) temperature equilibrium is approached but not achieved so that there is a plate efficiency E that describes the degree of approach of $T_{w,n}$ to $T_{g,n}$
- (3) the inflowing and outflowing streams have some average temperature which is assumed to be equal to the experimentally measured temperatures
- (4) working fluid is entrained in the geothermal fluid and is assumed to have an enthalpy equal to that of the outflowing working fluid at $T_{w,n}$
- (5) working fluid is dissolved in the geothermal fluid but the amount is in general so small that it has negligible effect on heat balance calculations for the column
- (6) water from the geothermal fluid phase is dissolved in the outflowing working fluid in substantial quantities when the working fluid phase

Figure 1. Schematic of tray operation showing location of experimental ^{temperature} measurements. Compare with simplified tray schematic, Figure 5.

and contacting zone around which heat balance is written for tray N.

is gaseous or when it is liquid but near the critical temperature and pressure

- (7) geothermal fluid entrained in the working fluid is assumed to be negligible because the geothermal fluid is the continuous phase in the lower portion of the column, and above the interface change the density difference is substantial with a large cross-sectional area for flow of the working fluid.

In addition, heat losses from the column Q are almost negligible, even for a minimally insulated column. For example, 1 inch of insulation would reduce the temperature loss of the geothermal fluid to 0.3°F between inlet and outlet at 10,000 lb/hr.

B. Experimental Measurements and Procedures

Using measured flowrates, the thermal time constant for the column is calculated by

$$\Theta_G = K_G/M_G \quad (8a)$$

$$\Theta_W = K_W/M_W \quad (8b)$$

where $K_G = 31,320$ and $K_W = 52,200 \text{ min/(lb/hr)}$.

After the column is operated at constant conditions for a time equal to twice the time constant, the column can be considered to be at steady state. Experimental measurements of temperatures and flows should then be taken, at the same time observing that the column remains at steady state. The carryunder of working fluid R_1 should be determined experimentally to allow the use of equation 3 for checking consistency of the experimental data, particularly the flowrates.

C. Theory of Analysis of Experimental Data

Mass throughput capacity of the column is determined by breakdown in thermal performance of the column and/or gross carryover or under of entrained fluid. It is expected that gross breakdown will be due to carryunder of working fluid. The column temperature profile is used to monitor and evaluate column thermal performance. A set of equations based on energy and material balances is used to determine the column temperature profile, plate efficiencies, and entrainment rates.

1. Data consistency

To evaluate column thermal performance in the above manner, a consistent set of overall temperatures and flowrates must be used. Consequently, the first step in the analysis is to adjust the experimentally measured flowrates so that the overall energy balance of equation 3 below is satisfied. This assumes that the temperatures used for measuring flowrate are accurate to $\pm 0.5^\circ\text{F}$. This means that calibrated temperature probes should be used and that there should be a means for being certain the electronics for readout are correct.

2. Thermodynamic analysis

A material balance around the entire column figure 2 gives

$$m_G = M_G - Y_{19}m_W \quad (1)$$

and

$$m_W = M_W - R \quad (2)$$

An energy balance gives

6

6

Fig 2.

Overall mass balance
schematic

$$M_G h_{G,20} + M_W h_{W,0} + (M_W - R) Y_{19} h_{G,0} = Q_C + (M_W - R)(h_{W,19} + Y_{19} h_{V,19}) + M_G h_{G,1} + R h_{W,1*} \quad (3)$$

where $h_{W,1*}$ is the enthalpy of working fluid at temperature of geothermal fluid leaving tray 1. The numeric subscript refers to column location as defined in figure 3 and the enthalpies are calculated at the temperature at that location. This equation can be used to determine the value of R or if R is known then the equation can be used to estimate the consistency of the experimental data. The water vapor is assumed to be at the temperature of the working fluid and in equilibrium with a layer of geothermal fluid at the temperature of the working fluid. Consequently the partial pressure of the vapor and its concentration Y_N is given by this equilibrium condition.

An energy balance around the bottom portion of the column (Figure 4) gives

$$Q_N + m_{W,N} h_{W,N} + Y_N m_N h_N - m_{G,N+1} h_{G,N+1} - R_{N+1} h_{W,N+1} = Q_6 \quad (4)$$

which is solved for $h_{G,N+1}$ to give

$$h_{G,N+1} = [m_{W,N} h_{W,N} + Y_N m_N h_N - R_{N+1} h_{W,N+1} - Q_6] / m_{G,N+1} \quad (5)$$

where

$$Q_6 = M_W h_{W,0} - R h_{W,1} - m_G h_{G,1} - Y_{19} m_W (h_{G,1} - h_{G,0}) \quad (6)$$

The efficiency $E(N)$ for the contacting zone as shown in figure 5 is given by

$$E(N) = (T_{W,N} - T_{W,N-1}) / (T_* - T_{W,N-1}) \quad (7a)$$

or alternatively by

Figure 3

Schematic of ~~direct contact heat exchange~~ column showing ~~simplified~~ flows and temperatures. The dotted line identifies the system boundaries for the energy balance Equations ~~of~~ *Hand G.*

water vapor = 1.3
 w.r. air = 1/2 = (1 - 1.3)

$$m_{W,N} = M_{W,N} + R_{N+1} - R_1$$

$$m_{G,N+1} = M_G + Y_{N+1} m_{W,N} - Y_{19} m_W$$

Figure 4. Schematic for Energy Balance.

