Evaporator Heat Transfer Coefficients for Beet Sugar Solution

ALLISON S. CHANG[1]

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Evaporaton plays one of the most important roles in the sugar refineries. The existing data available to give a functional relationship between heat transfer coefficients and operating pressures are somewhat limited. Kerr (2)[2] obtained the heat transfer coefficients for thirty-nine different evaporators, double-, triple-, and quadruple-effect in actual operation. He plotted heat transfer coefficients against operating pressures in pounds gage and in inches of mercury vacuum. The points scattered so badly that it requires a careful judgment to use them.

Several European technologists have worked out the formulas which take into consideration brix of the juice and the temperature of the heating vapor. However, the heat transfer coefficients calculated by the formulas do not agree with the actual values obtained by heat balance in this investigation.

The data reported here were obtained from full size evaporators in actual operation. Heat transfer coefficients were plotted against solids in solution rather than operating pressures. The result showed a better correlation between heat transfer coefficients and solids in solution. The curve shown on Figure 1 is applicable to both standard short vertical-tube evaporators and standard horizontal-tube evaporators with tubes in normal cleanliness.

A formula based on the curve shown on Figure 1 was proposed to estimate the heat transfer coefficients for beet sugar juice in the evaporator.

Apparatus

The apparatus used in this investigation were quintuple-effect full size evaporators at Factories #1 to #4. They were standard short vertical-tube evaporators with center downtake. Evaporators at Factory #5 were horizontal-tube evaporators except the first effect which was a standard vertical-tube evaporator with a center downtake.

The sizes of evaporator used in this investigation were as follows:

[1] Chemical Engineer, Engineering Department, The Amalgamated Sugar Company, Ogden, Utah.

[2] Numbers in parentheses refer to literature cited.

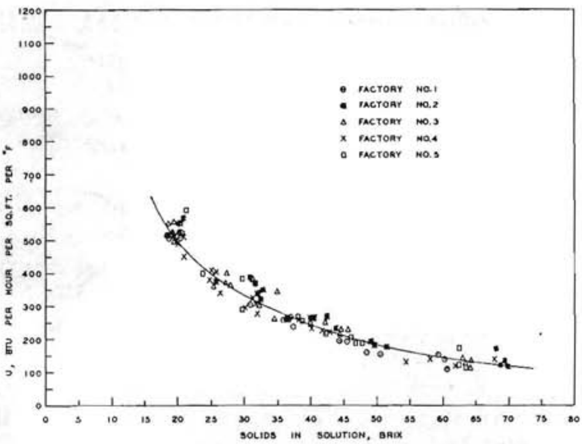


Figure 1.—Heat transfer coefficient for beet sugar solution.

Factory #1

1st Effect: Two bodies
25,176 sq.ft., 1¼″ OD, 14 ga. copper tubes, 11′-¼″ long.
10,750 sq.ft., 1¼″ OD, 0.049″ steel outside, 0.035″ copper inside, bi-metal tubes, 9′-6¼″ long.

2nd Effect: Three bodies
16,300 sq.ft., 1¼″ OD, 15 ga. copper tubes, 9′-⅜″ long.
15,400 sq.ft., 1¼″ OD, 15 ga. copper tubes, 8′-6⅜″ long.
10,730 sq.ft., 1¼″ OD, bi-metal tubes, 9′- 6¼″ long.

3rd Effect: 6,900 sq.ft., 1¼″ OD, 15 ga. copper tubes, 6′-2⅜″ long.

4th Effect: 6,630 sq.ft., 1¼″ OD, 14 ga. copper tubes, 6′-2⅜″ long.

5th Effect: 6,200 sq.ft., 1¼″ OD, 14 ga. copper tubes, 5′-6⅜″ long.

Factory #2

1st Effect: 16,744 sq.ft., 1¼″ OD, 14 ga. copper tubes, 9′-¼″ long.

2nd Effect: Two bodies
15,217 sq.ft., 44 1¼″ OD, 7/32 wall, steel tubes, 9′ ¼″ long.
5914 1¼″ OD, 14 ga. copper tubes, 9′- ¼″ long.
6,385 sq. ft., 1½″ OD, 14 ga. copper tubes, 5′-6¼″ long.

