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OFFICE OF SALINE WATER

COMPUTER MODEL AND CORRELATIONS FOR PREDICTION OF HORIZONTAL-TUBE CONDENSER PERFORMANCE IN SEAWATER DISTILLATION PLANTS

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D. M. Eissenberg
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NUCLEAR DESALINATION PROGRAM

R. P. Hammond, Director

OCTOBER 1970

OAK RIDGE NATIONAL LABORATORY
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INTRODUCTION

Large scale distillation plants for producing potable water from the sea by the multistage flash evaporation process have large amounts of condensing surface in the form of tube bundles. Since the cost of these tube bundles constitute a significant portion of the cost of the entire plant, unnecessary overdesign of the condensers must be avoided just as much as underdesign. The large safety factors,often utilized for chemical process condenser application and in the design of steam surface condensers for turbines wheregguaranteed performance is of utmost importance,is a luxury that cannot be afforded when the end product is potable water. Consequently, under sponsorship of the OSW, the Oak Ridge National Laboratory has prepared a computer program for calculating the detailed performance of condenser tube bundles on a row by row basis. With this program the interrelationships of non-condensable gas fraction, pressure drop across the tube bank, condensate rain, vapor velocity, and tube spacing, which cannot be studied using existing overall bundle design methods, can be determined and separately studied. Being able to predict such detailed performance of tube bundles will also hopefully lead to improvements in the layout of condenser bundles which avoid the pitfalls which lead to failure to meet design specifications.

The program ORCON is described in this report. An earlier version of the program[1] has been reported previously, but a considerable number of improvements have been added to the code since that time. These improvements are based on additional review of the literature, and on experimental investigations

referred to in this report. Brief descriptions of the computer program, its capabilities and of the important correlating equations which it employs, are presented in this report.

While the computer program is able to perform row-by-row calculations on large, complicated bundles such as the MSF module bundle, it is recommended that additional comparisons should be made between calculated and observed parameters before the present work is considered to be complete.

GENERAL DESCRIPTION OF THE COMPUTER PROGRAM

The program ORCON at present handles two types of bundle layouts, circular and rectangular, and can divide each into two sections in series (with respect to steam flow), the downstream section in both cases being a rectangular gas cooler section. The tube lattice options at present are limited to staggered equilateral triangles with varying S/D. With special modifications, the program can handle other layouts and lattices.

For the circular bundle layouts, the bundles are assumed to be divided into twelve equal sectors of 60° each, with the tubes that lie along the centerline of each sector taken as representative of that sector. For each such tube, the code calculates the number of tubes in a vertical column above it, according to the schematic arrangement shown in Figure 1. Row by row calculations of heat transfer and pressure drop are performed starting with the outside (steam inlet) row of tubes for each sector and using an assumed steam flow, pressure, and non-condensable gas fraction. The overall heat transfer coefficient for each representative tube is calculated based on the correlating equations evaluated for the conditions at that location. Then, from the calculated values of the steam mass velocity, non-condensable gas fraction and steam pressure for the steam approaching that row, values of these parameters for the steam leaving that row are calculated and the process repeated for the next tube downstream.

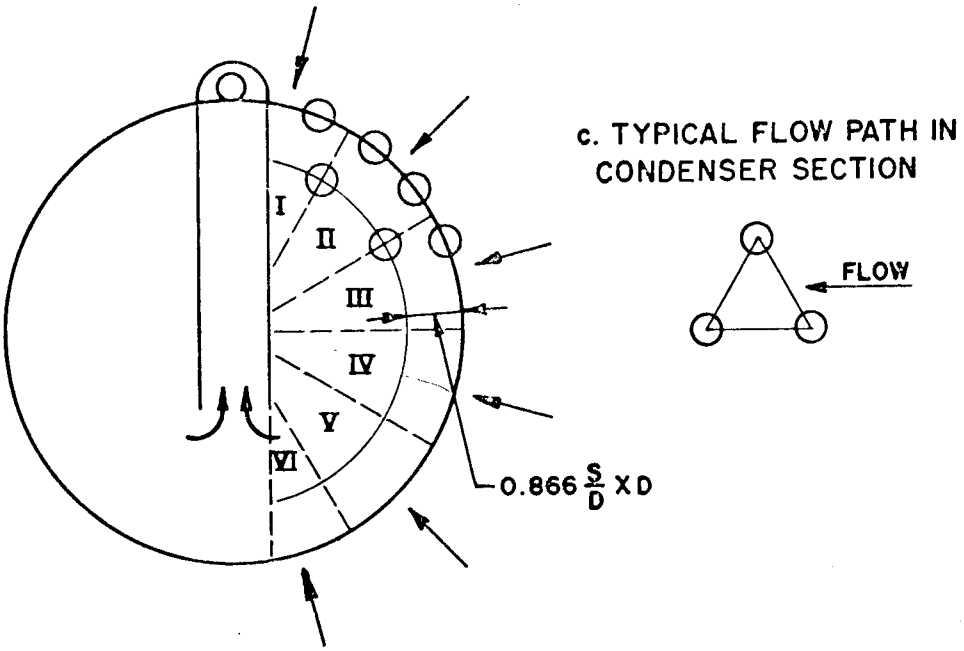

FIGURE 1. CIRCULAR CONDENSER BUNDLE

Calculations are performed only for one half of the tube bundle (sectors 1 to 6), since the circular bundle is symmetrical. Upon completing the row by row calculations for the six sectors, a check is made to see if the pressure drops through all of the sectors are essentially equal (to within ±1% of the average pressure drop for the six sectors). If the pressure drops are not in balance, then the steam flows entering each of the six sectors are adjusted until equal pressure drop in each sector has been attained. The flow is then followed similarly on a row by row basis through the gas cooler section, and on to the extraction point for the vent system.

