Class: Fourth Stage
Subject: Refrigeration Systems
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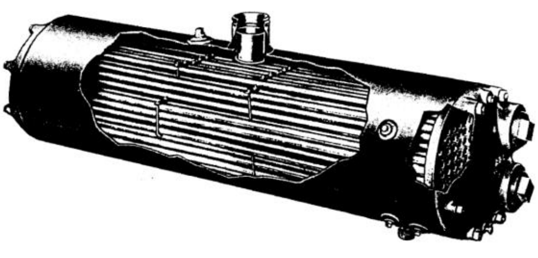
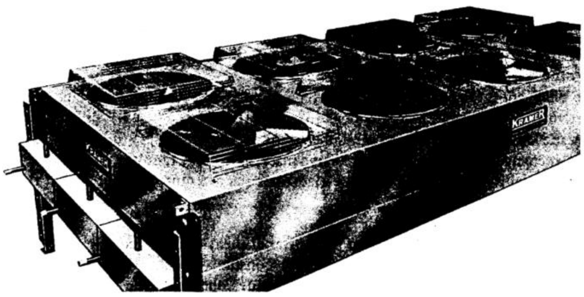
Chapter Two

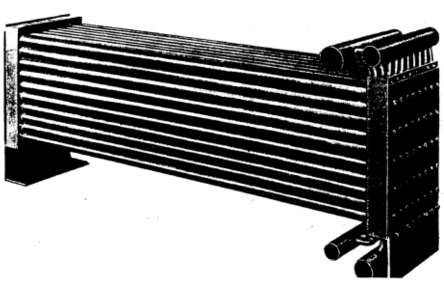
Condenser: Fluid Flows and Heat Transfer Analysis

1. Introduction

- The previous sections presented tools for computing heat-transfer coefficients and pressure drops of the fluid exchanging heat with the refrigerant in a condenser or evaporator. For the condenser the fluid to which heat is rejected is usually either air or water. Air-cooled condensers, a shell and- tube condenser. Also, another type of water-cooled condenser has cleanable tubes ash shown below.
- When the condenser is water-cooled, the water is sent to a cooling tower for ultimate rejection of the heat to the atmosphere. Some years ago air-cooled condensers were used only in small refrigeration systems (less than 100 kW refrigerating capacity), but now individual air-cooled condensers are manufactured in sizes matching refrigeration capacities of hundreds of kilowatts.
- The water-cooled condenser is favored over the air-cooled condenser where there is a long distance between the compressor and the point where heat is to be rejected. Most designers prefer to convey water rather than refrigerant in long lines. In centrifugal-compressor systems large pipes are needed for the low-density refrigerants (see Sec. 11-25), so that the compressor is close-coupled to the condenser. Water-cooled condensers there for predominate in centrifugal-compressor systems.







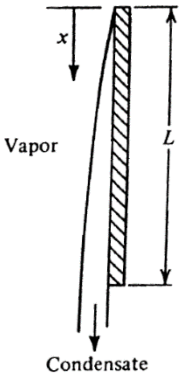
2. Required condensing capacity

- The required rate of heat transfer in the condenser is predominately a function of the refrigerating capacity and the temperatures of evaporation and condensation. The condenser must reject both the energy absorbed by the evaporator and the heat of compression added by the compressor. A term often used to relate the rate of heat flow at the condenser to that of the evaporator is the *heat-rejection ratio*

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

3. Condensing coefficient

The basic equation for calculating the local coefficient of heat transfer of vapor condensing on a vertical plate was developed by Nusselt by pure physical analysis. The equation for the local condensing coefficient is



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

where h_{cv} = local condensing coefficient on vertical plate, $W/m^2 \cdot K$
x = vertical distance measured from top of plate, m
g = acceleration due to gravity = 9.81 m/s^2
ρ = density of condensate, kg/m^3
h_{fg} = latent heat of vaporization, J/kg
μ = viscosity of condensate, $Pa \cdot s$
Δt = temperature difference between vapor and the plate, K

