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Problem: **Derive the following mathematical physical formula in full – details:**

$$\bar{h}_{cv} = 0.943\left[\frac{g\rho^2 h_{fg} k^3}{\mu k \Delta t L}\right]^{1/4}$$

Solution

Starting from;

$$\frac{h_{cv} x}{k} = \left[\frac{g\rho^2 h_{fg} x^3}{4\mu k \Delta t}\right]^{1/4}$$

$$\bar{h}_{cv} = \frac{\int_0^L h_{cv}\,dx}{L}$$

$$\bar{h}_{cv} = \frac{\int_0^L \frac{k}{x}\left[\frac{g\rho^2 h_{fg} x^3}{4\mu k \Delta t}\right]^{1/4} dx}{L}$$

$$\bar{h}_{cv} = \left(\frac{k}{L}\right)\left[\frac{g\rho^2 h_{fg}}{4\mu k \Delta t}\right]^{1/4}\int_0^L x^{-1/4}\,dx$$

$$\bar{h}_{cv} = \left(\frac{k}{L}\right)\left[\frac{g\rho^2 h_{fg}}{4\mu k \Delta t}\right]^{1/4}\left(\frac{4}{3}\right)\left[x^{3/4}\right]_0^L$$

$$\bar{h}_{cv} = \left(\frac{k}{L}\right)\left[\frac{g\rho^2 h_{fg}}{4\mu k \Delta t}\right]^{1/4}\left(\frac{4}{3}\right)L^{3/4}$$

$$\bar{h}_{cv} = \left(\frac{1}{4}\right)^{1/4}\left(\frac{4}{3}\right)\left[\frac{g\rho^2 h_{fg} k^3}{\mu k \Delta t L}\right]^{1/4}$$

$$\bar{h}_{cv} = 0.943\left[\frac{g\rho^2 h_{fg} k^3}{\mu k \Delta t L}\right]^{1/4}$$

Procedure for Solving the Condenser Design Problems

$$\text{Heat-rejection ratio} = \frac{\text{rate of heat rejected at condenser, kW}}{\text{rate of heat absorbed at evaporator, kW}}$$