3rd Effect: 10,032 sq.ft., 26 1¼″ OD, 7/32″ wall, steel tubes, 8′- ¼″ long.
4440 1¼″ OD, 14 ga. copper tubes, 8′- ¼″ long.
4th Effect: 6,854 sq.ft., 1¼″ OD, 14 ga. copper tubes, 6′- ¼″ long.
5th Effect: 7,231 sq.ft., 1¼″ OD, 14 ga. copper tubes, 6′- 4¼″ long.

Factory #3

1st Effect: 16,744 sq.ft., 1¼″ OD, 14 ga. copper tubes, 9′- ¼″ long.
2nd Effect: Two bodies
11,132 sq.ft., 1¼″ OD, 15 ga. copper tubes, 6′- 7¾″ long.
3,300 sq.ft., 2″ OD, 14 ga. copper tubes, 4′- 1¼″ long.
3rd Effect: 8,614 sq.ft., 1¼″ OD, 15 ga. copper tubes, 6′- 7¾″ long.
4th Effect: 6,058 sq.ft., 1½″ OD, 14 ga. copper tubes, 5′- 9¼″ long.
5th Effect: 6,854 sq.ft., 1¼″ OD, 14 ga. copper tubes, 6′- ¼″ long.

Factory #4

1st Effect: 15,843 sq.ft., 2,640 1¼″ OD, 14 ga. copper tubes, 9′- ⅜″ long.
2,106 2″ OD, 14 ga. copper tubes, 9′, ⅜″ long.
2nd Effect: 8,474 sq.ft., 1¼″ OD, 15 ga. copper tubes, 7′- 0″ long.
3rd Effect: 6,355 sq.ft., 1¼″ OD, 15 ga. copper tubes, 5′- 3″ long.
4th Effect: 4,540 sq.ft., 1¼″ OD, 15 ga. copper tubes, 3′- 9″ long.
5th Effect: 5,145 sq.ft., 1¼″ OD, 15 ga. copper tubes, 4′- 3″ long.

Factory #5

1st Effect: 5,860 sq.ft., vertical-tube, 2″ OD, 12 ga. copper, 5′- 5½″ long.
2nd Effect: 5,836 sq.ft., horizontal-tube, 1″ OD, 16 ga. admiralty brass, 15′- 4″ long.
3rd Effect: 3,945 sq.ft., horizontal-tube, 1″ OD, 16 ga. admiralty brass, 13′- 7″ long.
4th Effect: Same as above.
5th Effect: Same as above.

Factory steam flow rates, dome pressure and temperature recorders were supplied by Taylor Instruments Company. Thin juice brix to 1st effect and thick juice brix from 5th effect were measured by laboratory refractometer. All intermediate brixes of juice were measured by laboratory hydrometer. Quantities of thin juice to 1st effect and thick juice from 5th effect at #2 and #4 factory for run #4 were measured by Foxboro, Model No. 9650 C, Magnetic Flowmeter. Others were calculated by overall factory heat and material balances. Juice inlet temperatures at 1st effect were measured by Model R, Dillon Dial Thermometers.

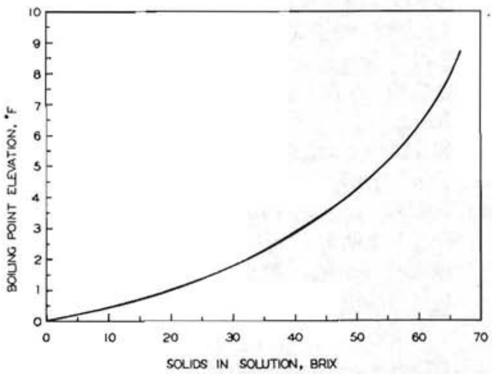


Figure 2.—Boiling Point elevation for sugar solution.