The mean condensing coefficient over the total height of the plate L is

$$\overline{h_{cv}} = \frac{\int_0^L h_{cv}\, dx}{L} = 0.943 \left(\frac{g\rho^2 h_{fg} k^3}{\mu \,\Delta t\, L}\right)^{1/4} \quad W/m^2 \cdot K$$

The equation for the mean condensing coefficient for vapor condensing on the outside of horizontal tubes is

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

where N = number of tubes in vertical row
D = OD of tube, m

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4. Fouling factor

After a water-cooled condenser has been in service for some time its *U* value usually degrades somewhat because of the increased resistance to heat transfer on the water side due to fouling by the impurities in the water from the cooling tower. The new condenser must therefore have a higher *U* value in anticipation of the reduction that will occur in service. The higher capacity with new equipment is provided by specifying a *fouling factor* l/h_{ff} m2 • K/W. This term expands Eq**. (12-8)** for the *U* value into

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{xA_o}{kA_m} + \frac{A_o}{h_{ff}A_i} + \frac{A_o}{h_iA_i}$$

Several different agencies have established standards for the fouling factor to be used. One trade association[12] specifies 0.000176 m^2 • K/W, which means that the condenser should leave the factory with a $1/U_o$ value 0.000176 A_o/A_i less than the minimum required to meet the quoted capacity of the condenser.

5. Desuperheating

Even when the refrigerant condenses at a constant pressure, its temperature is constant only in the condensing portion. Because the vapor coming from the compressor is usually superheated, the distribution of temperature will be as shown in Fig. 12-14. Because of the distortion in the temperature profile caused by the desuperheating process, the temperature difference between the refrigerant and the cooling fluid is no longer correctly re presented by the LMTD

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

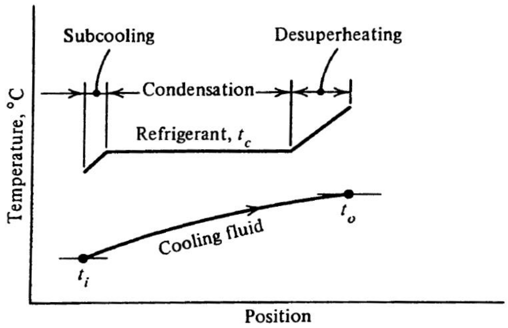

Figure 12-14 Temperature distributions in a condenser.

6. Condenser design

An example will illustrate how some of the principles described in the previous sections are combined in designing a condenser.

Example 12-3 The condensing area is to be specified for a refrigerant 22 condenser of a refrigerating system that provides a capacity of 80 kW for air conditioning. The evaporating temperature is 5°C, and the condensing temperature is 45°C at design conditions. Water from a cooling tower enters the condenser at 30°C and leaves at 35°C.

A two-pass condenser with 42 tubes, arranged as shown in Fig. 12-15, will be used, and the length of tubes is to be specified to provide the necessary area. The tubes are copper and are 14 mm ID and 16 mm OD.

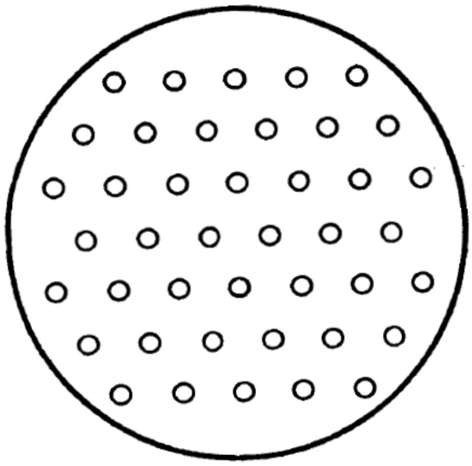

Figure 12-15 Tube arrangement of condenser in Example 12-3.