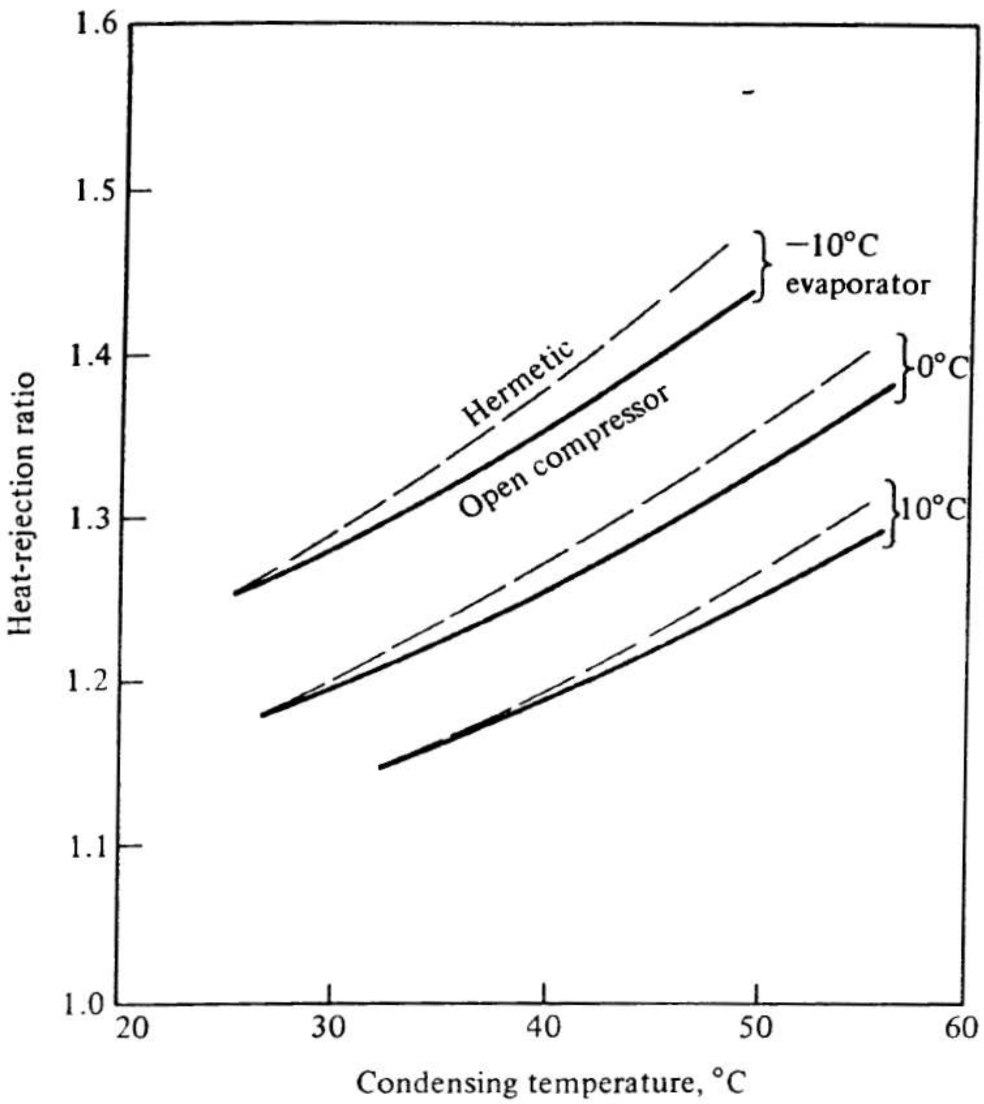

Figure 12-12: Typical values of the **ratio of the heat rejected** at the condenser to the refrigerating capacity for refrigerants 12 and 22.

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$$h_{ct} = 0.725\left(\frac{g\rho^2 h_{fg} k^3}{\mu \, \Delta t \, ND}\right)^{1/4} \quad \mathrm{W/m^2 \cdot K}$$

$$\mathrm{Nu} = C\,\mathrm{Re}^n\,\mathrm{Pr}^m$$

where n and m are exponents. The constant C and exponents in the equation are

$$\frac{hD}{k} = 0.023\left(\frac{VD\rho}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{0.4}$$

$$q = \dot{m}C_p(t_o - t_i) = U_oA_oLMTD$$

$$LMTD = \frac{(t_c - t_i) - (t_c - t_o)}{\ln\left[\frac{(t_c - t_i)}{(t_c - t_o)}\right]}$$

$$q = \dot{m}C_p(t_o - t_i)$$

$$q = U_oA_oLMTD$$

$$\dot{m} = \frac{q}{C_p(t_o - t_i)}$$

$$\dot{m} = \rho v A$$

$$vA = Q$$

$$\dot{m} = \rho Q$$

$$Q = \frac{\dot{m}}{\rho}$$

$$q = U_oA_oLMTD$$

$$A_o = \frac{q}{U_o\,LMTD}$$

$$A_o = \pi D L$$

Class: Fourth Stage
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Table A-6 Refrigerant 22: properties of liquid and saturated vapor[6]