In the case of a rectangular tube bundle layout, the bundle is considered to be composed of up to eight horizontal sections, as shown in Figure 2. Row by row calculations are performed through sections 1 through 4 (the performance of sectors 5 through 8 is assumed to be identical). Here again, the objective is to obtain equal pressure drops in each of the horizontal sectors by adjusting the flow distribution into the sectors in a fashion very similar to that for the six radial sectors of the circular layout. Upon achieving a satisfactory pressure drop balance between the sectors, the calculations continued through the gas cooler section, also on a row by row basis, until the extraction point for the vent system is reached.

Special modifications of the program cover trapezoidal bundles, such as the Clair Engle bundles, and bundles with concentric rings of tubes, such as the West Coast Test Module, in a similar way.

Input Information

The input information is shown in Table I. Most of the items shown are self-explanatory. For non-condensable gas, the physical properties of air and CO_2, the two most likely gases to be present in distillation plants, are incorporated into this program and either can be chosen.

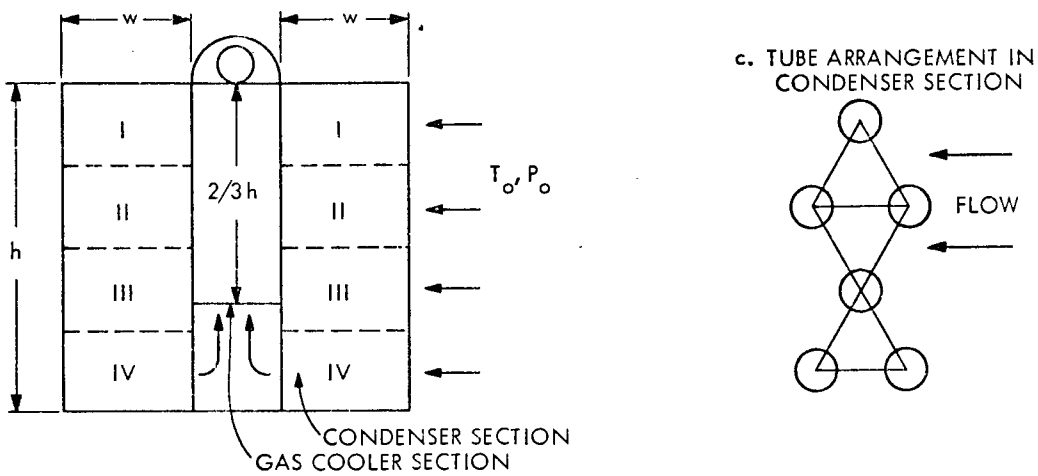

FIGURE 2. RECTANGULAR CONDENSER BUNDLE

TABLE I

List of Input Information Required by ORCON

1. Flows and Temperatures
   a. Steam or vapor flow rate, lb/hr
   b. Coolant flow rate, ft/sec or lb/hr
   c. Brine concentration in the coolant, wt frac.
   d. Non-condensable flow rate, lb/hr
   e. Exit steam fraction
   f. Inlet steam temperature, °F
   g. Inlet coolant temperature, °F
2. Bundle Information
   a. Total number of tubes in the bundle
   b. Per cent of tubes allocated to the gas cooler
   c. Ratio bundle height/bundle width (rectangular bundle)
   d. Bundle length, ft
   e. Direction of steam flow, vertical or horizontal (rectangular bundle)
   f. Tube spacing (S/D) in condenser (assumes equilateral triangles)
   g. Tube spacing (S/D) in the gas cooler (assumes equilateral triangles)
3. Tubing Information
   a. Tube OD, in.
   b. Wall thickness, in.
   c. Wall thermal conductivity, Btu/hr-ft^2-°F/ft
   d. Fouling factor, F_d
   e. Tube flooding factor
   f. Enhancement factor, inside
   g. Enhancement factor, fraction
4. Flags and Options

   EXITFR = 0. - calculate the vent rate of vapor
   >0. - target value in % of inlet vapor flow for desired vent rate of vapor

   INSTM = 1 - iterate to desired vent rate by adjusting inlet vapor rate
   = 0 - iterate to desired vent rate by adjusting tube length

   OUTPUT = 0.- summary page only
   = 1. - summary page plus row-by-row information
   = 2. - summary page plus row-by-row information; brine outlet temperatures punched out on cards
   = 3. - same as 2. except brine outlet temperatures are also retained in core for next case
   = 4. - same as 2. except brine outlet temperatures are retained in core for next case; no punched cards

In the tube information section, the items labeled "enhancement factors" are multipliers which are used to express the enhancement of the convective film heat transfer and tube side pressure drop. For the cases of smooth tubes, these enhancement factors are entered as 1.0.

In the section labeled "Flags and Options," are shown three items which add flexibility to the computer code. Specifying a value other than zero for the variable exit fraction is a flag indicating that the program will iterate to a desired vent rate of steam. The flag labeled "INSTM" will be specified at the same time to indicate whether the desired vent rate is to be arrived at by varying the inlet vapor flow rate or by adjusting the design length of the tubes in the bundle. Adjusting the inlet vapor flow rate to attain the desired vent rate is a means of adjusting the heat load on the condenser bundle to meet its capability. The other option (varying the length of the tubing) is a means of varying the heat transfer design in order to meet the specified heat load. If the item "EXITFR" is specified as 0, no iteration for the vent rate will be performed and the amount of steam entering the vent system will be simply that amount which remains uncondensed at the exit of the gas cooler section.

The output options are as follows:

OUTPUT - 0., only the summary page, such as shown in Figure 3, is printed.

OUTPUT = 1.0 - the summary page plus the row-by-row information such as shown in Figure 4 will be written out.

