Kolandjian Anna Christiane
Rizk Jean
Gabrielian Johnny

Ice cream Hardening

FIRST EDITION

ICE CREAM HARDENING

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TO OUR BELOVED PROFESSOR RAYANE SLIM.

With the hope that this refrigeration system will meet all requirements.

CONTENTS

CREDITS

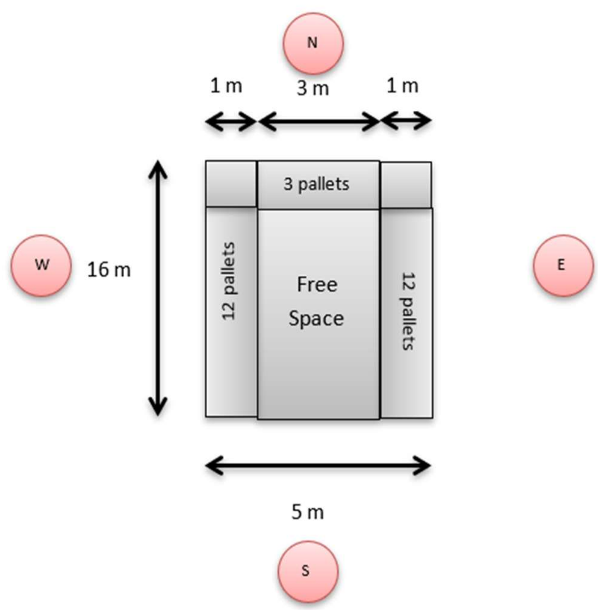
1 Design conditions

1.1 Location and climatic conditions

We chose to design an ice cream hardening container in the city of Beirut where the maximum temperature that we could get is in august and that would be +35 degrees Celsius, and a relative humidity of approximately 50%.

1.2 Container sizing

In order to know the dimension of the container that we should take we researched the standard dimensions of a pallet and of a fork lift in order to know how much space the stored ice cream will take and as well as how much space we need for the forklift to operate properly.
Pallet size:
According to US standards the dimension of a pallet in 48” x 40” which is equivalent to 1.2m x 1 m.
Forklift size:
Standard forklifts generally measure between 4 to 7 ft wide and 8 to 10 ft long and can lift as high as 17 to 20 ft , so we assumed a forklift to be 5 ft x 10 ft which is about 1.5 m x 3 m and we took the height of the container to be 5m(~16 ft).
So for the forklift to operate properly we decided to leave a space of 3 m wide in the center of the container, and to store the pallets in this format:



- Free space is for the workers and the forklift to operate.
- 5 pallet are laid down horizontally at the back (5x1= 5 m)
- 12 pallets are laid down vertically on the side walls (12 x 1.2 +1.2= 15.6 m and for rounding we took 16m)
- Height is 5 m

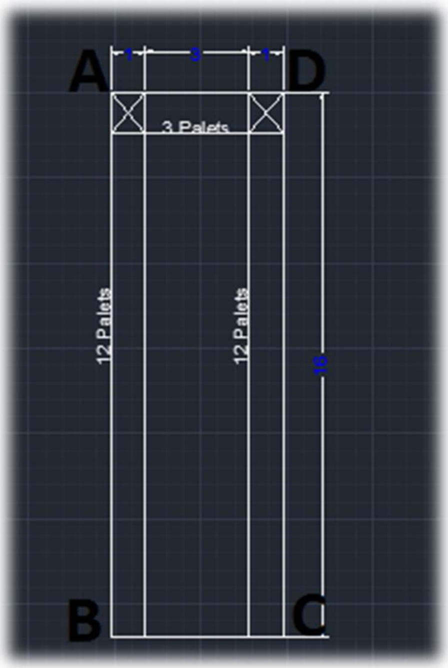
1.3 Charging conditions

For Ice cream hardening the temperature of the product should be -18 degree Celsius so in order to achieve that the storage temperature should be – 30 degree Celsius.

2 Cooling load calculations

2.1 Wall construction technique and material

Since this is a really cold storage container, the walls should have a relatively low U value which means a high thermal resistivity; so we opted for walls and roof made of 1" board on both sides of 2"x4" studs and filled with 10"of rock wool; this type of wall has a u value of 0.029 btu/h.F.ft^2. And for the floor we used 8" of corkboard laid on 5" slab and finished with 3" of concrete, and this floor has a U value of 0.035 btu/h.F.ft^2 .