		Enthalpy, kJ/kg		Entropy, kJ/kg · K		Specific volume, L/kg	
t, °C	P, kPa	h_f	h_g	s_f	s_g	v_f	v_g
-60	37.48	134.763	379.114	0.73254	1.87886	0.68208	537.152
-55	49.47	139.830	381.529	0.75599	1.86389	0.68856	414.827
-50	64.39	144.959	383.921	0.77919	1.85000	0.69526	324.557
-45	82.71	150.153	386.282	0.80216	1.83708	0.70219	256.990
-40	104.95	155.414	388.609	0.82490	1.82504	0.70936	205.745
-35	131.68	160.742	390.896	0.84743	1.81380	0.71680	166.400
-30	163.48	166.140	393.138	0.86976	1.80329	0.72452	135.844
-28	177.76	168.318	394.021	0.87864	1.79927	0.72769	125.563
-26	192.99	170.507	394.896	0.88748	1.79535	0.73092	116.214
-24	209.22	172.708	395.762	0.89630	1.79152	0.73420	107.701
-22	226.48	174.919	396.619	0.90509	1.78779	0.73753	99.9362
-20	244.83	177.142	397.467	0.91386	1.78415	0.74091	92.8432
-18	264.29	179.376	398.305	0.92259	1.78059	0.74436	86.3546
-16	284.93	181.622	399.133	0.93129	1.77711	0.74786	80.4103
-14	306.78	183.878	399.951	0.93997	1.77371	0.75143	74.9572
-12	329.89	186.147	400.759	0.94862	1.77039	0.75506	69.9478
-10	354.30	188.426	401.555	0.95725	1.76713	0.75876	65.3399
-9	367.01	189.571	401.949	0.96155	1.76553	0.76063	63.1746
-8	380.06	190.718	402.341	0.06585	1.76394	0.76253	61.0958
-7	393.47	191.868	402.729	0.97014	1.76237	0.76444	59.0996
-6	407.23	193.021	403.114	0.97442	1.76082	0.76636	57.1820
-5	421.35	194.176	403.496	0.97870	1.75928	0.76831	55.3394
-4	435.84	195.335	403.876	0.98297	1.75775	0.77028	53.5682
-3	450.70	196.497	404.252	0.98724	1.75624	0.77226	51.8653
-2	465.94	197.662	404.626	0.99150	1.75475	0.77427	50.2274
-1	481.57	198.828	404.994	0.99575	1.75326	0.77629	48.6517
0	497.59	200.000	405.361	1.00000	1.75279	0.77834	47.1354
1	514.01	201.174	405.724	1.00424	1.75034	0.78041	45.6757
2	530.83	202.351	406.084	1.00848	1.74889	0.78249	44.2702
3	548.06	203.530	406.440	1.01271	1.74746	0.78460	42.9166
4	565.71	204.713	406.793	1.01694	1.74604	0.78673	41.6124
5	583.78	205.899	407.143	1.02116	1.74463	0.78889	40.3556
6	602.28	207.089	407.489	1.02537	1.74324	0.79107	39.1441
7	621.22	208.281	407.831	1.02958	1.74185	0.79327	37.9759
8	640.59	209.477	408.169	1.03379	1.74047	0.79549	36.8493
9	660.42	210.675	408.504	1.03799	1.73911	0.79775	35.7624
10	680.70	211.877	408.835	1.04218	1.73775	0.80002	34.7136
11	701.44	213.083	409.162	1.04637	1.73640	0.80232	33.7013
12	722.65	214.291	409.485	1.05056	1.73506	0.80465	32.7239
13	744.33	215.503	409.804	1.05474	1.73373	0.80701	31.7801
14	766.50	216.719	410.119	1.05892	1.73241	0.80939	30.8683
15	789.15	217.937	410.430	1.06309	1.73109	0.81180	29.9874
16	812.29	219.160	410.736	1.06726	1.72978	0.81424	29.1361
17	835.93	220.386	411.038	1.07142	1.72848	0.81671	28.3131
18	860.08	221.615	411.336	1.07559	1.72719	0.81922	27.5173
19	884.75	222.848	411.629	1.07974	1.72590	0.82175	26.7477
20	909.93	224.084	411.918	1.08390	1.72462	0.82431	26.0032

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Table A-6 (continued)