Figure 5 Tray temperatures for the Tray N contacting zone.

$$E^*(N) = (T_{G,N+1} - T_{G,N}) / (T_{G,N+1} - T_*) \quad (7b)$$

where $T_* = (m_W c_W T_W + m_G c_G T_G) / (m_W c_W + m_G c_G)$. For the subcritical case Y_N is zero except for the boiling trays for which the temperature is known. Consequently the calculations using equations 5 and 7 can proceed from the bottom up or top down. For the most general use, calculations using equations 5, 6, and 7 and proceeding up the column are preferred and will be used.

3. Entrainment rate $R(N)$

The entrainment rate $R(N)$ may be approximated by assuming that all drops with terminal velocity u_T less than the downcomer velocity u_D are entrained. In this case,

$$R_T = \int_0^{D_*} m(D) dD \quad (10)$$

where D_* is the drop size with terminal velocity u_t as given by

$$D_* = 3\sqrt{\rho_W} C u_D^2 / 4g(\rho_W - \rho_B) \quad (11)$$

and $m(D)$ is the mass of drops with diameter smaller than D .

Assuming $m(D)$ is given by

$$m(D) = cD^{a-1} \quad (12)$$

for $m(D) < 0.4$, then

$$R = cD_*^a \quad (13)$$

where all constants are lumped into the arbitrary constant c of no particular value between equations.

Substituting D_* from equation 11, and using

$$u_D = m_G / A_D \rho_G \quad (14)$$

then

$$R = c_R m_G^{2a} / [\rho_G (\rho_G - \rho)]^a \quad (15)$$

If m_* is the mass velocity at which column flooding occurs, and assuming this corresponds to an entrainment rate of 10% of the working fluid rate which is $W^* m_G$, then substituting into equation 15, the value of the constant c_R is found to be

$$c_R = 0.1 W^* [\rho_{G*} (\rho_{G*} - \rho_{W*})]^a / 2 m_*^{2a-1} \quad (16)$$

In the absence of further data, a is taken to be 5, and using an estimated m_* of 11,300, c_R is evaluated to be 3.2×10^{-22} .

Due to density differences, entrainment will vary within the column. Since the geothermal flowrate is essentially constant in the column, the entrainment $R(N)$ flowing in the downcomer from plate N should be inversely proportional to $[\rho_G (\rho_G - \rho)]^a$. Thus,

$$R(N) = R(1) [\rho_{G1} (\rho_{G1} - \rho_1)]^a / [\rho_G (\rho_G - \rho_1)]^a \quad (17)$$

For an assumed value of entrainment in the downcomer from plate 1, all other entrainments can be estimated for use in equation 5.

At the base of the column, the geothermal fluid velocity u_B is related to mass flow rate by

$$u_B = m_G / A_c \rho_G \quad (18)$$

Consequently, the entrainment rate R_1 in the base of the column per unit geothermal fluid flow rate is given by

$$R_1 = c_R m_G^{2a-1} (A_D/A_C)^{2a} / [\rho_G (\rho_G - \rho)]^a \quad (19)$$

For this column $(A_D/A_C)^{2a} = 0.243$. Experimental data on entrainment R_1 from the bottom of the column will enable two constants, c_R and a to be revised.

4. Column thermal performance

Equations 5, 6, and 7a are used to calculate temperature profile, plate efficiencies and/or tray entrainment rates from experimental temperatures measured at various locations in the column.

Trays for which $T_{G,out}$ and $T_{W,in}$ (figure 2) are measured, E_N , is calculated by equation 7a and $R(N)$ is calculated from equation 4.

Efficiency E_N is a smooth function of tray location and should not vary radically with location. On the other hand, entrained working fluid rate R_N may vary suddenly with location even though it also is a smooth function of physical properties. This is because there is a critical condition of physical properties and flow rates where working fluid will be entrained at a significant rate. Consequently, at trays for which only one temp is experimentally known, E_N is assumed to calculate the other temperature by equation 7a and $R(N)$ is calculated by equation 4. On trays for which no temp is known, $E(N)$ and $R(N)$ are assumed based on previous data and $T_{G,out}$ and $T_{W,in}$ are calculated

5. Results of Thermal and Entrainment Analysis of Experimental Data

The result of the above analysis for the data from a single steady state run will be a plot of temperatures in the column, both experimental and calculated, as shown in figure 6. In addition the plate efficiencies and entrainment rates, either by calculation or interpolation, will be tabulated and plotted as shown in figure 7.

Once experimental data for a number of steady state runs is obtained, an iterative calculation of the entire collection of data will determine $E(N)$ and $R(N)$ as a function of the appropriate operating variables. Since the calculation using a single set of data for just one assumed set of $E(N)$ and $R(N)$ is tedious, and involves 30 or 40 experimental numbers, it is clear that this iterative procedure for determining E_N and R_N from the entire collection of data sets must be done by a carefully thought out computerized computational and data-handling procedure.