Solution;

Heat-rejection ratio at a condensing temperature of 45°C and an evaporating temperature of 5°C is 1.27

$$q = (80\ \text{kW})\,(1.27) = 101.6\ \text{kW}$$

Condensing coefficient From Eq. (12-24)

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

The density ρ and latent heat of vaporization h_{fg} at 45°C are available from Table A-6

$$\rho = \frac{1}{0.90203\ \text{L/kg}} = 1.109\ \text{kg/L} = 1109\ \text{kg/m}^3$$

$$h_{fg} = 160{,}900\ \text{J/kg}$$

The conductivity k and viscosity μ of the liquid refrigerant at 45°C are available from Table 15-5

$$k = 0.0779\ \text{W/m}\cdot\text{K} \qquad \mu = 0.000180\ \text{Pa}\cdot\text{s}$$

The average number of tubes in a vertical row N is

$$N = \frac{2+3+4+3+4+3+4+3+4+3+4+3+2}{13} = 3.23$$

The temperature difference between the vapor and the tube is unknown at this point; therefore Δt will be assumed to be 5 K and the value adjusted later if necessary.

$$h_{cond} = 0.725 \left[\frac{9.81(1109^2)\,(160{,}900)\,(0.0779^3)}{0.000180(5)\,(3.23)\,(0.016)} \right]^{1/4}$$

$$= 1528\ \text{W/m}^2\cdot\text{K}$$

Resistance of metal The conductivity of copper is 390 W/m · K, and the resistance of the tube is

$$\frac{xA_o}{kA_m} = \frac{(0.016 - 0.014)/2}{390}\,\frac{16}{(14+16)/2} = 0.000002735\ \text{m}^2\cdot\text{K/W}$$

a value that will prove to be negligible in comparison to the other resistances.

Fouling factor From Sec. 12-10

$$\frac{1}{h_{ff}} = 0.000176\ \text{m}^2\cdot\text{K/W}$$

Water-side coefficient The flow rate of water needed to carry the heat away from the condenser with a temperature rise from 30 to 35°C is

$$\frac{101.6 \text{ kW}}{(4.19 \text{ kJ/kg} \cdot \text{K})(35.0 - 30.0)} = 4.85 \text{ kg/s}$$

and the volume flow rate is

$$\frac{4.85 \text{ kg/s}}{1000 \text{ kg/m}^3} = 0.00485 \text{ m}^3\text{/s}$$

The water velocity through the tubes V is

$$V = \frac{0.00485 \text{ m}^3\text{/s}}{(21 \text{ tubes per pass})(\pi/4)(0.014^2)} = 1.5 \text{ m/s}$$

Equation (12-9) can be used to calculate the water-side heat-transfer coefficient h_w using the water properties at 32°C

$$\rho = 995 \text{ kg/m}^3 \qquad \mu = 0.000773 \text{ Pa} \cdot \text{s}$$

$$c_p = 4190 \text{ J/kg} \cdot \text{K} \qquad k = 0.617 \text{ W/m} \cdot \text{K}$$

Tabla 7-3

$$h_w = \frac{0.617(0.023)}{0.014}\left[\frac{1.5(0.014)(995)}{0.000773}\right]^{0.8}\left[\frac{4190(0.00773)}{0.617}\right]^{0.4}$$

$$h_w = 1.014(27030^{0.8})(5.25^{0.4}) = 6910 \text{ W/m}^2 \cdot \text{K}$$

Required area

$$\frac{1}{U_o} = \frac{1}{1528} + 0.000002735 + \frac{0.016}{0.014}(0.000176) + \frac{0.016}{0.014}\frac{1}{6910} = 0.001023$$

$$U_o = 977 \text{ W/m}^2 \cdot \text{K}$$

The LMTD is

$$\text{LMTD} = \frac{(45 - 30) - (45 - 35)}{\ln \dfrac{(45 - 30)}{(45 - 35)}} = 12.33°\text{C}$$

$$A_o = \frac{101{,}600 \text{ W}}{977(12.33)} = 8.43 \text{ m}^2$$

Length of tubes

$$\text{Length} = \frac{8.43 \text{ m}^2}{(42 \text{ tubes})(0.016\pi)} = 4.0 \text{ m}$$