<u>Calculations:</u>

- <u>West wall:</u> U= 0.029 btu/h.F.ft^2 =0.16467 W/m^2.k
- <u>North wall</u>: U = 0.16467 W/m^2.k
- <u>East wall:</u> U = 0.16467 W/m^2.k
  $\Delta T=(\Delta T + \Delta Ts) = 68.33^\circ C$ → Q = 900.152 W
- <u>South wall:</u> U=0.16467 W/m^2.k A=25 m^2
  $\Delta T=35-(-30) = 65^\circ C = 149^\circ F$ → table 10-7: $\Delta Ts = 4^\circ F$ → $\Delta T=153^\circ F =67.22^\circ C$
  Q= 276.728 W

Wall	U-value ($W/m^2.K$)	Area (m^2)	ΔT (°F ,°C)	Direction	ΔTs (°F)	ΔT total (°C)	Q=U.A.ΔT (W)
AB	0.16467	16x5= 80	65°C = 149°F	West	6	68.33	**900.152**
AD	0.16467	5x5=25	65°C = 149°F	North	-	65	**267.588**
DC	0.16467	16x5= 80	65°C = 149°F	East	6	68.33	**900.152**
BC	0.16467	5x5=25	65°C = 149°F	South	4	67.22	**276.728**

Floor:

Table 10.6A → Tground= 60˚F= 15.55˚C (assumed in Idaho Boise)
ΔT= 15.55 - (-30)= 45.55˚C
U= 0.035 btu/h.F.ft² = 0.19874 W/m².k
A= 80 m²

$$\boldsymbol{Q\ ground\ = U * A * \Delta T = \ 724.208\ W}$$

Q1= ∑Q= 3068.83 W= 251310.757 Btu/24hr

2.2 Air circulation technique

In Ice cream hardening application , ventilation is not needed that much ; so it will be neglected for calculation simplification purpose and only infiltration will be taken into account.
V= 16x5x5= 400 m³ = 14125.9 ft³
T=-30˚C=-22˚F < 32˚F → Table 10.9B: ACN =3
Table 10.8B + interpolation → ACF=4.33 btu/ft³
Q=14125.9 x 3 x 4.33 = 183495 btu /24hr

2.3 Packaging of the goods

This ice cream product comes in boxes of dimension 40 cm x 40 cm x 25 cm. So on each pallet we can put 6 boxes in 1 layer, and to not crush the ice cream due to the weight of stacked pallet we decided to put 3 layers of boxes on each pallet so we will be at a total of 5 stacked pallet + 3 layer of ice cream boxes. Based on that we can calculate the number of ice cream boxes which is 6 x 3 x 5 x (12+ 12 +3) and we will get a total of 2430 box.
V=0.4 x 0.4 x0.25 = 0.04 m³ → Vt=2430 x 0.04 = 97.2m³ = 97.2 x 10^6 mL
We found from various sources that the average ice cream density is about 0.7 g/mL

Mass of product:

Number of boxes = 2430
Volume of 1 box V = 0.04 m^3
Density of icecream ρ= 0.7 g/ml

Assuming that all boxes are full of icecream :

$$m = \rho * V = 68040 \text{ kg} = 1500002.6 \text{ lb}$$

From table 10-13 : specific heat for icecream Cp =0.77 Btu/lb.°F
ΔT= -18 –(-30) = 12°C = 53.6 °F

$$Q = m * c * \Delta T = 6190907.307 \; Btu\,/24hr$$

2.4 Miscellaneous load

2.4.1 Lighting

The area that needs to be illuminated is the free area in the middle because the other part will be stacked with ice cream, A= 3 x (16 – 1.2) =44.4 m^2 =477.9176 ft^2
According to researches a 250 ft^2 place needs approximately 5000 lumens to be properly lighted. So our place needs 9600 lumens, we can achieve that by using 4 LED lights of 24W each and they will be more than enough.
4 lights of 24 W each ➔ $Q = 4 * 24 * 342 = 32832$ Btu/hr
Multiplying by 24 leads to **Q =787968 Btu/24hr**