OUTPUT = 3.0 - the same information as outputed by the flag 1.0, the summary page plus the row-by-row information and in addition, row-by-row information on the brine temperature (exit and ; TB2 in Figure 4) will be punched out on cards in format suitable for employing as input information for a future calculation.

MSF TEST MOD STAGE 6B DECK4 4/13 RADFLG=1.1 5% TUBES IN COOLER

SUMMARY OF RESULTS

	AREA AVERAGE U, BTU/HR/SQ.FT. /DEG. F.	BACK CALC. LOG MEAN DELTA TEMP. DEG.F.	PRESSURE DROP LBS/SQ.IN.	TEMP. DROP DEG.F.	STEAM VELOCITY FT/SEC INLET	STEAM VELOCITY FT/SEC OUTLET	TUBE SPACING RATIO, S/D	TUBE FRACTION REMOVED, PERCENT	HEAT REMOVED, MILLION BTU/HR	HEAT TRF. SURFACE, SQ.FT.
CONDENSER	501.78	9.4641	0.0058	0.6077	56.75	5.69	1.333	95.74	18.9964	4000.17
COOLER	507.90	8.4404	0.0125	2.0811	85.27	18.46	1.333	4.26	0.7625	177.89
OVERALL	502.04	9.4200	0.0234	2.8511					19.7590	4178.06

OUTSIDE BUNDLE DIAM., FT. 5.03 INSIDE VOID DIAM., FT. 2.12 NUMBER OF RADIAL TUBE ROWS 20.

COOLER HEIGHT, FT. 1.51 COOLER WIDTH, FT. 0.56 BUNDLE LENGTH, FT. 7.550

EXIT STEAM, PERCENT OF INPUT 0.98 EXIT NON-CONDENSIBLES, PERCENT OF TOTAL EXIT FLOW 9.57

	AVG. BRINE TEMPS ENTRANCE	AVG. BRINE TEMPS EXIT
CONDENSER	93.9916	96.1154
COOLER	93.8767	95.7931
OVERALL	93.9822	96.0890

	FLOWS LBS/HR
STEAM TO CONDENSER	19284.
COOLANT TO BUNDLE	9999996.
COOLANT VELOCITY	6.0684 F/S
CONDENSATE FROM CONDENSER	18359.
CONDENSATE FROM COOLER	736.

DTCND2	UPCOND	DTCOL2	UPCOOL	DLTOT2	UPAVG
9.6577	491.7244	9.2279	464.5557	9.6331	490.8250

FIGURE 3

SUMMARY PAGE OF OUTPUT FROM CONDENSER CODE ORCON

NSF TEST MOD STAGE 6B DECK4 4/13 RADFLG=1.1 5% TUBES IN COOLER J = 1

	STSAT	PMIX	WS	VEL	RC	UN	SHNF	SHI	1/ROUT
1	104.70	1.0928	1630.4	56.7	0.0010	545.	3251.	1212.	3243.
2	104.68	1.0922	1516.3	54.5	0.0011	545.	3253.	1212.	3244.
3	104.66	1.0916	1405.7	52.1	0.0012	527.	2712.	1211.	2705.
4	104.64	1.0911	1301.3	49.8	0.0013	527.	2711.	1211.	2703.
5	104.63	1.0906	1200.3	47.5	0.0014	520.	2540.	1211.	2532.
6	104.61	1.0901	1103.7	45.1	0.0015	520.	2538.	1211.	2530.
7	104.59	1.0897	1010.4	42.8	0.0017	515.	2434.	1211.	2425.
8	104.58	1.0893	921.0	40.5	0.0018	515.	2433.	1211.	2423.
9	104.56	1.0890	834.9	38.1	0.0020	512.	2359.	1211.	2348.
10	104.55	1.0887	752.5	35.7	0.0022	511.	2358.	1211.	2346.
11	104.54	1.0884	673.3	33.3	0.0025	509.	2303.	1211.	2289.
12	104.52	1.0881	597.7	30.8	0.0028	509.	2301.	1211.	2285.
13	104.51	1.0879	525.3	28.3	0.0032	506.	2256.	1211.	2238.
14	104.49	1.0877	456.4	25.8	0.0037	506.	2255.	1210.	2233.
15	104.47	1.0875	390.6	23.2	0.0043	504.	2217.	1210.	2191.
16	104.45	1.0874	328.3	20.5	0.0051	503.	2217.	1210.	2183.
17	104.42	1.0873	269.2	17.7	0.0062	501.	2135.	1210.	2143.
18	104.39	1.0872	213.4	14.9	0.0079	500.	2187.	1210.	2127.
19	104.33	1.0871	161.0	11.9	0.0104	497.	2162.	1210.	2075.
20	104.23	1.0871	112.1	8.9	0.0149	494.	2158.	1210.	2021.
	104.02	1.0870	66.7						