		Enthalpy, kJ/kg		Entropy, kJ/kg · K		Specific volume, L/kg	
t, °C	P, kPa	h_f	h_g	s_f	s_g	v_f	v_g
21	935.64	225.324	412.202	1.08805	1.72334	0.82691	25.2829
22	961.89	226.568	412.481	1.09220	1.72206	0.82954	24.5857
23	988.67	227.816	412.755	1.09634	1.72080	0.83221	23.9107
24	1016.0	229.068	413.025	1.10048	1.71953	0.83491	23.2572
25	1043.9	230.324	413.289	1.10462	1.71827	0.83765	22.6242
26	1072.3	231.583	413.548	1.10876	1.71701	0.84043	22.0111
27	1101.4	232.847	413.802	1.11290	1.71576	0.84324	21.4169
28	1130.9	234.115	414.050	1.11703	1.71450	0.84610	20.8411
29	1161.1	235.387	414.293	1.12116	1.71325	0.84899	20.2829
30	1191.9	236.664	414.530	1.12530	1.71200	0.85193	19.7417
31	1223.2	237.944	414.762	1.12943	1.71075	0.85491	19.2168
32	1255.2	239.230	414.987	1.13355	1.70950	0.85793	18.7076
33	1287.8	240.520	415.207	1.13768	1.70826	0.86101	18.2135
34	1321.0	241.814	415.420	1.14181	1.70701	0.86412	17.7341
35	1354.8	243.114	415.627	1.14594	1.70576	0.86729	17.2686
36	1389.2	244.418	415.828	1.15007	1.70450	0.87051	16.8168
37	1424.3	245.727	416.021	1.15420	1.70325	0.87378	16.3779
38	1460.1	247.041	416.208	1.15833	1.70199	0.87710	15.9517
39	1496.5	248.361	416.388	1.16246	1.70073	0.88048	15.5375
40	1533.5	249.686	416.561	1.16659	1.69946	0.88392	15.1351
41	1571.2	251.016	416.726	1.17073	1.69819	0.88741	14.7439
42	1609.6	252.352	416.883	1.17486	1.69692	0.89097	14.3636
43	1648.7	253.694	417.033	1.17900	1.69564	0.89459	13.9938
44	1688.5	255.042	417.174	1.18315	1.69435	0.89828	13.6341
45	1729.0	256.396	417.308	1.18730	1.69305	0.90203	13.2841
46	1770.2	257.756	417.432	1.19145	1.69174	0.90586	12.9436
47	1812.1	259.123	417.548	1.19560	1.69043	0.90976	12.6122
48	1854.8	260.497	417.655	1.19977	1.68911	0.91374	12.2895
49	1898.2	261.877	417.752	1.20393	1.68777	0.91779	11.9753
50	1942.3	263.264	417.838	1.20811	1.68643	0.92193	11.6693
52	2032.8	266.062	417.983	1.21648	1.68370	0.93047	11.0806
54	2126.5	268.891	418.083	1.22489	1.68091	0.93939	10.5214
56	2223.2	271.754	418.137	1.23333	1.67805	0.94872	9.98952
58	2323.2	274.654	418.141	1.24183	1.67511	0.95850	9.48319
60	2426.6	277.594	418.089	1.25038	1.67208	0.96878	9.00062
62	2533.3	280.577	417.978	1.25899	1.66895	0.97960	8.54016
64	2643.5	283.607	417.802	1.26768	1.66570	0.99104	8.10023
66	2757.3	286.690	417.553	1.27647	1.66231	1.00317	7.67934
68	2874.7	289.832	417.226	1.28535	1.65876	1.01608	7.27605
70	2995.9	293.038	416.809	1.29436	1.65504	1.02987	6.88899
75	3316.1	301.399	415.299	1.31758	1.64472	1.06916	5.98334
80	3662.3	310.424	412.898	1.34223	1.63239	1.11810	5.14862
85	4036.8	320.505	409.101	1.36936	1.61673	1.18328	4.35815
90	4442.5	332.616	402.653	1.40155	1.59440	1.28230	3.56440
95	4883.5	351.767	386.708	1.45222	1.54712	1.52064	2.55133

Table 15-5 Thermal conductivities and viscosities of saturated refrigerant liquid and vapor