2.4.2 Occupancy

Considering we need 1 person to drive the forklift and at max 2 to help him so we can say that we may have a maximum of 3 persons present in that room in the same time. The heat equivalent to 1 person is ~~1500
Number of persons N=3
Heat equivalent/pers H = 1500Btu/hr

$$Q = N * H * 24 = 108000 Btu/24hr$$

2.5 Total cooling load

Total cooling load: Q= ∑Q = 7521681.504 Btu/24hr = 91.85 KW
Assuming an electric defrost method, we will assume that the equipment running time is approximately 20 hours so we get a refrigeration capacity of Q/20
Refrigeration capacity= 376084.07 Btu/hr

3 Refrigeration cycle

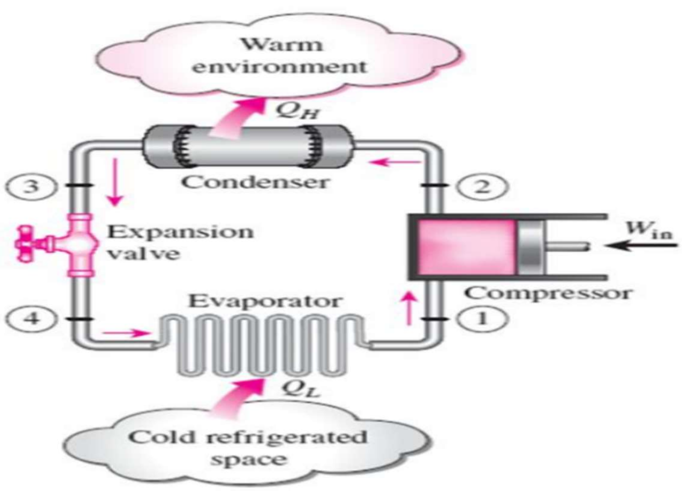
3.1 Refrigerant selection

R-134a has the benefit of being a single-component refrigerant and, therefore, does not have any glide. In addition, the direct HGWP of R-134a is low relative to other options that have been evaluated.

TYPE	ASHRAE NUMBER	IUPAC CHEMICAL NAME	MOLECULAR FORMULA	NORMAL BOILING OR BUBBLE/ DEW/AZEOTROPIC POINT(S) °C	CRITICAL TEMP °C	CRITICAL PRESSURE (absolute) kpa
HFC	R-134a	1,1,1,2-Tetrafluoroethane	C2H2F4	−26.3	101.06	4.059

3.2 The Ideal Vapor Compression Refrigeration cycle

<u>The system in question is defined below:</u>



- Component #1 is the compressor

It takes refrigerant vapor in from the low pressure side of the circuit, and discharges it at a much higher pressure into the high pressure side of the circuit.
The operating pressures will depend on the refrigerant being used and the desired evaporator temperature.

- Component #2 is the condenser.

When the hot refrigerant vapor discharged from the compressor travels through the condenser, the cool air or water flowing through the condenser coil absorbs enough heat from the vapor to cause it to condense.

Why do we want the refrigerant to condense at this relatively high temperature? So that the air or water flowing through the condenser will be very cold relative to the temperature of the discharge vapor,Which will allow the heat energy in the vapor to move into that relatively cold air or water. And cause the refrigerant to condense.

- Component #3 is the expansion valve.

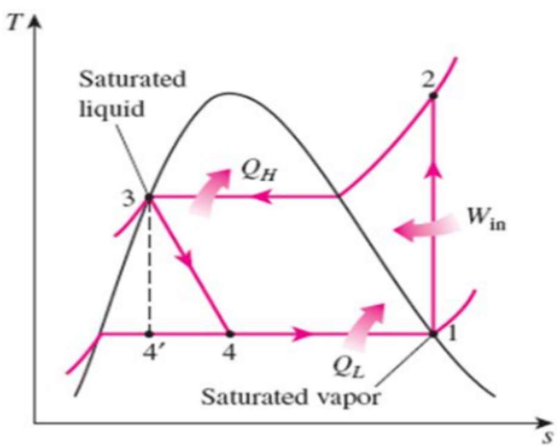
I need a pressure drop, so I lose the work that I would have taken from the turbine.

- Component #4 is the evaporator.

The refrigeration system is designed so that the refrigerant will evaporate in the evaporator at a temperature that's about 0°.

So, when you turn on your refrigerator, the system is designed so that the evaporator will stay colder than whatever it's cooling, and will continuously remove heat from it and cool it.

3.2.1 T-S diagram



Realistically a wet compressor can damage the compressor so 1 is pushed to the extremity of the dome to a saturated vapor point.