	RENOS	HEAT FLUX	SF	GFLOW	TB1	TB2	HEFF	TBVPR	CUM DELP
1	1515.	5120.	0.1364	657.900	94.11	96.40	1.25333E 06	16.	0.0582
2	1451.	5112.	0.1380	639.870	94.11	96.39	1.13932E 06	15.	0.0742
3	1387.	4975.	0.1396	611.627	94.06	96.29	1.03678E 06	15.	0.0890
4	1325.	4967.	0.1414	584.356	94.06	96.28	9.36660E 05	14.	0.1027
5	1263.	4910.	0.1433	556.860	94.04	96.24	8.43515E 05	14.	0.1153
6	1201.	4902.	0.1454	529.573	94.04	96.23	7.55002E 05	13.	0.1269
7	1138.	4863.	0.1478	502.013	94.03	96.20	6.72767E 05	13.	0.1375
8	1076.	4855.	0.1505	474.444	94.03	96.20	5.94201E 05	12.	0.1471
9	1012.	4824.	0.1535	446.533	94.01	96.17	5.22035E 05	12.	0.1558
10	949.	4817.	0.1570	418.460	94.01	96.17	4.53707E 05	11.	0.1636
11	884.	4791.	0.1610	389.952	94.01	96.15	3.90970E 05	11.	0.1706
12	819.	4785.	0.1657	361.133	94.00	96.14	3.32596E 05	11.	0.1767
13	752.	4760.	0.1713	331.750	94.00	96.13	2.78891E 05	10.	0.1821
14	684.	4752.	0.1782	301.889	93.99	96.12	2.29770E 05	10.	0.1867
15	615.	4728.	0.1868	271.299	93.99	96.10	1.85137E 05	9.	0.1906
16	544.	4717.	0.1978	240.016	93.98	96.09	1.44961E 05	9.	0.1939
17	470.	4689.	0.2127	207.778	93.98	96.07	1.09353E 05	8.	0.1965
18	395.	4668.	0.2337	174.569	93.97	96.06	7.81638E 04	8.	0.1986
19	317.	4623.	0.2661	140.112	93.96	96.03	5.15190E 04	7.	0.2001
20	236.	4562.	0.3223	104.371	93.94	95.98	2.98870E 04	7.	0.2011

FIGURE 4

ROW-BY-ROW OUTPUT FROM CONDENSER CODE ORCON FOR SECTOR Y = 1

OUTPUT - 4.0 - the same information as OUTPUT - 1.0 plus the row-by-row information on the brine temperature (exit and ; TB2 in Figure 4) will be retained in core for use as input data for the next case.

STBI - when this item has a value greater than 1.0, the program assumes that this is a real temperature for the brine entering the tube bundle and will employ this as the inlet brine temperature for all tubes in the bundle.

STBI = 0. the program will look for data cards supplying the incoming brine temperature on a row-by-row basis. These data cards can be obtained by specifying the option OUTPUT = 3.0 as explained above.

STB - 1.0 - the program will look for data stored in core from the previous calculation to supply the incoming brine temperatures on a row-by-row basis. These data were made available by specifying the option OUTPUT = 4.0 as explained above.

Heat Transfer and Pressure Drop Correlations

During the initial preparation of the computer code, it was found that the published correlating equations for heat transfer and pressure drops in condenser bundles were often contradictory and occasionally too general for use in row-by-row calculation. The original version of ORCON employed what was felt to be the best equations available in the open literature at that time. Experiments at ORNL since that time have done much to fill the gaps in the information on condensing heat transfer and pressure drop, and much of this information has now been incorporated in ORCON during the recent updating work. Correlations upon which the current ORCON code is based are as follows:

1. Single tube condensate film coefficient (Nusselt equation):

$$h_1 = 0.725 \left(\frac{k^3 \rho_f^2 \lambda}{\mu_f D_o \Delta T}\right)^{1/4} \qquad (1)$$

2. Condensate rain factor (mean of n tubes in a vertical column):

$$F(n) = 0.6 \times F_d + \left(\frac{1-0.5647XF_d}{n^{0.20}}\right) \qquad (2)$$

where F_d is an input item with a value between 0 and 1 which is related to the tube spacing.

3. Effective heat transfer coefficient (h_{eff}) due to non-condensable gas:

$$j_M = e^{.53883-.544 \ln Re} \qquad (3)$$

where

$$j_M = \frac{k_G P_{gs}}{G} N_{sc}^{2/3} \qquad (4)$$

and

$$h_{eff} \Delta t_f = k_G \Delta P_f \lambda \qquad (5)$$

4. Convective film coefficient (h_c):

$$\frac{h_c D_i}{k} = E_i \times .023 \times \left(\frac{D_i V \rho}{\mu}\right)_b^{0.8} \times \left(\frac{C_p \mu}{k}\right)_b^{0.33} \qquad (6)$$

where E_i is an input item giving the convective film enhancement.

5. Shellside total pressure drop:

$$f = 0.102 + \frac{52.2}{N_{Re}} \qquad (7)$$

where

$$f = \frac{\Delta P \, g_c \, \rho}{2 \, G^2 \, N} \qquad (8)$$

The origins and/or confirming experimental data for these correlating equations are described in a later portion of this article.

In addition, the program requires as an input item, a (constant) value of a fouling resistance to apply to each tube in computing its overall heat transfer coefficient.

Values between 0.0003 and 0.0008 °F/Btu/hr-ft^2 have been used in past designations. However, recent analyses of the performance of an experimental vapor shear preheater at the Freeport Texas Demonstration Plant[2], and of fouling resistances calculated from VTE tube performance[3] indicate that the fouling resistance for

a distillation plant with acid feed treatment is 0.00015, considerably less than the normally used values. Work currently in progress in which the fouling tendency of desalting plant feed is measured with a fouling detector, is expected to further reinforce the tentative conclusion that fouling factors may be reduced below those commonly used today. However, careful control of pH; oxygen concentration and brine velocity may be necessary for long-term operation at 0.00015. Meanwhile, this input number is generally selected at 0.0003 - 0.0007.

Description of the Computer Output for Circular Bundle

In Figures 3 and 4 are shown examples of the output pages from the condenser code ORCON. Figure 3 is the summary tabulation and lists the overall performance information for the condenser section of the tube bundle and for the gas cooler section separately and then combined or overall.

The area averaged or area weighted heat transfer coefficients for the condenser, the gas cooler and the combined or overall are used, together with the amount of heat removed in these respective portions of the condenser bundles to arrive at the "back calculated" log mean Δt. This Δt_m reflects the loss in thermal driving force due to the pressure drop encountered by the vapor flowing through the bundle. Pressure drops and temperature drops are simply the difference between the values entering the first row and exiting the last row as obtained from the row-by-row calculations.