6. Column Thermodynamic Performance

The thermodynamic efficiency of the column is really determined by the net electricity produced, but since it is difficult to separate other system component effects on net electricity, it is useful to estimate the lost work resulting from temperature differences in the column. This may be estimated by equation 8.26 of Wahl (Wahl, 1977):

$$W_L = \int_Z (\Delta T/T_Z) dQ_Z \quad (20)$$

Using the temperature profile, $T_1(N)$ and $T_2(N)$, versus enthalpy, $H_Z(N)$, data calculated from experimental data, the above integral may be evaluated stepwise. For a finite section from N to J where $J = N + 1$, the

Figure 6a. Simulated results, ~~not~~ plotted, of analysis of experimental data

COLUMN PERFORMANCE 9/23/80 14:25:40 SIMULATED

W.F. Rate: 9275 lbs/hr
G.F. Rate: 12289 lbs/hr

Plate No	Efficiency $E, \%$	Entrainment $R,$	$T_{G,out}$ of	$T_{W,out}$ of
0e			152.1 e	83.4 e
0*			157.5 e*	83.2 e*
1	70 c	0.023 e	157.5 e*	134.2
2	70 i	0.023 i	180.7	165.3
3	71 i	0.022 i	196.2	185.4
4	71 i	0.022 c	207.1 e	199.2
5	71 i	0.021 i	215.0	209.0
6	72 i	0.021 c	220.9 e	216.3
7	72 i	0.020 i	225.5	221.9 e
8	72 c	0.020 c	229.2 e	226.2
9	72 i	0.019 i	232.1	229.7 e
10	72 c	0.019 c	234.5 e	232.5
11	72 i	.018 i	236.5	234.8
12	72 i	.017 c	238.2 e	236.8
13	73 i	.015 i	239.6	238.4
14	73 i	.013 c	240.9 e	239.8
15	73 i	.016 i	241.9	241.0
16	73 i	.005 c	242.9 e	242.1
17	73 c	0 i	243.7	243.0 e
18	74 c	0 i	244.4	243.4
19	74 c	0	245.0 e	243.4 e*
20*			240.1 e*	
20e			240.3 e	243.2 e

i = interpolated

c = calculated from experimental data

e = experimentally measured; * smoothed using overall energy balance, Eqn. 3

average ΔT for the section is

$$\Delta T = [T_1(J) + T_1(J+1) - T_2(N) - T_2(J)]/2 \quad (21)$$

The average T_z is

$$T_{z,ave} = [T_1(J) + T_1(J+1)]/2 + 460 \quad (22)$$

and the value of dQ for the finite interval is

$$\Delta Q = [H_2(J) - H_2(N)] * W(J) * M_G \quad (23)$$

Consequently,

$$W_L = \sum_{N=0}^{18} (\Delta T_{ave}/T_{z,ave}) \Delta Q \quad (24)$$

or,

$$W_L = \sum_{N=0}^{18} [1 - \{(920 + T_2(N) + T_2(J))/(920 + T_1(J) + T_1(J+1))\}] * W(J) * M_G [H_2(J) - H_2(N)] \quad (25)$$

If the lost work were zero, that is, if ΔT in the column was everywhere zero, then the direct contact heat exchanger would be thermodynamically perfect, i.e., have an efficiency of 100%. Since the maximum work which could be produced by the heat transferred from the geothermal fluid is given by equation 8.14 of Wahl (Wahl, 1977),

$$W_{SR} = \Delta h_{G1} - T_{Ex}(\Delta S_G)$$

or

$$W_{SR} = \{H_1(T_1) - H_1(T_4) - T_6[S_1(T_1) - S_1(T_4)]\} * M_G \quad (26)$$

Consequently, the column efficiency is given by

$$E_{col} = (1 - w_L)/w_{SR} \quad (27)$$

II. DETAILED PROCEDURE FOR CALCULATING COLUMN PERFORMANCE FOR ISOBUTANE WORKING FLUID AS PROGRAMMED ON THE HP-85 COMPUTER

This program reads through an RS232C interface the flowrates, temperatures, pressures, and other data from the data logger. This is done continuously as the data logger scans the data and sends updated information. This data is checked for consistency by a set of material and energy balances, the results of which are continuously displayed and printed out at operator-selected intervals. This data is averaged in an appropriate manner using the material and energy balance checks to give the best consistent set of data for calculating column thermal performance. This performance is calculated and displayed in the form of a temperature plot and tabulated results of temperature plate efficiency and entrainment. On operator demand this information is produced in hard-copy form on a printer. Also, on operator-specified intervals and on demand, the raw data is logged on tape. The raw data is logged rather than calculated results because it is the basic data, calculated results are easily regenerated from these, and changes in calculation can easily be made.