In order to achieve the heat transfer required, we work on TH a bit greater than the TH we have. Same goes to Tc but this time a Tc smaller than the Tc we have.

In compression from 1 to 2, there is no point to do a heat rejection with increase of pressure. So it's gonna be isobaric instead of isothermal.

I use an expansion valve instead of using a turbine since this latter needs too much treatment.

1-2: Isentropic compression from Pevap to Pcond. The saturated vapor at state 1 is superheated to state 2.

$$\boxed{W_c = \dot{m}(h_2 - h_1)}$$

2-3: Isobaric heat rejection in the condenser. The working substance is condensed to a saturated liquid at 3.

$$\boxed{\dot{Q}_{out} = \dot{m}(h_2 - h_3)}$$

3-4: Isenthalpic expansion. The refrigerant enters the evaporator at state 4 as a low-quality saturated mixture.

$$\boxed{h_3 = h_4}$$

4-1: Isobaric heat addition in the evaporator. The refrigerant (two-phase mixture) is evaporated to a saturated vapor at state point 1.

$$\boxed{\dot{Q}_{in} = \dot{m}(h_1 - h_4)}$$

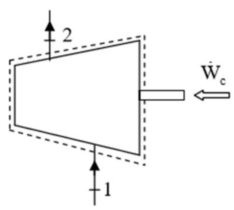
3.2.2 Assumptions

- Each component is an open system operating at steady-state.
- All processes are internally reversible, except the expansion valve, which is an isenthalpic throttling processes.
- The compressor and valves operate adiabatically.
- Kinetic and potential energy changes are negligible.
- There are no pressure drops for flow through the heat exchangers.

3.2.3 Analysis

3.2.3.1 Putting states

Compressor:



State 1: T_1 = -37°C, saturated vapor => $\boxed{\mathbf{h_1 = 227.755\ kJ/kg,}}$ $\boxed{\mathbf{s_1 = 0.950995 kJ/kg.K}}$

T	P	h	S
-38	56.86	227.12	0.96584
-37	59.905	227.755	0.950995
-36	62.95	228.39	0.96315

State 2: $P_2 = P_{sat@30}$= 0.72731 MPa, $s_2 = s_1$

Extrapolation:

We did 4 extrapolations to find entropies and enthalpies of P=0.72731 MPa at 30 °C and 40 °C.

P=0.6 MPa			P=0.7 MPa			P=0.72731 MPa		
T(°C)	h(KJ/Kg)	s(KJ/Kg.K)	T(°C)	h(KJ/Kg)	s(KJ/Kg.K)	T(°C)	h(KJ/Kg)	s(KJ/Kg.K)
30	270.81	0.9499	**30**	268.45	0.9313	30	**267.8054**	**0.92622**
								0.950995
40	280.58	0.9816	**40**	278.57	0.9641	40	**278.021**	**0.95932**

We did 2 extrapolations to find the entropy and the enthalpy of P=0.8 MPa at 30 °C and 40 °C.

P=0.7 MPa			P=0.72731 MPa			P=0.8 MPa		
T(°C)	h(KJ/Kg)	s(KJ/Kg.K)	T(°C)	h(KJ/Kg)	s(KJ/Kg.K)	T(°C)	h(KJ/Kg)	s(KJ/Kg.K)
30	268.45	0.9313	30	267.805	0.92622	30	**266.088**	**0.912698**
					0.950995			
40	278.57	0.9641	40	278.021	0.95932	40	276.45	0.9480

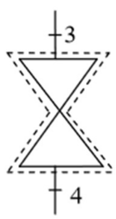
Double interpolation:

We did 2 interpolations to find the temperature at state 2 and the enthalpy at this temperature.

P=0.7 MPa			P=0.72731 MPa			P=0.8 MPa		
T(°C)	h(KJ/Kg)	s(KJ/Kg.K)	T(°C)	h(KJ/Kg)	s(KJ/Kg.K)	T(°C)	h(KJ/Kg)	s(KJ/Kg.K)
30	268.45	0.9313	30	267.805	0.92622	30	**266.088**	**0.912698**
37.485				**275.4516**	0.950995			
40	278.57	0.9641	40	278.021	0.95932	40	276.45	0.9480

Therefore, **T2= 37.485 °C** **and** **h2 = 275.4516 KJ/Kg**

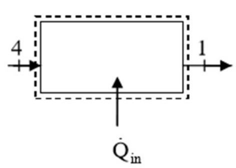
Expansion Valve:



State 3: T_3 = 30°C, saturated liquid => Throttling process: $\boxed{h_3 = 93.58 \text{ kJ/kg}}$

State 4: T_4=-37 °C , P_4 = $P_{sat@-37}$ = 59.905 (interpolation) ; $\boxed{h_4 = h_3 = 93.58 \text{ kJ/kg}}$

Evaporator:



$$\boxed{\dot{Q}_{in} = \dot{m}(h_1 - h_4) = 91.85\ kW}$$

$$\Rightarrow \boxed{\dot{m} = \left(\frac{91.85}{227.755-93.58}\right) * 60 = 41.07322 \text{ kg/min}}$$

3.2.3.2 Heat of the condenser

$$\boxed{\dot{Q}_{out} = \dot{m}(h_2 - h_3) = \left(\frac{41.07322}{60}\right) * (275.4516 - 93.58) = 124.5\ kW = 126\ kW}$$

3.2.3.3 Work of the compressor

$$W_c = \dot{m}(h_2 - h_1)$$

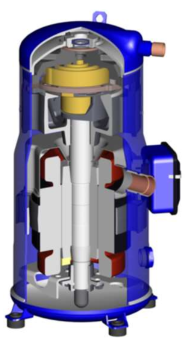
$$\boxed{W_c = \left(\frac{41.07322}{60}\right) * (275.4516 - 227.755) = 32.65088\ kW = 33\ kW}$$

4 Equipments selections

4.1 Compressor:

There are different types of compressors in the field, for example: open compressors, hermetic, semi hermetic, rotary scroll, rotary vane and centrifugal and the list goes on. However, each type of compressor has its own advantages, disadvantages and applications. So for our project we are obviously dealing with an industrial application and with a power output of approximately 33 kW so based on researches made we discovered that usually the compressors used in this application are either the reciprocating hermetic compressor or the rotary scroll compressor.

Rotary-scroll compressor



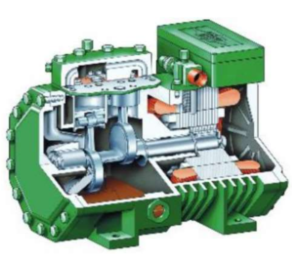
Pros:

- Higher reliability due to simpler structure and less components
- Higher efficiency due to less losses because it requires neither suction nor discharge valves, meanwhile there is no clearance volume.
- Less vibration and less surging due to continuous gas displacement through the sweeping motion of the rotors.

Cons:

- Smaller capacity compared to hermetic compressor

Hermetic reciprocating compressor



Pros:

- Broad applications: this compressor type is capable of compressing a wide range of gases such as refrigerant, hydrogen, natural gas, etc. As a result, it can be used in different industries such as building, refrigeration, mining, metallurgy, etc.
- Broad capacity range: welded hermetic compressors can be designed to a very small capacity which is normally used for residential freezers. Open and serviceable semi-hermetic compressors can be designed to a hundred tons (350 kW) for residential and commercial air conditioning applications.

Cons:

- Low energy efficiency: this compressor type suffers from higher losses as a result of clearance volume, resistance due to suction and discharge valves, and gas leakage between the piston and cylinder.
- Sensitive to liquid slugging inherent with this design (see sidebar for details).
- Compared with other compressor types discussed below, it normally has larger dimensions and greater weight per unit capacity.
- Difficult to maintain due to complex structure.
- Vibration due to discontinuous gas displacement.

So based on this information we decided to choose the rotary-scroll compressor with a capacity of 33 kW offered by the company Copeland, product code ZR160 KCE .

4.2 Expansion Valve

In the industry there are 7 types of EVs (manual EV, capillary, orifice, AEV, TEV, float type, EEV) each one has its own applications. The 2 best ones to use in our system are the thermostatic expansion valve TEV or the electric expansion valve EEV because we need a superheated mixture at the exit of the evaporator. From this information the expansion valve that we will use is an EEV from the company Carel, product code E3V smart which can withstand the power demand that we need.

4.3 Evaporators

There are 2 main types of evaporators flooded or dry, one is used when the exit of the evaporator is not superheated and the second is the opposite; so we will go with the dry type one.

Then we can subdivide this category in 3, bare tube, finned tube or plate type evaporators. Plate type evaporator is used in household applications, and bare tube evaporators are for small capacities which are not our case too and in the end the finned tube evaporator is the one that is used in industrial applications and that’s the one we will use.