The Exit Steam, Per Cent of Input, shows the amount of steam which passes on to the vent system after having passed through all the rows of tubes in the bundle and represents the value which was arrived at by varying the entering vapor flow. The vapor flow rate which satisfied the target value for the exit or vent rate is labeled "steam to the condenser." The average brine temperature leaving the respective sections is listed under brine average temperature column and represents flow weighted averages.

The values DTCOND2, DTCOI2 and DLTOT2 are log mean Δt's calculated by using the vapor temperature, the average entering brine temperature and the average exit brine temperatures for the condenser, the gas cooler and the combined sections, respectively. Since these might be considered the standard fashion of calculating log mean Δt's, it can be seen that the difference between these values of the back calculated log mean Δt's mentioned above represent the average loss in thermal driving force due to pressure drops within the bundle.

In Figure 4 is shown the row-by-row output for section 1 of a circular bundle as indicated by the label "j = 1." The column tables are described briefly as follows:

First column is the row number.

STSAT	vapor temperature entering the row, °F
PMIX	pressure of vapor plus non-condensable, psia
WS	steam flow in the sector, lb/hr
VEL	vapor velocity at the minimum cross section, ft/sec
RC	fraction of non-condensables by weight
UN	overall heat transfer coefficient for the "typical" tube in the row
SHNF	condensing coefficient, Btu/hr-ft^2-°F
SHI	tube side coefficient, Btu/hr-ft^2-°F
1/ROUT	shell side film coefficient composed of gas film plus condensing film, Btu/hr-ft^2-°F
RENOS	Reynolds number based on mass flow at minimum cross section, dimensionless
HEAT FLUX	heat flux per square foot of tube, Btu/hr-ft^2
SF	friction factor, dimensionless
GFLOW	mass flow rate of vapor at minimum cross section, lb/hr

TB1	temperature of brine at inlet end of tube, °F
TB2	temperature of brine at the exit end of tube, °F
HEFF	heat transfer coefficient for the non-condensable film, Btu/hr-ft^2-°F
TBNPR	number of tubes per row
CUMDELP	total pressure drop from entrance (row 1) to row N, inches H_2O

DISCUSSION OF CORRELATIONS

Each of the correlating equations upon which the ORCON calculations are based has been experimentally tested at ORNL. The conclusions of these investigations will be described in this section along with a brief description of the correlating equations and their limitations.

Convective Film Coefficient

Extensive testing of tubes in the single tube horizontal and vertical condensers has been carried out at ORNL as part of the OSW program to develop economical types of enhanced heat transfer tubing. The results obtained both with smooth tubing and with enhanced tubing of a wide variety of configurations have confirmed that the widely accepted Colburn form of the convective film heat transfer correlation will predict coefficients with sufficient accuracy for all types of smooth or enhanced tubes for water and brine solutions in the temperature range of interest to this program (100-300°F) with only one undetermined parameter, the enhancement coefficient (E_i) in the equation:

$$\frac{h\,D_i}{k} = E_i \times .023 \left(\frac{D_i\,V\,\rho}{\mu}\right)_b^{0.8} \left(\frac{C_p\,\mu}{k}\right)_b^{0.33} \qquad (6)$$

For smooth tubes the accepted value of the numerical constant lies in the range 0.023-0.027, with the lower value being used in this program. For enhanced tubes, the enhancement coefficient can take on values as high as 2 or 3, depending on the type of tube. Experimental values of the coefficient for rope tube[4] have been in the range 1.85 - 2.0, with the lower value recommended for this program.

Tubeside Pressure Drop

Although not calculated in ORCON, the tube side pressure drop is a needed quantity in comparing condenser performance of enhanced tube condensers. The tube side pressure drop for any type tube can be calculated using the conventional Fanning friction factor equation written in general form:

$$\frac{D_i \ \Delta P \ g_c}{2L \ \rho V^2} = C_f \left(\frac{D_i \ V\rho}{\mu}\right)^{-m} \qquad (9)$$

where $C_f = 0.046$ and $m = 0.2$ for smooth tubes.

For enhanced surface tubes, both the coefficient multiplying the Reynolds number (C_f) and the exponent on the Reynolds number (m) may have different values depending on the type of tube. This is in contrast to the convective film coefficient equation for enhanced tubes, in which the Reynolds number exponent does not appear to change with tube types.

For rope tube, the Reynolds number exponent has been found to be the same as smooth tube (0.2) and the coefficient C_f has been determined to be 0.10 (2.25 x the smooth tube value).

Condensate Film Coefficient

The mean condensate film coefficient for a vertical column of n tubes in film-wise condensation is calculated from the equation:

$$\bar{h}_n = h_1 \times F_n \qquad (10)$$

where

$$h_1 = 0.725 \left(\frac{k^3 \rho_f^2 \lambda}{\mu_f D \Delta t}\right)^{1/4} \qquad (1)$$

and

$$F_n = 0.6 \times F_d + \left(\frac{1-0.5647XF_d}{n^{0.20}}\right) \qquad (2)$$

and F_d is a tube spacing parameter. The form of the equation has been verified in tests at ORNL using an experimental multitube condenser[4] and by comparison with previously published data. These tests have shown that the effects of steam temperature and log mean ΔT on the mean condensate film coefficient

are correctly handled by using the form of the Nusselt equation (equation 1). The effect of condensate rain is handled by equation (2) in which a recently developed tube spacing parameter F_d is included as an input variable.

This parameter represents the fraction of the tube bundle in which condensate drains from tube bottom to tube side; as illustrated in Figure 5, rather than from tube bottom to tube top. For this drainage path the value of the condensate rain factor can be theoretically shown to be:

$$F_1 = 0.6 + \frac{.4353}{n^{0.20}} \qquad (11)$$

For the alternate (bottom to top) drainage path, the rain factor has been experimentally shown to be:

$$F_2 = \frac{1}{n^{0.20}} \qquad (12)$$

for the case of a single vertical column of tubes[5,6] or for a single tube with recycle condensate spray.[7] Combining the two paths using the parameter F_d:

$$F_n = F_d \times F_1 + (1-F_d)\, F_2 \qquad (13)$$

results, or substitution, in equation (2).