This computer program has been carefully checked for correctness as follows. First, all calculated physical properties were checked. Then all individual calculations were checked by hand calculation from block diagrams that represented that part of the process so the result could be checked for technical correctness. Finally, and fundamentally, a consistent set of assumed experimental values to be used by the program were prepared by calculation for given column operating conditions, tray efficiency, and

entrainment. The results from the program using the assumed experimental values were compared with the known conditions from which the experimental values were calculated.

The performance of the column is analyzed in the following sequence.

- (1) The inlet and outlet temperatures and flowrates are checked for consistency and correctness. The program provides printouts, figures 9 and 10, which allow the operator to evaluate this.
- (2) From the above, a consistent set of process parameters is selected for the following calculations.
- (3) The temperature profile, plate efficiencies, and entrainment are determined that match the experimental data. The program provides printouts for this purpose as in figure 11.

The following analysis is for the column operating as shown in figure 8 with boiling above tray 18.

The use of subscripts is a convenient method for subjugating the less important elements in mathematical equations. However, their use is difficult and therefore inaccurate for typing in report form or for conversion to computer programs. For this latter case, it is particularly useful to use the more meaningful function form such as $f(x,y)$ rather than $f_{x,y}$. For example, the temperatures T throughout the sieve plate column are a function of the location plate number N and the phase geothermal fluid = 1 or working fluid = 2. Thus, in function form these temperatures would be written

$$T(G,N) ; T(N,N)$$

April 8

2

9

22

10

23

11

24

Figure 11. Schematic of Column showing planes for energy balance equations. Flowrates and temperatures at each plane are shown

or

$$T(1,N) ; T(2,N)$$

or

$$T1(N) ; T2(N)$$

instead of in subscript form as

$$T_{G,N} ; T_{W,N}$$

Since this work is directed at a computational procedure, the more familiar subscript form has been converted to the more useful functional form.

Therefore, for convenience of typing as well as providing nomenclature more easily converted to computer program format, functions are used, quite correctly, rather than subscripts. Also, a variable is written as a letter followed by a number such as

$$T2$$

which is the boiling temperature in the column, or

$$T2(N)$$

which is the temperature of the working fluid leaving plate N. Mostly 1 is used for geothermal fluid and 2 as working fluid, but this is not always the case.

The properties of the working fluid and geothermal fluid needed for these computations is given by the set of functions listed in table 1. These functions were specially prepared for this program to minimize the computation time and memory required. These functions cover the specific

TABLE 1

Functions for Calculating Physical Properties

<u>Item</u>	<u>Function</u>	<u>Description</u>	<u>Fluid</u>	<u>Valid Range</u>
1	H1	h vs T	water liquid	130 to 300°F
2	H2	h vs T	water vapor (sat'd)	130 to 300°F
3	P1	p vs T	sat'd water	170 to 280°F
4	H4	h vs T	iB liquid	60 to 240°F
5	H5	h vs T	iB vapor (sat'd)	130 to 260°F
6	P2	p vs T	sat'd iB	130 to 260°F
7	T7	reserved		
8	T8	reserved		
9	T3	T vs p	sat'd water	130 to 300°F
10	D1	ρ vs T	liquid water	100 to 250°F
11	D2	ρ vs T	liquid iB	60 to 240°F
12	T4	T vs P	sat'd iB	
--	C1	C_p vs T	geothermal fluid	
--	C2	C_p vs T	isobutane	
--		T vs H	water, liquid	130 to 300°F
--		T vs h	iB, liquid	60 to 240°F

range of variables required. The use of general state properties programs would increase computation time and memory by orders of magnitude with no benefit.

The nomenclature for important process parameters is given in table 2.

For ease of comparing data for different runs, all calculations and results discussed below are on the basis of 1 lb of geothermal fluid fed to the DCHX.

A. Experimental Input Measurements

The experimental flowrates, temperatures, and column pressure can be read directly from the data logger via an RS232C interface directly into the computer memory. These experimental values are converted to appropriate units, averaged if necessary over time, and stored as the variables given in table 3. This data is stored on magnetic tape for future processing. Calculations and printout of results are executed as described below.

The basic column process data is printed out as shown in figure 9.

B. Determination and Check of Basic Process Data

1. Temperatures and pressures

The working fluid outlet temperature T(22) should equal the overhead temperature T(11) or T(12). For subsequent calculations,

$$T3 = [T(22) + T(11) + T(12)]/3 \quad (101)$$

The flash temperature T7 of the geothermal fluid is assumed to be equal to the overhead temperature, so

$$T7 = T3 \quad (102)$$

TABLE 2

Nomenclature for Principle Process Parameters

E(N)	Plate efficiency for tray N
G(N)	Geothermal fluid flowrate from tray N
M0	Working fluid flowrate into column, lbs/hr
M1	Geothermal fluid flowrate into column, lbs/hr
H4(N)	Enthalpy of working fluid leaving plate N
N	Tray number, 1 = bottom tray
R(N)	Entrainment of working fluid in geothermal fluid leaving tray N
T0	Temperature of working fluid entering the DCHE = T(20)
T1	Temperature of geothermal fluid entering the DCHE = T(21)
T2	Temperature of boiler plate
T3	Temperature of working fluid leaving the DCHE = T(22)
T4	Temperature of geothermal fluid leaving the DCHE = T(23)
T(K)	Experimental temperatures at location K, °F
T1(N)	Temperature of geothermal fluid leaving tray N
T2(N)	Temperature of working fluid leaving tray N
R1(N)	Value of R(N) calculated from experimental data for tray N-1
W	Working fluid flowrate into column on basis of unit of geothermal fluid feed flowrate, i.e., $W = M0/M1$
W(N)	Working fluid flowrate leaving tray N on basis of unit geothermal fluid feed flowrate