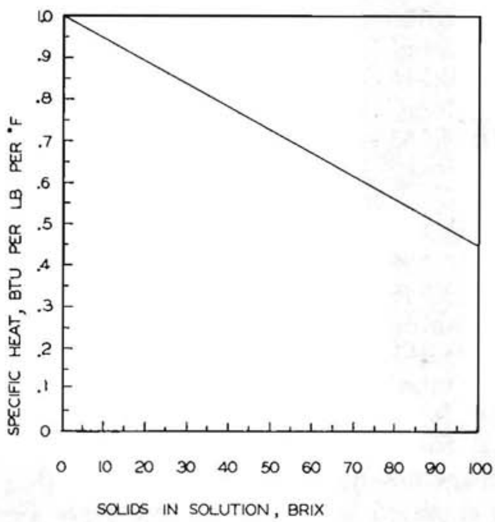
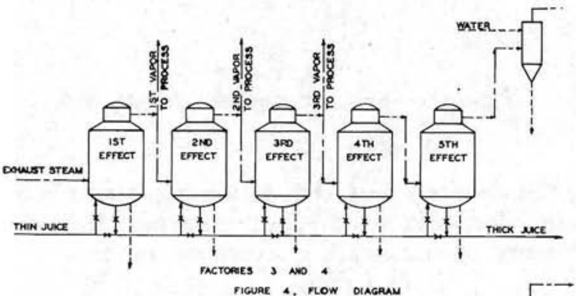


Figure 3.—Specific heat of sugar solution taken from laboratory data.

General arrangement of evaporators for factories #3 and #4 is shown on Figure 4. General arrangements of evaporators and flash tanks for factories #1 and #2 are shown on Figure 5. General arrangement of evaporators for factory #5 is shown on Figure 6.



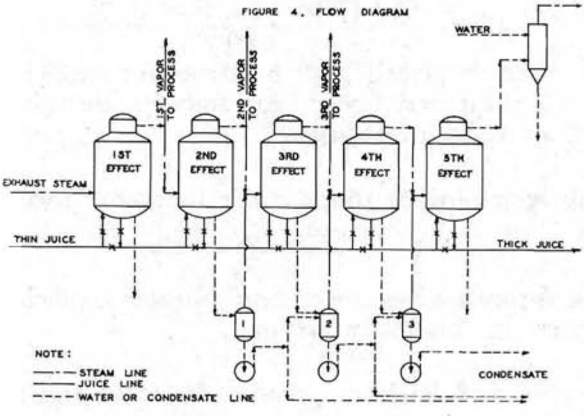


Figure 4.—Flow diagram (top) for factories #3 and #4.

Figure 5.—Flow diagram (below) for factories #1 and #2.

Over-all Heat Transfer Coefficients

The heat transfer coefficients depend on the cleanliness of surfaces on both the vapor and juice sides, on the metal of which the tubes are made, on the ratio length and diameter of the tubes, on the temperature difference between the vapor and juice side and, finally, on the brix of the juice and the temperature of juice.

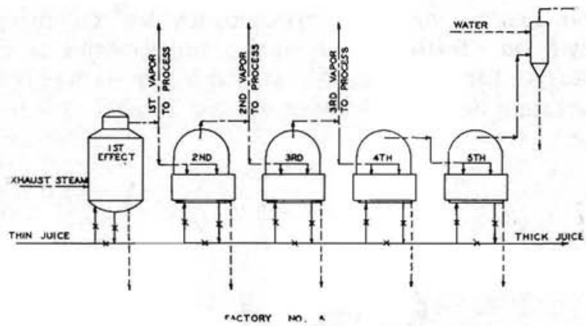


Figure 5.—Flow diagram for factory #5.

Dessin has worked out the following formula which takes into consideration brix of the juice leaving the evaporator and the temperature of the heating steam or vapor.

$$U = \frac{960\ (100 - B_x)\ (t_v - 130)}{16{,}000}$$

The above formula gives higher heat transfer coefficients for 1st, 2nd and 3rd effect and lower heat transfer coefficients for 4th and 5th effect under investigation.

Swedish technologists propose the following formula:

$$U = \frac{49.2\ (t_j - 32)}{B_x}$$

The above formula gives lower heat transfer coefficients for 4th and 5th effect in this investigation.

MacDonald and Rodgers propose the following formula:

$$U = \frac{55\left(\frac{t_j - 32}{100}\right)^2}{\sqrt{\mu_j} \times \sigma_j}$$

The above formula gives lower heat transfer coefficients for every effect from 1st to 5th body in this investigation.

Data shown in Table 1 were 24 hours average. Dome pressures, dome temperatures, exhaust steam pressures were recorded every hour on the hour. Juice inlet temperatures, brixes of juice to and from each effect between 2nd and 4th effect were measured and recorded once every two hours. Juice and steam flow rates to 1st effect and thick juice from 5th effect were calculated by overall heat and material balance to within 2% accuracy for every factory without magnetic flowmeter.

TABLE I.