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

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

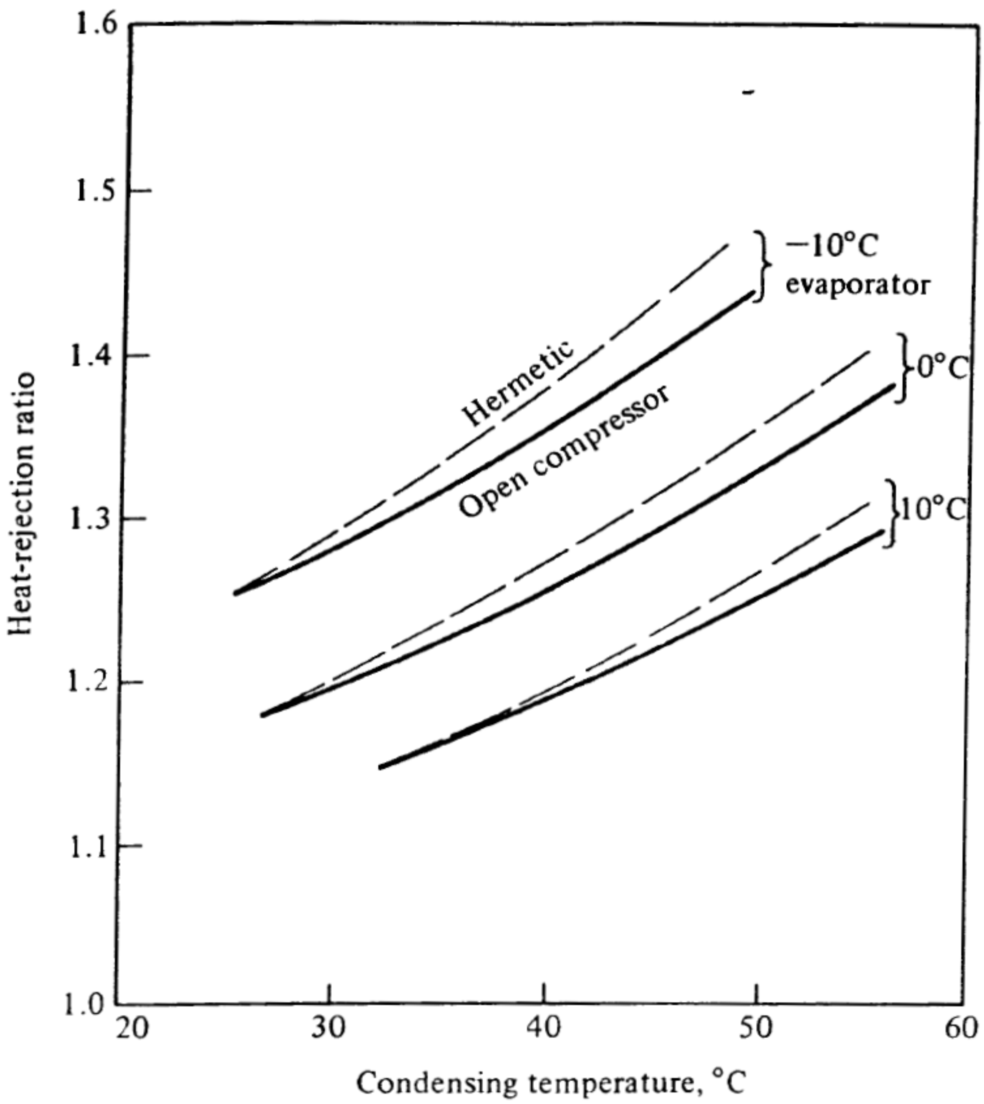

Figure 12-12: Typical values of the **ratio of the heat rejected** at the condenser to the refrigerating capacity for refrigerants 12 and 22.

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

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

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

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

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

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

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

$$q = U_o A_o LMTD$$

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

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

$$vA = Q$$

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

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

$$q = U_o A_o LMTD$$

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

$$A_o = \pi D L$$

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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