TABLE 3

Experimental Measurements and Calculation NomenclatureFlow measurements, M is lbs/hr

M7: FI-WF7 total working fluid to turbine

M6: FI-WF46 geo fluid to DCHE

M5: FI-WF1 total working fluid to DCHE

Temperature measurements, T is °F

T3 = T(22): TI-WF40 = T3

T0 = T(20): TI-WF59 = T0

T4 = T(23): TI-GF30 = T4

T1 = T(21): TI-GF28 = T1

Column temperatures = T(J)

T(J): column temperatures, see figure 13

Composition measurements, weight %Weight % water in condenser outlet = $X_W = X1$ Weight % working fluid in DCHE outlet = $x_R = X2$ Pressure measurements

P0(psia): column pressure

FIGURE 13 EXPERIMENTAL TEMPERATURES $T(K)$
AND CALCULATED TEMPERATURES $T1(N)$ AND $T2(N)$

The vapor pressure P_1 of the water is

$$P_1 = P_1(T_7) \quad (103)$$

and

$$P_2 = P_0 - P_1 \quad (104)$$

The boiler temperature T_2 should equal the value calculated from the partial pressure P_2 of the working fluid by

$$T_2 = T_4(P_2) \quad (105)$$

and should be compared with the experimental geothermal fluid temperature $T(17)$ and T_9 since the geothermal fluid is cooled to within T_9 °F of the temperature. It should also equal T_2 if the lower column approaches a zero ΔT which it should. So,

$$T_9 = T(17) - T_2 \quad (106)$$

where $T_1(18) = T(17)$.

Also, the overhead temperature T_3 should be greater than the boiler temperature T_2 , else condensation will occur. The working fluid temperature T_2 in the boiler will be cooler than the geothermal fluid by the boiler "pinch" temperature difference, T_9 . Thus,

$$T_2(18) = T_2 - T_9 \quad (107)$$

The overhead water content Y_1 per unit of working fluid is calculated from the partial pressure of water vapor at the overhead temperature T_3 and by

$$Y1 = 0.3098 P1/P2 \quad (108)$$

This is to be compared with the experimental value $X1/100$ of the water content in the overhead working fluid.

These comparisons are easily made by using the first part of the printout, a sample of which is given in figure 11.

2. Working fluid entrained in the underflow

The entrainment $R1$ is calculated by three methods and is to be compared with the experimental value $R0 + X2/100$ of the underflow entrainment.

Method A. The entrainment R calculated from the hydraulic equation 15 and called $R8$ is

$$R8 = (C3 * M6^{2C4-1} / [D * D2(T4)])^{C4} \quad (109)$$

where

$$D = D1(T4) \quad (110)$$

and $C3$ and $C4$ are determined by experimental values of $R0$ at various flow-rates $M6$. In the absence of experimental data, $C3 = 2.5 \times 10^{-21}$ and $C4 = 5$.

Method B. The entrainment calculated by the overall energy balance equation. From the overall energy balance (equation 4), written by combining equations 225 and 226, an estimate of $R1$, $R6$ by this method is

$$R6 = \{H1(T1) - H1(T4) + W2[Y1\{H1(T0) - H2(T3)\} + H4(T0) - H5(T3)]\} / [H4(T4) - H4(T0)] \quad (111)$$

where $W2$ is obtained by solving $Q7 = Q9$, equations 137 and 138, as described later, giving equation 125. For this estimate of $R1$ for a consistency check, equation 125 is used.

Method C. The entrainment calculated from the flowrate differences and called R7 is

$$R7 = [(M5 - M7)/M6] \quad (112)$$

This is derived from the definition of flowrates per unit geothermal flowrate (refer to table 3 and figure 12):

$$(M5 - M7)/M6 = W + W3 - (W2 + W3) \quad (113)$$

and an overall balance on working fluid which gives

$$W = W2 + R1 \quad (114)$$

so that

$$(M5 - M7)/M6 = R1 \quad (115)$$

These three values are printed out (see figure 10) for comparison. The value R8 as calculated by method A is used for R1 in subsequent calculations.

Since R1 makes a small correction to the energy balance equation for the column, this estimate of R1 is sufficient for subsequent calculations.