Factory No.	Run No.	Thin Juice to 1st Effect #/hr.	Thin Juice to 1st Effect Brix	Exhaust steam to 1st effect #/hr.	Exhaust steam to 1st effect Pressure psig	Exhaust steam to 1st effect Temp. °F	1st effect Pressure psig	1st effect Sat. vapor temp. °F	1st effect 1st vapor to process #/hr.	Juice out brix	Condensate to 1st flash tank #/hr.
1	1	551,000	12.6	192,000	25.6	266	17.3	251	34,600	18.7	
	2	538,000	13.5	193,500	25.6	266	17.3	251	23,900	20.3	
	3	700,000	12.9	282,000	28.0	270	20.2	255	83,300	20.7	180,700
2	1	521,000	12.4	175,000	24.5	264	13.4	244	67,100	18.3	98,900*
	2	497,000	13.2	187,000	25.1	265	13.4	244	57,000	20.3	117,500
	3	504,000	13.5	195,500	27.5	268	15.4	248	66,300	20.8	111,700
	4	510,000	13.3	188,000	24.5	264	13.4	244	54,400	20.2	120,100
3	1	462,000	13.3	151,000	28.5	270	18.1	253	44,200	19.2	
	2	450,000	13.4	151,000	27.0	267	16.0	249	55,300	19.5	
	3	492,000	12.7	169,000	27.5	268	16.8	250	72,700	18.6	
	4	514,000	13.0	178,700	26.4	266	15.3	247	73,800	19.4	
4	1	378,000	12.9	131,000	26.5	266	18.7	250	73,100	19.4	
	2	339,000	13.2	127,500	27.0	267	18.5	249	85,000	20.9	
	3	353,000	12.3	141,000	26.2	265	15.5	247	97,150	20.0	
	4	363,000	13.2	138,500	26.2	265	16.2	248	91,500	20.8	
5	1	235,000	14.1	57,500	18.8	253	10.1	234	20,100	18.7	
	2	224,000	13.7	81,300	22.2	259	10.8	236	34,500	21.2	
	3	222,000	13.7	72,700	21.9	258	10.8	236	25,300	20.2	
	4	226,000	14.1	77,500	22.2	259	11.2	237	29,000	21.1	

*1st flash tank in service only.

TABLE 1.—(Continued)

Factory No.	Run No.	2nd effect				Condensate to 2nd flash tank #/hr.	3rd effect				
		Pressure psig	Sat. vapor temp. °F	2nd vapor to process #/hr.	Juice out brix		Pressure psig	Pressure "Hg vac.	Sat. vapor temp. °F	3rd vapor to process #/hr.	Juice out brix
1	1	9.23	235	112,500	30.9		1.11		212	7,800	37.3
	2	7.58	231	132,500	37.1			0.55	207	13,500	44.3
	3	9.96	237	155,000	36.0	148,990	1.11		212	19,000	42.3
2	1	7.40	231	51,300	25.6		2.14		215	7,470	32.6
	2	5.87	226	86,100	32.5	151,900	0.71		210	13,750	40.2
	3	8.25	232	76,700	32.2	149,900	2.14		215	15,550	40.2
	4	6.40	228	74,200	31.9	169,200		0.33	207	32,000	42.5
3	1	9.57	234	51,700	27.8		1.59		211	18,500	36.2
	2	8.76	232	46,500	27.4		1.31		210	11,500	34.7
	3	8.83	233	35,800	25.2		1.89		212	13,250	32.4
	4	7.97	230	49,700	27.3		2.50		214	14,500	35.0
4	1	9.82	234	18,250	25.1		2.34		213	6,090	32.0
	2	9.82	234	13,400	26.2		3.34		216	1,915	32.1
	3	9.82	234	12,650	24.8		4.15		217	2,650	30.1
	4	10.20	238	13,650	25.8		4.29		219	2,510	31.4
5	1	4.13	218	11,000	23.7			4.97	193	3,100	29.9
	2	3.30	215	29,500	31.2			3.15	197	4,250	38.2
	3	3.30	215	28,900	29.6			4.06	195	4,340	36.7
	4	3.50	216	29,300	31.1			4.06	195	5,850	38.7

TABLE 1.—(Continued)