The tube spacing parameter (F_d) will assume values between 0 and 1 depending on tube orientation and spacing. Based on a survey of the available published data, the values of F_d of Table II should be used.

TABLE II

Tentative Recommended Values of the Tube Spacing Parameter

Tube Lattice		F_d
in line		0
staggered	S/D > 1.40	0
	S/D = 1.33	0.5
	S/D < 1.25	1

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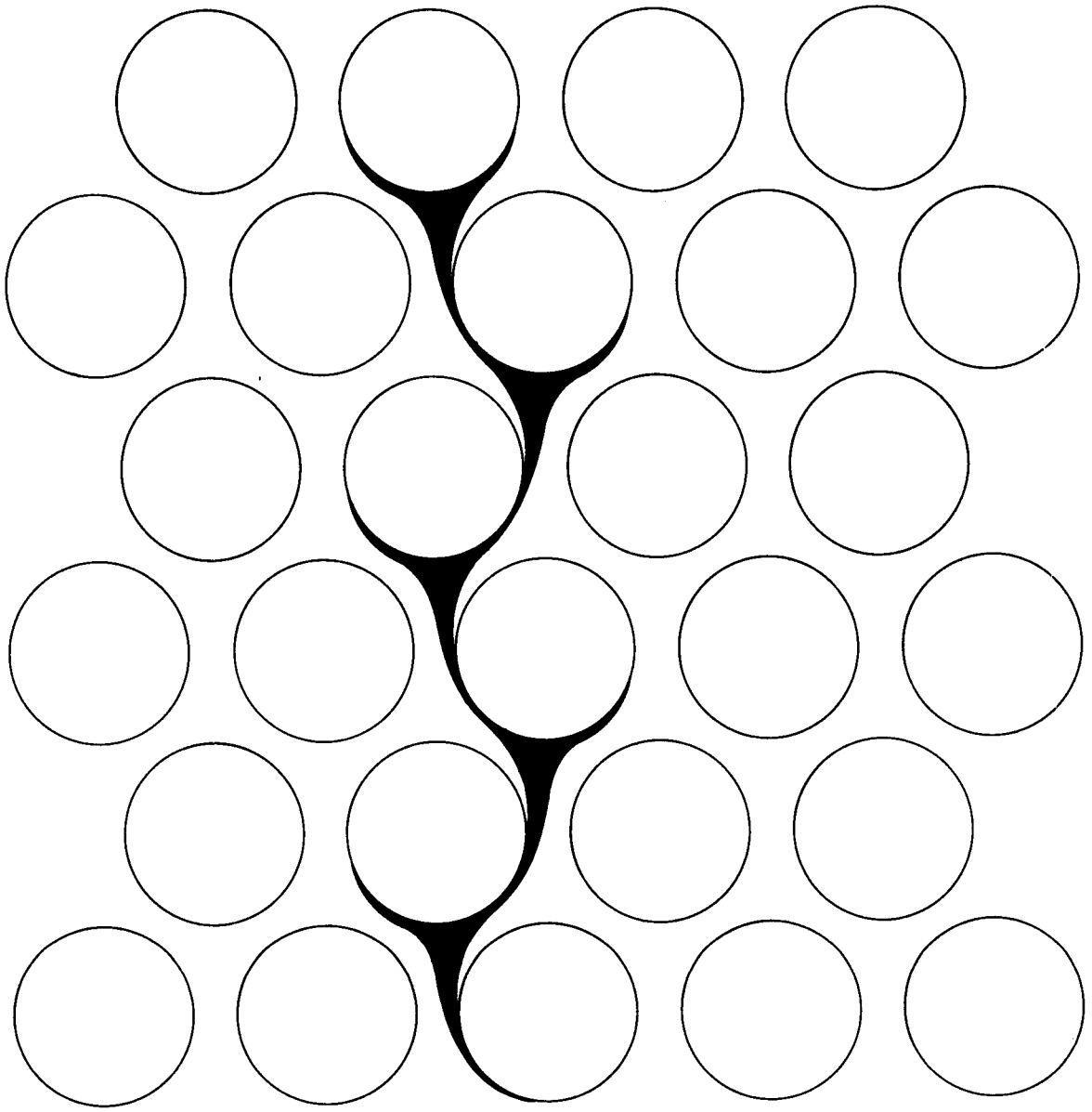

FIGURE 5. STAGGERED TUBE LATTICE

The heavy line shows a possible path followed by condensate. Note that top halves of tubes receive no drainage.

Figure 6 is a plot of F_n for values of F_d of 0, 0.5 and 1. It is expected that the value of the tube spacing parameter will be a function of the tube diameter and of the steam velocity. Further work is currently in progress aimed at increasing the understanding of this important parameter.

Effective Film Coefficient

The effective gas film heat transfer coefficient is defined based on the assumption that all of the heat transferred across the non-condensable gas film is in the form of latent heat:

$$h_{eff} = \frac{\lambda k_G \, \Delta P_f}{\Delta T_f} \tag{14}$$

and that the mechanism of heat transfer is therefore mass transfer of one gas (steam) through another (air). Thus turbulent mass transfer methods should apply to the system. The most widely used mass transport equation, the Colburn equation, which has been shown to correlate turbulent mass transfer data with Reynolds number,has not previously been tested for the case of steam condensation in tube bundles in the presence of non-condensing gas although it has been used in that application.A test program recently completed at ORNL[8] has produced much data which shows that a modified mass transfer factor, defined as

$$J_M = \frac{k_G \, P_{gs}}{G} \, (N_{sc})^{2/3} \tag{4}$$

rather than the conventional J_D factor will correlate experimental data against vapor Reynolds number for steam condensation in the presence of nitrogen.