3. Experimental flowrate relationships

The experimental flowrates are related to the flowrate nomenclature in figure 12, which is on the basis of 1 lb of geothermal feedrate into the column, by

$$M7/M6 = W2 + W3 \quad (116)$$

and

$$M5/M6 = W + W3 \quad (117)$$

Since

$$W = W_2 + R_1, \quad (118)$$

$$M_5/M_6 = W_2 + W_3 + R_1 \quad (119)$$

and therefore

$$R_1 = (M_5 - M_7)/M_6 \quad (120)$$

Since

$$W_3 = Y_1 * W_2 \quad (121)$$

$$M_5/M_6 = W_2 * (1 + Y_1) + R_1 \quad (122)$$

which can be solved for W_2 :

$$W_2 = [(M_5/M_6) - R_1]/(1 + Y_1) \quad (123)$$

4. Working fluid flowrate, W_2 in column

From equation 2,

$$W_2 = W - R_1 \quad (124)$$

There are four methods for calculating the working fluid flowrate W_2 to compare data consistency. Two are calculated by the energy balance equations described later.

Solving $Q_7 = Q_9$ for W_2 , using $W_3 = W_2 * Y_1$, equation 131, gives

$$W_7 = [H_1(T_1) - H_1(T_1(18))]/[Y_1 * \{H_2(T_3) - H_1(T_1(18))\} + H_5(T_3) - H_4(T_2)] \quad (125)$$

where $W_7 = W_2$ by this method.

Solving $Q_8 = Q_9$ for W_2 , as above, using $W = W_2 + R_1$, equation 130, gives

$$W_8 = \frac{[H_1(T_1) - H_1(T_4) - R_1 * \{H_4(T_4) - H_4(T_0)\}]}{[Y_1\{H_2(T_3) - H_1(T_0)\} + H_5(T_3) - H_4(T_0)]} \quad (126)$$

where $W_8 = W_2$ by this method.

From the inlet flowrate M_5 , equation 122

$$W_9 = [(M_5/M_6) - R_1]/(1 + Y_1) \quad (127)$$

From the outlet flowrate M_7 , $W_6 = W_2$ by this method

$$W_6 = M_7/[M_6 * (1 + Y_1)] \quad (128)$$

These values of W_6 , W_7 , W_8 , and W_9 of W_2 are printed out in figure 10 for comparison. If they do not compare adequately, then a comparable error exists and the full data set and operations should be checked for the cause. In subsequent calculations,

$$W_2 = (W_6 + W_9)/2 \quad (129)$$

5. Determination of flowrates of components

Material balances on the column (see figure 9) give:

--the working fluid flowrate W fed to the columns:

$$W = W_2 + R_1 \quad (130)$$

--the water flowrate W_3 in the vapor and condensate line:

$$W_3 = W_2 * V_1 \quad (131)$$

--the geothermal fluid rate $G(N)$ in the column:

$$G(N) = 1 - W3 + W(N) * Y(N) \quad (132)$$

--the working fluid rate $W(N)$ in the column:

$$W(N) = W2 + R(N + 1) \quad (133)$$

Water dissolved or entrained in upflowing working fluid is assumed to be zero, so $Y(N) = 0$ for N below the boiling tray. Above the boiling tray $Y(N) = Y1$ since boiler pressure is constant and superheat is assumed negligible where working fluid and water are in contact. Any superheat would increase $Y1$ so that $Y(19) = Y1$ but if 18 is the boiler tray then $Y(18)$ would be calculated for boiler temperature $T2$ whereas $Y1$ would be for a temperature equal to the outlet temperature of tray 19.

Consequently, below the boiler tray,

$$G(N) = 1 - W3 \quad (134)$$

Because of the large density difference between working fluid vapor and water, it is assumed that entrainment $R(N)$ is zero at the boiler tray as is entrainment of water in the working fluid entering the boiler tray. Consequently, for the boiler tray,

$$W(N) = W2 \quad (135)$$

and

$$G(N) = 1 - W3 \quad (136)$$

6. Comparison of energy balance equations on column and determination of Q6 for equation 4

The energy balance equation 3 determines the consistency of the data.

The energy balance equation 3 around the entire column is through planes 8 and 9 (see figure 8). At any place, there will be a net flow of enthalpy, Q6, downward which must be equal everywhere. An energy balance around the boiler provides an additional means of checking the data because the temperature differences of the fluids just below the boiler tray are very small.

Thus energy balances give, just below the boiler, plane 7:

$$Q7 = (1 - W3) * H1(T1(18)) - W2 * H4(T2(17)) \quad (137)$$

at the top, plane 9:

$$Q9 = H1(T1) - W2[Y1 * H2(T3) + H5(T3)] \quad (138)$$

at the bottom, plane 8:

$$Q8 = H1(T4) + R1 * H4(T4) - W * H4(T0) - W3 * H1(T0) \quad (139)$$

and just above the boiler, plane 5, assuming the temperature differences are zero:

$$Q5 = (1 - W3) * H1(T1(18)) - W2 * H4(T2) \quad (140)$$

If flowrates and temperatures are correctly measured and steady state exists, then the net energy flows must everywhere be equal, so

$$Q5 = Q7 = Q8 = Q9 \quad (141)$$

These are printed out in figure 10 for comparison. If they do not compare

favorably, then a serious flaw in the data exists and the data set and operation should be examined for the cause. If the above comparisons indicate satisfactory experimental data, then arbitrarily