Factory No.	Run No.	Condensate to 3rd flash tank #/hr.	4th Effect Pressure "Hg vac.	4th Effect Sat. vapor temp. °F	4th Effect Juice out brix	5th Effect Pressure "Hg vac.	5th Effect Sat. vapor temp. °F	5th Effect Juice out brix	Thick juice from 5th effect #/hr.	Thin juice inlet temp. at 1st effect °F
1	1		12.0	181	45.6	22.5	135	60.4	115,100	232
	2		11.7	182	50.7	21.1	144	60.7	119,300	232
	3	139,970	11.4	183	48.5	21.0	145	59.5	151,300	234
2	1		10.9	183	43.8	22.2	135	68.1	94,900	232
	2	176,850	9.89	186	49.1	21.5	140	68.7	95,700	225
	3	176,550	9.12	188	49.7	20.8	144	69.5	97,900	220
	4	190,900	11.4	182	51.5	22.2	135	70.0	96,800	223
3	1		8.96	185	45.8	21.5	130	64.2	95,700	235
	2		10.5	181	44.5	21.6	129	63.6	94,700	232
	3		9.96	183	42.4	21.5	130	63.1	98,900	230
	4		9.26	184	44.8	21.3	132	64.3	103,600	235
4	1		11.85	175	43.0	23.5	101.5	68.0	72,000	244
	2		8.36	185	41.8	21.5	126	62.0	72,000	246
	3		6.10	191	38.3	19.7	140	54.5	79,400	241
	4		7.31	188	40.2	20.4	135	58.0	82,400	239
5	1		14.8	163	40.0	22.3	114	62.5	53,280	232
	2		11.5	175	46.9	19.9	136	62.3	49,450	232
	3		12.3	172	46.1	21.1	126	63.8	47,950	235
	4		12.3	172	47.9	21.0	127	63.6	49,550	235

Atmospheric pressure

Factory No. 1: 13.59 psia, 27.63 "Hg.
Factory No. 2: 13.41 psia, 27.33 "Hg.
Factory No. 3: 12.81 psia, 26.03 "Hg.
Factory No. 4: 12.56 psia, 25.52 "Hg.
Foctory No. 5: 12.4 psia, 25.2 "Hg.

Overall heat transfer coefficients were calculated by

$$U = \frac{Q}{\Delta T \times A}$$

and tabulated in Table 2.

Where ΔT = effective temperature difference, °F
= apparent temperature difference − b.p.r., °F.

Apparent temperature difference:

1st effect = exhaust steam temperature − 1st vapor sat. temperature, °F.
2nd effect = 1st vapor sat. temperature − 2nd vapor sat. temperature, °F.
3rd effect = 2nd vapor sat. temperature − 3rd vapor sat. temperature, °F.
4th effect = 3rd vapor sat. temperature − 4th vapor sat. temperature, °F.
5th effect = 4th vapor sat. temperature − 5th vapor sat. temperature, °F.

Sample calculations: Factory #2, Run 4.

Thin juice to 1st effect = 510,000 #/hr.
Solids in juice = 67,800 #/hr. @ 13.3 brix.
Steam to 1st effect = 188,000 #/hr. @ 24.5 psig and 264 °F.

1st Effect:

Heat from steam = 188,000 (936) = 176,000,000 Btu/hr.
Heating juice = 510,000 (245-223) (0.925) = 10,350,000 Btu/hr.
Available heat = 165,650,000 Btu/hr.

$$\text{1st vapor} = \frac{165{,}650{,}000}{949.5} = 174{,}500 \ \#/\text{hr.}$$

	Juice	Brix
	510,000 #/hr.	
To process = 54,400 #/hr.	−174,500 #/hr.	
To 2nd effect = 120,100 #/hr.	335,500 #/hr.	20.2

B.P.R. = 1.0°F from Figure 2
$\Delta T = 264 - 244 - 1 = 19°F$
Heating surface = 16,744 sq.ft.

$$U = \frac{176{,}000{,}000}{19 \times 16{,}744} = 553 \text{ Btu per hr. per sq.ft. per °F.}$$

2nd Effect:

Heat from vapor = 120,100 (949.5) = 114,000,000 Btu/hr.
Juice flash = 335,500 (245 − 230) 0.82 = 4,130,000 Btu/hr.
Available heat = 118,130,000 Btu/hr.