The correlating equation was found to be

$$J_M = e^{.54 - .544 \ln Re} \tag{3}$$

with 95% of the data lying within a band ±25% of this equation. Figure 7 shows a parametric plot of the predicted effect of non-condensable gas on the overall coefficient of a tube based on this correlating equation.

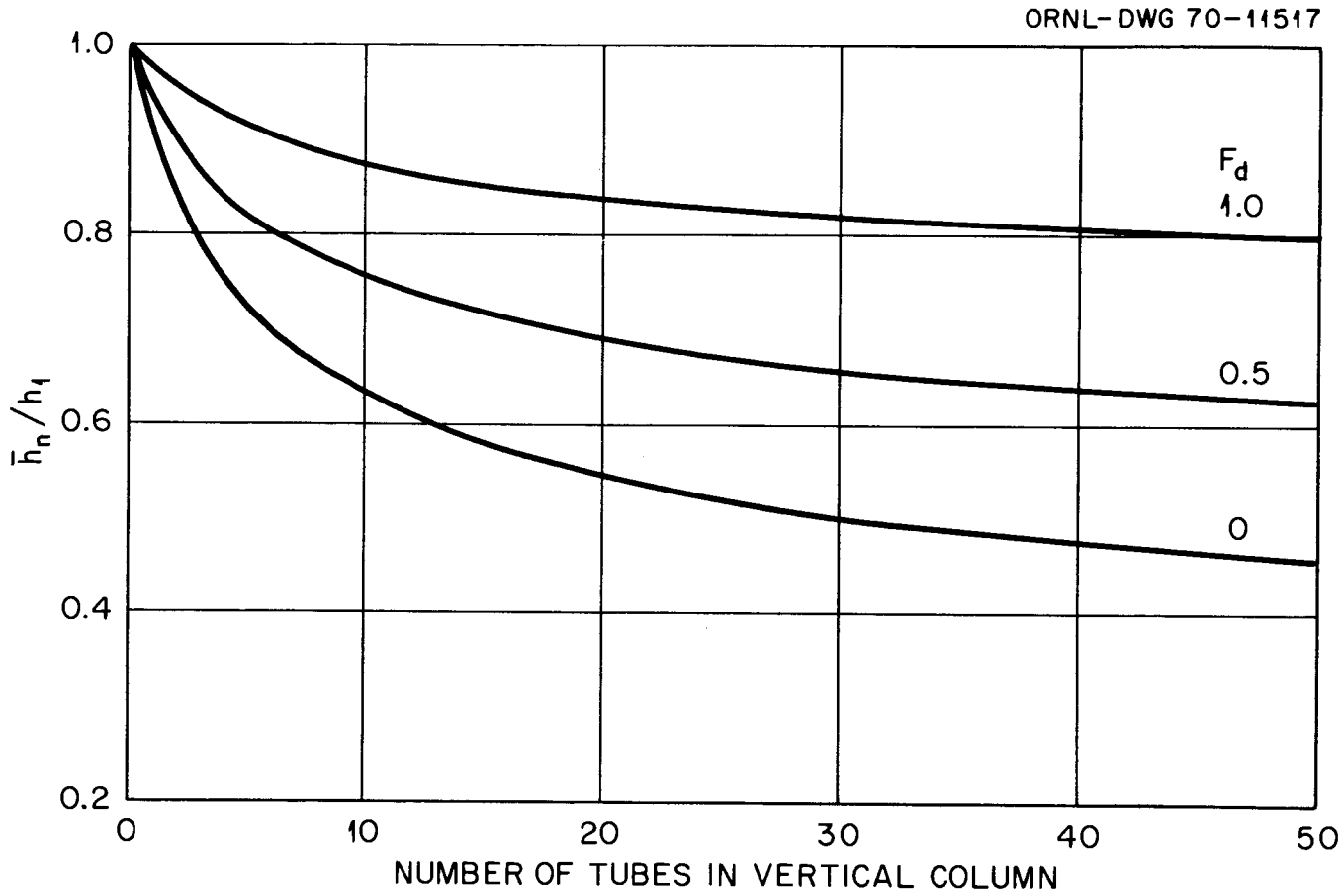

FIGURE 6. EFFECT OF TUBE SPACING PARAMETER ON CONDENSATE RAIN FACTOR

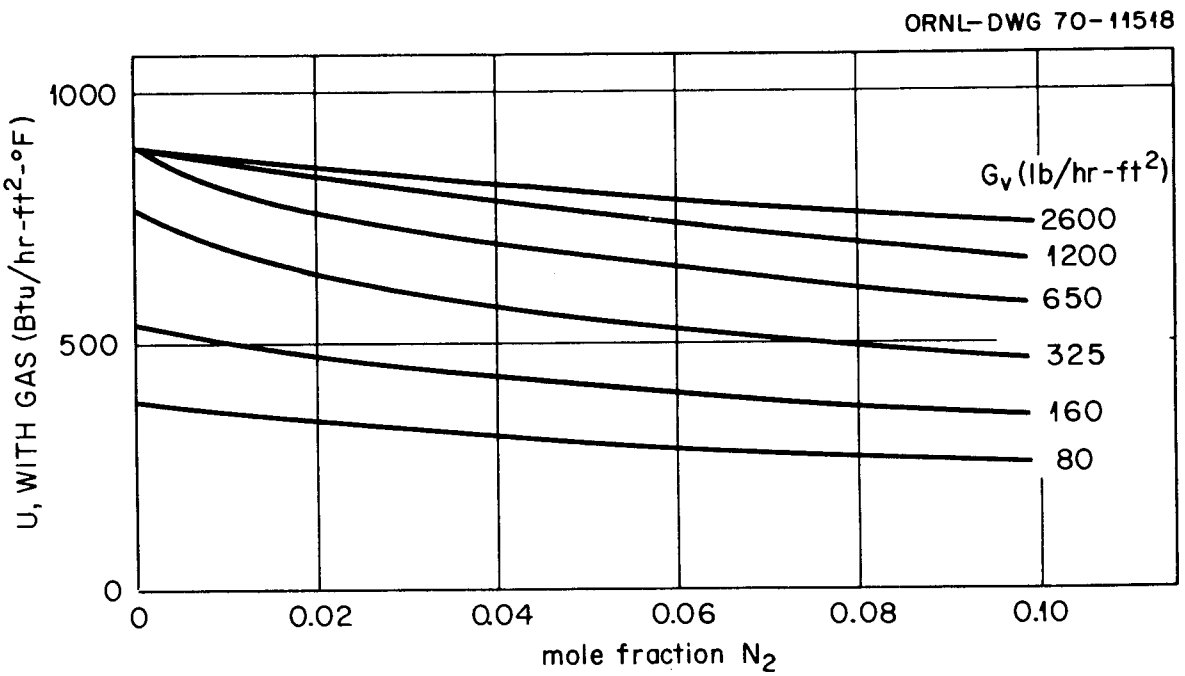

FIGURE 7. PREDICTED EFFECT OF NON-CONDENSABLE GAS ON THE OVERALL HEAT TRANSFER COEFFICIENT

The assumed conditions include:

Log Mean ΔT:	18°F
Steam Temperature:	230°F
No-Gas Overall Coefficient:	880 Btu/hr-ft^2-°F

The data on which the correlation was based was taken with both smooth and rope tube, and with filmwise and dropwise condensation.

It has been concluded, from the results of the test program, that, at moderate to high vapor velocities, the effect of non-condensables on condenser performance is very small. On the other hand, at low vapor velocities even small amounts of non-condensables substantially reduce performance. Properly designed condenser bundles should provide adequate vapor velocities throughout.

Pressure Drop for Flow of Steam Through Condenser Bank

The basis for calculating the pressure drop through a bank of condenser tubes is the existing correlation for single phase pressure drop across a tube bank. The two phase pressure drop is larger than for single phase due to the flow area decrease resulting from the film of condensate surrounding each tube and to the condensate dripping vertically. The steam velocities used in normal condensers are far below the range in which condensate is entrained by the steam stream (which would have the effect of increasing the flow area occupied by condensate). The correlations by Diehl and Unruh[8,9], which were derived from tests at high vapor velocities, are not relevant. Recent tests carried out at ORNL using a dummy condenser bundle with air in both up and down flow, and using various rates of condensate flow, have shown that the effect of the condensate is small (a maximum of a 15% increase in pressure drop over single phase results for the bottom tubes of large bundles in upflow) for condensate drainage rates (<1500 lb/hr-ft^2) and steam velocities (<1500 lb/hr-ft^2) commonly found in MSF condensers. For flow through tube banks consisting of equilateral