$$Q6 = (Q7 + Q8 + Q9 + Q5)/4 \quad (142)$$

for subsequent calculation of interior column performance. Stepwise calculation using equations 5, 6, and 7 will arrive at the correct upper temperatures only if the overall energy balance, equation 3, is satisfied. This can be done using the above value of Q6 and W2 and R1 in equation 139 and solving for $T4 = T1(0)$ to give

$$T1(0) = T1(H) \quad (143)$$

where

$$(144)$$

The boiler temperature consistent with W2, Q6, R1, and inlet-measured temperatures is calculated by solving equation 137, the energy equation, on plane 7, for T2 by

$$H4 = [(1 - W3) * H1(T1(18)) - Q6]/W2 \quad (145)$$

and

$$T2 = T2(H4) \quad (146)$$

If T2 so calculated agrees with the experimental boiler temperature T(17), then this is an excellent check on the overall data consistency and the calculations can proceed.

If the temperature T_2 is not satisfactory, then an alternative approach is to use the value of R_1 given by method C and the value of W_2 given by equation 126, namely W_8 . In this case Q_6 is obtained by

$$Q_6 = (Q_8 + Q_9)/2 \quad (147)$$

where Q_8 and Q_9 are obtained from equations 138 and 139. Again, consistency is checked by calculating T_2 as above, equations 145 and 146.

7. Values used in column performance calculation

The values of Q_6 , R_1 , W , W_2 , and W_3 used in subsequent calculations are printed out, as in figure 10.

Experimental temperatures are assumed correct and are printed out in appropriate places in the following described displays.

C. Determination of Internal Column Performance

1. Significance of experimental downcomer temperatures

Since geothermal fluid contains entrained working fluid at a temperature lower than the geothermal fluid temperature, the experimental temperature will be lower than the geothermal temperature by a small amount. It will be equal to the thermal average of the two fluids. The entrained working fluid will have heated up to the same temperature as the working fluid leaving the fluid for the upper plate, or perhaps a bit more. Since this temperature difference is about 30% of the ΔT for the tray and since the amount of entrained fluid is about 5% with half the c_p of water, this means the measured temperature is at most 0.75% of the ΔT for the tray. Typically the tray temperature rise is 10°F or less so that this temperature discrepancy is less than 0.1°F which is less than the accuracy of the measurement. Therefore in subsequent calculations, it is assumed that the

entrained working fluid is at the temperature of the geothermal fluid leaving the tray and that this is equal to the experimental temperature in the downcomer. This will make a small difference in the heat balance equations because the entrained working fluid entering, $R(N)$, and leaving, $R(N + 1)$, will be at an assumed higher temperature of about 30% of the ΔT . Since the error will be a function of the difference between $R(N + 1)$ and $R(N)$, or about 20% of 5% of the flow, the error in energy will correspond to a ΔT of less than 0.03°F and again is insignificant.

2. Calculation of bottom conditions

For stepwise calculation using equation 4, the temperatures $T_2(0)$ and $T_1(1)$ must be known. These are not exactly equal to T_0 and T_4 respectively because there will be heat transfer through the inlet piping inside the column and because of separation of some working fluid in the lower portion as well as water entrained in the inlet working fluid. Since these temperatures are known experimentally,

$$T_2(0) = T(13) \quad (150)$$

$$T_1(1) = T(1) \quad (151)$$

An energy balance through plane 0 is solved to give

$$R_1(1) = [Q_6 + W_2 * H_4(t_2(0)) - G(1) + H_1(T_1(1))]/[H_4(T_1(1)) - H_4(T_2(0))] \quad (152)$$

where

$$R_1(1) > R_1 \quad (153)$$

B?
14 Tray temperature profile, plant to
Simplified zone.
Figure 1. Tray temperature schematic
showing ~~some~~ scientific nomenclature
and computer ~~nomenclature~~ ^{functional nomenclature for} calculational and
programming ~~nomenclature~~ ^{use}. Compare with
Figure 1.

If this latter criterion is not satisfied or if $R(1)$ is unreasonably large, then the experimental temperatures are incorrect. However, since $R(1)$ is sensitive to small temperature differences, $R(1)$ is better estimated by the hydraulic equation, equations 15 and 16, rewritten here as

$$R(1) = C3(M6)^{2C4-1}/[D1(D1 - D2)]^{C4} \quad (154)$$

3. Tray calculations for plate N

The overall energy balance equation 4 and tray efficiency equation 7a are used. For simplicity in subsequent equations,

$$J = N + 1 \quad (155)$$

These equations are rewritten for plane N as

$$G(J) * H1(T1(j)) + R(J) * H4(T1(J)) - W(N) * H4(T2(N)) = Q6 \quad (156)$$

and

$$E(N) = [T2(N) - T2(N - 1)]/[T_* - T2(N - 1)] \quad (157)$$

where

$$T_* = [C7 * T1(N) + C6 * T2(N)]/C8 \quad (158)$$

$$C6 = [W(N) + R(N) * C2()] \quad (159)$$

$$C7 = G(N) * C1() \quad (160)$$

$$C8 = C6 + C7 \quad (161)$$

$$C1() = \text{heat capacity of geothermal fluid at } T1(N) \quad (162)$$

$$C2() = \text{heat capacity of working fluid at } T1(N) \quad (163)$$

In all cases, $R(J)$ is estimated by

$$R(J) = R(1) * [1 + B1 * J + B2 * J^2] * D3/[D1 * \{D1 - D2(T1(N))\}]^{C4} \quad (164)$$

where

$$D1 = D1(T1(N)) \quad (165)$$

and

$$D3 = [D1 * \{D1 - D2(T1(1))\}]^{C4} \quad (166)$$

for $N = 1$.