$$\text{2nd vapor} = \frac{118{,}130{,}000}{960.1} = 123{,}300 \ \#/\text{hr.}$$

		Juice	Brix
To process – 74,200 #/hr.		335,500 #/hr.	
To 3rd effect = 49,100 #/hr.		–123,300 #/hr.	
		212,200 #/hr.	31.9

B.P.R. = 2.0 °F

T = 244 –228 –2 = 14 °F

Heating surface = 21,602 sq.ft.

$$U = \frac{114{,}000{,}000}{14 \times 21{,}602} = 377 \text{ Btu per hr. per sq. ft. per } ^\circ\text{F.}$$

1st Flash Tank: Condensate = 120,100 #/hr.

$$\text{Vapor} = \frac{120{,}100\ (212.4 - 196.2)}{960.1} = 2{,}030 \ \#/\text{hr. to 3rd effect}$$

3rd Effect:

Heat from vapor = (49,100 + 2,030) 960.1 = 49,100,000 Btu/hr.

Juice flash = 212,200 (230 – 210.2) 0.77 = 3,230,000 Btu/hr.

Available heat = 52,330,000 Btu/hr.

$$\text{3rd vapor} = \frac{52{,}330{,}000}{973} = 53{,}700 \ \#/\text{hr.}$$

		Juice	Brix
To process = 32,000 #/hr.		212,200 #/hr.	
To 4th effect = 21,700 #/hr.		– 53,700 #/hr.	
		159,500 #/hr.	42.5

B.P.R. = 3.2 °F

T = 228 – 207 – 3.2 = 17.8 °F

Heating surface = 10,032 sq.ft.

$$U = \frac{49{,}100{,}000}{17.8 \times 10{,}032} = 275 \text{ Btu per hr. per sq.ft. per } ^\circ\text{F.}$$

2nd Flash Tank: Condensate = 169,200 #/hr.

$$\text{Vapor} = \frac{169{,}200\ (196.2 - 175)}{973} = 3{,}690 \ \#/\text{hr. to 4th effect}$$

4th Effect:

Heat from vapor = (21,700 + 3,690) 973 = 24,700,000 Btu/hr.

Juice flash = 159,500 (210.2 – 186.5) 0.72 = 2,720,000 Btu/hr.

Available heat = 27,420,000 Btu/hr.

$$\text{4th vapor} = \frac{27{,}420{,}000}{989} = 27{,}700 \ \#/\text{hr.}$$

		Juice	Brix
		159,500 #/hr.	
B.P.R. = 4.5 °F		– 27,700 #/hr.	
T = 207 – 182 – 4.5 = 20.5 °F		131,800 #/hr.	51.5

Heating surface = 6,854 sq.ft.

$$U = \frac{24{,}700{,}000}{20.5 \times 6{,}854} = 176 \text{ Btu per hr. per sq.ft. per } ^\circ\text{F.}$$

3rd Flash Tank: Condensate = 190,000 #/hr.

$$\text{Vapor} = \frac{190{,}900\ (175 - 150)}{989} = 4{,}830\ 3/\text{hr. to 5th effect}$$

5th Effect:

Heat from vapor = (27,700 + 4,830) 989 = 32,100,000 Btu/hr.
Juice flash = 131,800 (186.5 —144.2) 0.63 = 3,500,000 Btu/hr.
Available heat = 35,610,000 Btu/hr.

$$\text{5th vapor} = \frac{35{,}610{,}000}{1017} = 35{,}000\ \#/\text{hr.}$$

Juice	Brix
131,800 #/hr.	
— 35,000 #/hr.	
96,800 #/hr.	70

B.P.R. = 9.2 °F

T = 182 — 135 —9.2 = 37.8 °F

Heating surface = 7,231 sq.ft.

$$U = \frac{32{,}100{,}000}{37.8 \times 7{,}231} = 117.5 \text{ Btu per hr. per sq.ft. per } ^\circ\text{F.}$$

Evaporator heat transfer coefficients are one of the most important data for sugar refineries. With the data of heat transfer coefficients it enables the refineries to estimate the required heating surface for certain operation by rearranging the equation to the following form.

$$A = \frac{Q}{\Delta T \times U}$$

Apparent temperature difference = ΔT + B.P.R.

1st effect: 1st vapor sat. temperature = exhaust steam temperature — apparent temperature difference at 1st effect.

2nd effect: 2nd vapor sat. temperature = 1st vapor sat, temperature — apparent temperature difference at 2nd effect.