triangular spaced tubes (any orientation) with S/D greater than 1.30, the single phase pressure drop can be calculated from the equation:

$$f = 0.102 + \frac{52.2}{N_{Re}} \tag{7}$$

where

$$f = \frac{\Delta P \; g_c \; \rho}{2G^2 N} \; . \tag{8}$$

NOMENCLATURE

C_f	friction coefficient, equation (9)
D_i	inside diameter of tube
D_i, D	outside diameter of tube
E_i	enhancement factor, equation (6)
f	friction factor, equation (8)
F_d	tube spacing parameter
F(n)	condensate rain factor
F_1	F(n) for all side drainage, equation (11)
F_2	F(n) for all top drainage, equation (12)
g_c	conversion constant
G	steam mass velocity
h_c	convective heat transfer coefficient
h_{eff}	non-condensable gas film coefficient
h_n	mean condensate film coefficient for n tubes
h_1	condensate film coefficient for top tube
J_M	modified mass transfer factor, equation (4)
k	tubeside liquid thermal conductivity
k_G	mass transfer coefficient
L	length of tube
m	friction exponent; equation (9)
n	number of tubes in vertical column
N	number of tubes in steam flow path to vent
N_{Re}	Reynolds number
N_{sc}	Schmidt number
S	tube spacing (center to center)
P_{gs}	partial pressure of non-condensable gas at condensate film surface
ΔP	pressure drop in tube
ΔP_f	partial pressure drop of steam across non-condensable gas film
ΔT	temperature difference across condensate film
ΔT_f	temperature across non-condensable film
ΔT_m	log mean temperature difference (bulk liquid to bulk steam)
V	tubeside liquid velocity
λ	latent heat
μ	viscosity
ρ	density

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EISSENBERG, D. M. AND NORITAKE, H. M.
COMPUTER MODEL AND CORRELATIONS FOR PREDICTION OF
HORIZONTAL-TUBE CONDENSER PERFORMANCE IN SEAWATER DISTILLATION PLANTS
Oak Ridge National Laboratory, Tenn. 37830
ORNL-TM-2972 (Sept. 1970) 23 p, 7 fig, 9 ref

Report describes a computer program which performs row-by-row performance calculations for horizontal tube bundles of circular or rectangular cross section. Values are calculated for overall heat transfer coefficient, and for the steam mass velocity, noncondensable gas fraction, and steam pressure approaching the row and leaving it. The computer program automatically balances the calculated pressure drops through the bundle.

Multistage Flash Distillation + Condenser Tubing + *Horizontal-Tube Condensers + Heat Transfer Improvements + Noncondensables Removal + Steam Flow + OSW Sponsored + *programs (computers).

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