		Viscosity, Pa · s		Conductivity, W/m · K	
Refrigerant	t, °C	Liquid	Vapor	Liquid	Vapor
11	-40	0.000922		0.106	
	-20	0.000694		0.100	
	0	0.000546		0.0943	
	20	0.000441	0.0000103	0.0890	
	40	0.000367	0.0000119	0.0832	0.00841
	60	0.000312	0.0000127	0.0777	0.0093
12	-40	0.000409		0.0931	
	-20	0.000325	0.0000108	0.0857	0.00734
	0	0.000267	0.0000118	0.0784	0.00838
	20	0.000225	0.0000126	0.0711	0.00938
	40	0.000194	0.0000135	0.0637	0.0105
	60	0.000169	0.0000148	0.0564	0.0118
22	-40	0.000330	0.0000101	0.120	0.0069
	-20	0.000275	0.0000110	0.110	0.00817
	0	0.000237	0.0000120	0.100	0.00942
	20	0.000206	0.0000130	0.090	0.0107
	40	0.000182	0.0000144	0.0805	0.0119
	60	0.000162	0.0000160	0.0704	0.0133
502	-40	0.000356	0.0000100	0.0898	0.00796
	-20	0.000284	0.0000111	0.0820	0.00907
	0	0.000233	0.0000120	0.0742	0.0102
	20	0.000193	0.0000132	0.0665	0.0114
	40	0.000153	0.0000146	0.0585	0.0124
	60	0.000117	0.0000161	0.0486	0.0144
717	-40			0.632	
	-20	0.000236	0.0000097	0.585	0.0204
	0	0.000190	0.0000104	0.540	0.0218
	20	0.000152	0.0000112	0.493	0.0267
	40	0.000122	0.0000120	0.447	0.0318
	60	0.000098	0.0000129	0.400	0.0381

Problem. 1: An air-cooled condenser is to reject 70 kw of heat from a condensing refrigerant to air. The condenser has an air-side area of 210 m^2 and a U value based on this area is 0.037 $kW/m^2.K$; it is supplied with 6.6 m^3/s of air, which has a density of 1.15 kg/m^3. If the condensing temperature is to be limited to 55 C, what is the maximum allowable temperature of inlet air?

Solution: $A_o = 210\ m^2$

$U_o = 0.037\ kW/m^2.K$

$q = 70$ kw

$\rho = 1.15\ kg/m^3$

Condensing Temperature = 55 C

$w = (6.6\ m^3/s) / (1.15\ kg/m^3) = 5.739\ kg/s$

$c_p = 1.0\ kJ/kg.K$

$$LMTD = \frac{(t_c - t_i) - (t_c - t_o)}{\ln\left[\frac{(t_c - t_i)}{(t_c - t_o)}\right]}$$

$q = U_o A_o LMTD$

$$LMTD = \frac{q}{U_o A_o} = \frac{70}{(0.037)(210)} = 9.009\ K$$

But $q = wc_p(t_o - t_i)$

$$t_o - t_i = \frac{q}{wc_p} = \frac{70}{(5.739)(11)} = 12.197\ K$$

$$LMTD = \frac{(t_c - t_i) - (t_c - t_o)}{\ln\left[\frac{(t_c - t_i)}{(t_c - t_o)}\right]}$$

$$9.009 = \frac{12.197}{\ln\left[\frac{(55 - t_i)}{(55 - t_o)}\right]}$$

$$\frac{55 - t_i}{55 - t_o} = 3.8724$$

$55 - t_i = 3.8724(55 - 12.197 - t_i)$

$\mathbf{t_i = 38.6\ C}$ **- - - Ans.**

Problem. 2: An air-cooled condenser has an expected U value of 30 W/m^2.K based on the air-side area. The condenser is to transfer 60 kW with an airflow rate of 15 kg/s entering at 35 C. If the condenser temperature is to be 48 C, what is the required air-side area?
Note; There is an error in the solution inserted below, find it and write the correct answer [HW]