3rd effect: 3rd vapor sat. temperature = 2nd vapor sat, temperature — apparent temperature difference at 2nd effect.

4th effect: 4th vapor sat. temperature = 3rd vapor sat, temperature — apparent temperature difference at 4th effect.

5th effect: 5th vapor sat. temperature = 4th vapor sat. temperature — apparent temperature difference at 5th effect.

TABLE 2.

Factory No.	Run No.	1st Effect Heat load 10³Btu/hr.	B. P. R. ○F	Apparent T, ○F	Effective T, ○F	U*	2nd Effect Heat load 10³Btu/hr.	B. P. R. ○F	Apparent T, ○F	Effective T, ○F	U*
1	1	179,500	0.9	15	14.1	508	136,000	1.9	16	14.1	304
	2	181,000	1.0	15	14.0	517	149,000	2.5	20	17.5	269
	3	263,000	1.0	15	14.0	522	170,500	2.4	18	15.6	258
2	1	164,000	0.9	20	19.1	512	94,000	1.4	13	11.6	375
	2	175,000	1.0	21	20.0	522	111,500	2.1	18	15.9	324
	3	182,000	1.0	20	19.0	572	105,700	2.0	16	14.0	349
	4	176,000	1.0	20	19.0	553	114,000	2.0	16	14.0	377
3	1	141,000	0.9	17	16.1	523	90,600	1.6	19	17.4	364
	2	141,000	1.0	18	17.1	496	81,300	1.6	17	15.4	370
	3	157,500	0.9	18	17.1	550	79,100	1.4	17	15.6	355
	4	167,200	1.0	19	18.0	554	90,900	1.6	17	15.4	409
4	1	122,500	1.0	16	15.0	516	51,000	1.4	16	14.6	412
	2	120,500	1.0	18	17.0	448	38,400	1.5	15	13.5	336
	3	141,000	1.0	18	17.0	489	37,200	1.4	13	11.6	379
	4	129,500	1.0	17	15.9	515	39,800	1.4	13	11.6	405
5	1	54,300	0.9	19	18.1	512	34,500	1.2	16	14.8	400
	2	76,500	1.1	23	21.9	596	42,600	1.9	21	19.1	382
	3	68,500	1.1	22	20.9	559	43,700	1.8	21	19.2	289
	4	72,600	1.1	19	17.9	592	44,300	1.9	21	19.1	390

*Btu per hour per sq.ft. per ○F

TABLE 2.—(Continued)

Factory No.	Run No.	3rd effect					4th effect				
		Heat load 10^3Btu/hr.	B. P. R. ○F	Apparent T, ○F	Effective T, ○F	U*	Heat load 10^3Btu/hr.	B. P. R. ○F	Apparent T, ○F	Effective T, ○F	U*
1	1	33,100	2.5	23	20.5	239	29,600	3.6	31	27.4	192
	2	27,300	3.4	24	20.6	192	17,700	4.3	25	20.7	152
	3	32,100	3.1	25	21.9	213	22,200	4.0	29	25.0	158
2	1	49,600	2.0	16	14.0	353	45,500	3.3	32	28.7	231
	2	35,200	2.9	16	13.1	268	26,700	4.0	24	20.0	195
	3	38,300	2.9	17	14.1	270	28,400	4.1	27	22.9	181
	4	49,100	3.2	21	17.8	275	24,700	4.5	25	20.5	176
3	1	46,200	2.4	23	20.6	261	32,000	3.6	26	22.4	238
	2	41,200	3.3	22	18.7	257	33,700	3.4	29	25.6	219
	3	49,400	2.0	21	19.0	301	40,700	3.1	29	25.9	259
	4	48,300	2.3	16	13.7	351	37,400	3.5	30	26.5	233
4	1	37,000	2.0	21	19.0	307	34,500	3.3	38	34.7	219
	2	28,100	2.0	18	16.0	276	28,600	3.1	31	27.9	226
	3	27,600	1.9	17	15.1	291	27,500	2.7	26	23.3	260
	4	29,300	1.9	16	14.1	327	29,400	2.8	31	28.2	230
5	1	26,100	1.8	25	23.2	285	25,800	2.8	30	27.2	241
	2	16,350	2.7	18	15.3	270	13,550	3.8	22	18.2	186
	3	18,200	2.5	20	17.5	264	15,450	3.7	23	19.3	203
	4	18,350	2.7	21	18.3	255	14,150	3.9	23	19.1	188

*Btu per hour per sq.ft. per ○F.