These equations are solved using the experimental data. There are three cases to be considered:

Case A. No experimental temperatures are known

Case B. $T1(N + 1)$ is known experimentally

Case C. $T1(N + 1)$ and $T2(N)$ are known experimentally.

a. Case A The efficiency is estimated by interpolation using

$$E(N) = E0 * (1 + E1 * N + E2 * N^2) \quad (167)$$

where $E0$, $E1$, and $E2$ are estimated from previous experiments.

In practice, after sufficient data sets are obtained, it will be possible to determine the plate efficiency $E(N)$ as a function of the appropriate parameters such as working fluid jet velocity, so that

$$E(N) = f(N, M2) \quad (168)$$

This function can then be approximated by a function of the form of equation 167. The temperature $T2(N)$ of working fluid leaving the tray is

calculated by solving equation 157 for $T_2(N)$. Thus,

$$T_2(N) = [T_2(N - 1) * (1 - E) + E * T_1(N) * C_7/C_8] / [1 - E * C_6/C_8] \quad (169)$$

Equation 156 is solved for the enthalpy H_4 of the incoming geothermal fluid:

$$H_4 = [Q_6 + W(N) * H_4(T_2(N)) - R(J) * H_4(T_1(J))] / G(J) \quad (170)$$

and its temperature by

$$T_1(J) = T_1(H_4) \quad (171)$$

where $T_1(H_4)$ is the temperature versus enthalpy function for geothermal fluid.

These two equations are solved iteratively for $T_1(J)$.

b. Case B $T_1(N + 1)$ is known experimentally. If the experimental temperature of geothermal fluid leaving the tray above, i.e., $T_1(J)$ is known, then equation 156 is solved for the enthalpy H_2 of the leaving working fluid:

$$H_2 = [G(J) * H_1(T_1(J)) + R(J) * H_4(T_1(J)) - Q_6] / W(N) \quad (172)$$

The temperature is obtained from the enthalpy by

$$T_2(N) = T_2(H_2) \quad (173)$$

The efficiency is calculated by equation 157:

$$E(N) = \text{equations 157 through 163} \quad (174)$$

Alternatively, equation 156 can be solved for $R(J)$ for an assumed plate efficiency.

The interpolation equation for $E(N)$, equation 166, is corrected for the following upper-tray calculations by revising E_0 to a new value $E_0(N)$ by

$$E_0(N) = E(N)/[1 + E_1 * N + E_2 * N^2] \quad (175)$$

c. Case C $T_1(N + 1)$ and $T_2(N)$ are known experimentally. If both temperatures, $T_2(N)$ and $T_1(J)$, are known experimentally, then the efficiency is calculated by equation 157 as above and equation 156 is solved for $R(J)$.

Thus

$$R_1(J) = [Q_6 - G(J) * H_1(T_1(J)) + W_2 * H_4(T_2(N))]/[H_4(T_1(J)) - H_4(T_2(N))] \quad (176)$$

This should be compared with estimated values of $R(J)$ by equation 15 and if not reasonable should be discarded together with $T_2(N)$, since a small temperature error can make a large difference in $R(J)$. If it is accepted, then $W(N)$ is revised by

$$W(N) = W_2 + R_1(J) \quad (177)$$

4. Results

The results of the above and following calculations are printed out as shown in figure 11.

The efficiency of tray 18 is given by

$$E(18) = [T_1(19) - T_1(18)]/[T_1(19) - T_2(18)] \quad (178)$$

and of tray 19 by

$$E(19) = [T_1(20) - T_1(19)]/[T_1(20) - T_2(19)] \quad (179)$$

or for both by

$$E(N) = [T_1(J) - T_1(N)]/[T_1(J) - T_2(N)] \quad (180)$$

5. Thermodynamic efficiency

The thermodynamic efficiency of the column is estimated by calculating the lost work. From equation 22, the lost work W_6 is given by

$$W_6 = \sum_{N=0}^{18} W(J) * M_6 * [H_2(J) - H_2(N)] * [1 - \{(920 + T_2(N) + T_2(J))/(920 + T_1(J) + T_1(J + 1))\}] \quad (181)$$

The thermodynamic efficiency E_6 as obtained from equations 23 and 24 is

$$E_6 = (1 - W_6)/\{[H_1(T_1) - H_1(T_4) - T_6\{S_1(T_1) - S_1(T_4)\}] * M_6\} \quad (182)$$