Solution:

$$q = U_o A_o LMTD$$

$$q = wc_p(t_o - t_i)$$

$$w = 15 \text{ kg/s}$$

$$c_p = 1.0 \text{ kJ/kg.K}$$

$$t_o = t_i + \frac{q}{wc_p}$$

$$t_o = 35 + \frac{60}{(15)(1)}$$

$$t_o = 39 \text{ C}$$

$$LMTD = \frac{(t_o - t_i)}{\ln\left[(t_c - t_i) / (t_c - t_o)\right]}$$

$$LMTD = \frac{(39 - 35)}{\ln\left[(48 - 35) / (48 - 39)\right]} = 10.878 \text{ K}$$

$$q = U_o A_o LMTD$$

$$60 \text{ kw} = (30 / 1000)(A_o)(10.878)$$

$$\mathbf{A_o = 184 \text{ m}^2 \text{ - - - Ans.}}$$

Problem. 3: A shell-and-tube condenser has a U value of 800 W/m^2.K based on the water-side are and a water pressure drop of 50 kPa. Under this operating condition 40 percent of the heat-transfer resistance is on the water side. If the water-flow rate is doubled, what will the new U value and the new pressure drop be?

U_1 = 800 W/m2.K

h_1 = Water-side coefficient

$$h_1 = \frac{1}{(0.40)\left(\frac{1}{800}\right)} = 2{,}000$$

Eq. 12-13, replace 0.6 by 0.8 for condenser.

Water-side coefficient = (const)(flow rate)$^{0.8}$

For $w_2 / w_1 = 2$

$$\frac{h_2}{h_1} = \left(\frac{w_2}{w_1}\right)^{0.8}$$

$h_2 = (2000)(2)^{0.8} = 3482.2$ W/m^2.K

Remaining resistance = (0.60)(1 / 800) = 0.00075

New U-Value:

$$\frac{1}{U_2} = \frac{1}{3482.2} + 0.00075$$

U_2 = 964 W/m^2.K - - - Ans.

New Pressure Drop:

$$\Delta p_2 = \Delta p_1 \left(\frac{w_2}{w_1}\right)^2$$

$$\Delta p_2 = (50)(2)^2$$

Δp_2 = 200 kPa - - - Ans.

Problem. 4: What is the UA value of a direct-expansion finned coil evaporator having the following areas: refrigerant side, 15 m^2; air-side prime, 13.5 m^2, and air-side extended, 144 m^2? The refrigerant-side heat-transfer coefficient is 1300 W/m^2.K, and the air-side coefficient is 48 W/m^2.K. The fin effectiveness is 0.64.

Solution: $\eta = 0.64$

$A_i = 15\ m^2$

$h_i = 1300\ W/m^2.K$

$h_f = 48\ W/m^2.K$

$A_p = 13.5\ m^2$

$A_e = 144\ m^2$

Eq. 12-20 neglect tube resistance.

$$\frac{1}{U_oA_o} = \frac{1}{h_f\left(A_p + \eta A_e\right)} + \frac{1}{h_iA_i}$$

$$\frac{1}{U_oA_o} = \frac{1}{(48)(13.5 + 0.64(144))} + \frac{1}{(1300)(15)}$$

U_oA_o = 4,025 W/K - - - Ans.

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Problem. 5: A refrigerant 22 system having a refrigerating capacity of 55 kW operates with an evaporating temperature of 5 C and rejects heat to a water-cooled condenser. The compressor is hermetically sealed. The condenser has a U value of 450 W/m2.K and a heat-transfer area of 18 m2 and receives a flow rate of cooling water of3.2 kg/s at a temperature of 30 C. What is the condensing temperature?