TABLE 2.—(Continued)

Factory No.	Run No.	5th effect Heat load 10^3Btu/hr.	B. P. R. °F	Apparent T, °F	Effective T, °F	U*
1	1	33,800	6.6	46.0	39.4	138
	2	20,580	6.6	38.0	31.4	106
	3	30,700	6.5	38.0	31.5	152
2	1	50,140	9.1	48.0	38.9	178
	2	33,800	9.3	46.6	36.7	127
	3	36,300	9.1	44.0	34.9	143.5
	4	32,100	9.2	47.0	37.8	117.5
3	1	35,160	7.6	55.0	47.4	108.5
	2	37,150	7.5	52.0	44.5	123
	3	44,840	7.1	53.0	45.9	142.5
	4	41,580	7.7	52.0	44.3	137
4	1	38,760	9.5	73.5	64.0	141
	2	31,800	6.7	59.0	52.3	118
	3	30,370	5.1	51.0	45.9	129
	4	32,980	5.9	53.0	47.1	136
5	1	28,320	7.3	49.0	41.7	179
	2	14.700	7.2	39.0	31.8	117.5
	3	16,750	7.7	46.0	38.3	111
	4	15,470	7.2	45.0	37.8	103.5

*Btu per hour per sq.ft. per °F.

It also enables the refineries to estimate the vapor temperature and pressure for existing heating surface by rearranging the equation to the following form.

$$\Delta T = \frac{Q}{A \times U}$$

From the data obtained in this investigation, the following formula is proposed.

$$U = \frac{40\ (t_j - 32)}{\dfrac{(1 - n \times 0.028)}{B_x}} \quad \ldots\ldots\ldots (1)$$

Over-all heat transfer coefficients calculated by the above formula agree with the values obtained from Figure 1.

Summary and Conclusions

The result of this investigation showed a better correlation between heat transfer coefficients and solids in solution.

The curve shown on Figure 1 is applicable to both standard short vertical-tube evaporators and standard horizontal-tube evaporators with tubes in normal cleanliness provided that the tube size and operating conditions are within the following ranges:

For vertical-tube evaporator:

1st effect: L/D = 32.7 — 105.8
t_v = 244°F — 255 °F
Juice brix out = 18.3 — 20.8
Tube material: copper or bi-metal tubes

2nd effect: L/D = 24.6 — 91.4
t_v = 226 °F — 237 °F
Juice brix out: 24.8 — 37.1
Tube material: copper or steel or bi-metal tubes

3rd effect: L/D = 50.4 — 77
t_v = 207 °F — 219 °F
Juice brix out: 30.1 — 44.3
Tube material: copper or steel tubes

4th effect: L/D = 36 — 59.5
t_v = 175 °F — 191 °F
Juice brix out: 38.3 — 50.7
Tube material: copper tubes

5th effect: L/D = 40.8 — 61
t_v: 101.5 °F — 145 °F
Juice brix out: 54.5 — 70
Tube material: copper tubes

Tube data and operating conditions for horizontal-tube evaporator are shown on pages 155-157 and Table 1 at factory #5.

Figure 1 and Equation (1) may or may not be applicable to long-tube evaporator, since the data were not available and no attempt was made to investigate the overall heat transfer coefficients for vertical long-tube evaporator.

Equation (1) or Figure 1 will aid the designer to design a new evaporator or to estimate the vapor pressure from the existing evaporator.

Nomenclature

U = over-all heat transfer coefficient, Btu per hour per square foot per °F.
Q = heat load, B.t.u. per hour.
A = heating surface, square feet.
ΔT = effective temperature difference, °F.
B_x = brix, solids in solution.
t_v = temperature of vapor, °F.
t_j = boiling temperature of juice, °F.
μ_j = viscosity of juice at t_j and brix leaving evaporator, centipoises.
σ_j = specific heat of juice at t_j and brix leaving evaporator, B.t.u./lb. °F.
n = sequence position of the evaporator, 1, 2, 3, . . . etc.
Factory #1 = Nyssa, Oregon.
Factory #2 = Nampa, Idaho.
Factory #3 = Twin Falls, Idaho.
Factory #4 = Rupert, Idaho.
Factory #5 = Lewiston, Utah.

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