$$H.R.R. = \frac{Q_c}{Q_E}$$

$$Q_c = U A \, LMTD$$

$$LMTD = \frac{(T_c - T_i) - (T_c - T_o)}{\ln \frac{T_c - T_i}{T_c - T_o}}$$

$$H.R.R. = \frac{Q_c}{Q_E}$$

H.R.R. based upon Figure 12-12; We can assume H.R.R. at $T_{evap} = 5\,^\circ C$ within the range [1.25–1.3]

let us assume that H.R.R. = 1.27

$$\therefore H.R.R. = \frac{Q_c}{Q_E} \Rightarrow 1.27 = \frac{Q_c}{55}$$

$$\therefore Q_c = 69.85 \text{ kW}$$

Since; $Q_c = U A \, LMTD$ where $U = 450 \text{ W/m}^2 \text{K}$

Then; $69850 = 450 * 18 * LMTD$

$$\therefore LMTD = 8.62345679 \text{ K}$$

According to the Conservation of Energy:

(Heat lost by Condenser) = (Heat absorbed by Water)

$$Q_{cond} = Q_{water} \Rightarrow Q_{cond} = \dot{m} C_w (T_o - T_i)_w$$

$$69850 = 3.2 * 4200 * (T_o - 30)$$

$$\therefore T_o = 35.19717262\,^\circ C$$

If $C_w = 4.18$ kJ/kg K, then "T_o" will be $T_o = 35.22203947\,^\circ C$

Finally;

$$LMTD = \frac{(T_c - T_i) - (T_c - T_o)}{\ln \frac{T_c - T_i}{T_c - T_o}}$$

$$8.6234 = \frac{(T_c - 30) - (T_c - 35.2220)}{\ln \frac{(T_c - 30)}{(T_c - 35.2220)}}$$

$$\Rightarrow T_c = 41.22\,^\circ C$$

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Problem. 6: Calculate the mean condensing heat-transfer coefficient when refrigerant 12 condenses on the outside of the horizontal tubes in a shell-and-tube condenser. The outside diameter of the tubes is 19 mm, and in the vertical rows of tubes there are respectively, two, three, four, three, and two tubes. The refrigerant is condensing at a temperature of 52 C and the temperature of the tubes is 44 C.

Solution:

Condensing Coefficient: Eq. 12-24.

$$h_{cond} = 0.725\left(\frac{g\rho^2 h_{fg} k^3}{\mu \Delta t N D}\right)^{1/4}$$

Table A-5 at 52 C.

h_{fg} = 370.997 - 251.004 kJ/kg = 119.993 kJ/kg

h_{fg} = 199,993 J/kg

ρ = 1 / (0.83179 L/kg) = 1202 kg/m^3

Table 15-5, Liquid Refrigerant 12

μ = 0.000179 PA.s

k = 0.05932 W/m.K

N = (2 + 3 + 4 + 3 +2) / 5 = 2.8

Δt = 52 C - 44 C = 8 K

g = 9.81 m/s^2

D = 19 mm = 0.019 m

$$h_{cond} = 0.725\left(\frac{(9.81)(1202)^2(119{,}993)(0.05932)^3}{(0.000174)(8)(2.8)(0.019)}\right)^{1/4}$$

h_{cond} = 1065 W/m^2.K - - - Ans.

Class: Fourth Stage
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Problem. 7: A condenser manufacturer guarantees the U value under operating conditions to be 990 W /m^2 • K based on the water-side area. In order to allow for fouling of the tubes, what is the U value required when the condenser leaves the factory?

$$\left(\frac{1}{U_i A_i} = \frac{1}{h_o A_o} + \frac{x}{k A_m} + \frac{1}{h_i A_i} + \frac{1}{h_{ff} \cdot A_i}\right) \times A_i$$

$$\frac{1}{U_i} = \boxed{\frac{1}{h_o}\frac{A_i}{A_o} + \frac{x}{k}\frac{A_i}{A_m} + \frac{1}{h_i}} + \frac{1}{h_{ff}} \qquad \boxed{\ } \rightarrow \frac{1}{U_{i\,new}}$$

$$\frac{1}{U_i)_{old}} = \frac{1}{U_i)_{new}} + \frac{1}{h_{ff}}$$

$$\frac{1}{990} = \frac{1}{U_i)_{new}} + 0.000176$$

$$\Rightarrow U_i)_{new} = 1198.89563 \ W/m^2 \cdot K$$