So for the evaporator we will use one made by the company Koxka with a capacity of 93.13 KW (calculated was 91.85), product code IRP-931

4.4 Condenser:

There are 3 types of condensers, air-cooled, water-cooled or evaporative condenser

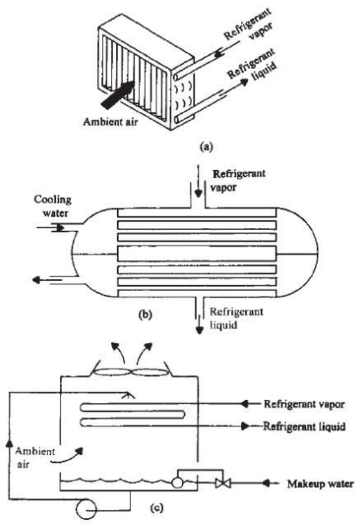


FIGURE 7.1
Types of condensers: (a) air-cooled, (b) water-cooled and (c) evaporative.

Since the evaporator and the condenser are both considered as heat exchangers we will choose our condenser of the same company of the evaporator (Koxka), but of course when installing them the inlet and outlet will be switched for both so one can absorb heat and the other reject it.

For the condenser we need Qout to be 124.5 KW so we will use the IRP-1221 which has 122.1 KW capacity.

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	CFC	HCFC	HFC	Hallogen-free
R-12	•			
R-502	•			
R-22		•		
R-123		•		
R-404A			•	
R-507			•	
R-134a			•	
R-410A			•	
R-407C			•	
Propane				•
Ammonia				•
CO2				•

Table 1. Quick reference to refrigerants.

Identification	Ingredients	Glide	HGWP	Toxic/flammable
R-404A	125/143a/134a	0.5	0.94	No
R-134a	134a	0	0.28	No
R-410A	32/125	0.11	0.44	No
R-407C	32/125/134a	5.4	0.37	No
R-290	Propane	0	0.02	Yes
R-717	Ammonia	0	0	Yes

Table 2. Chlorine-free replacements for R-22.

TABLE A–11

Saturated refrigerant-134a—Temperature table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
−40	51.25	0.0007054	0.36081	−0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866
−38	56.86	0.0007083	0.32732	2.475	206.04	208.51	2.515	224.61	227.12	0.01072	0.95511	0.96584
−36	62.95	0.0007112	0.29751	4.992	204.67	209.66	5.037	223.35	228.39	0.02138	0.94176	0.96315
−34	69.56	0.0007142	0.27090	7.517	203.29	210.81	7.566	222.09	229.65	0.03199	0.92859	0.96058
−32	76.71	0.0007172	0.24711	10.05	201.91	211.96	10.10	220.81	230.91	0.04253	0.91560	0.95813
−30	84.43	0.0007203	0.22580	12.59	200.52	213.11	12.65	219.52	232.17	0.05301	0.90278	0.95579
−28	92.76	0.0007234	0.20666	15.13	199.12	214.25	15.20	218.22	233.43	0.06344	0.89012	0.95356
−26	101.73	0.0007265	0.18946	17.69	197.72	215.40	17.76	216.92	234.68	0.07382	0.87762	0.95144
−24	111.37	0.0007297	0.17395	20.25	196.30	216.55	20.33	215.59	235.92	0.08414	0.86527	0.94941
−22	121.72	0.0007329	0.15995	22.82	194.88	217.70	22.91	214.26	s237.17	0.09441	0.85307	0.94748
−20	132.82	0.0007362	0.14729	25.39	193.45	218.84	25.49	212.91	238.41	0.10463	0.84101	0.94564
−18	144.69	0.0007396	0.13583	27.98	192.01	219.98	28.09	211.55	239.64	0.11481	0.82908	0.94389
−16	157.38	0.0007430	0.12542	30.57	190.56	221.13	30.69	210.18	240.87	0.12493	0.81729	0.94222
−14	170.93	0.0007464	0.11597	33.17	189.09	222.27	33.30	208.79	242.09	0.13501	0.80561	0.94063
−12	185.37	0.0007499	0.10736	35.78	187.62	223.40	35.92	207.38	243.30	0.14504	0.79406	0.93911
−10	200.74	0.0007535	0.099516	38.40	186.14	224.54	38.55	205.96	244.51	0.15504	0.78263	0.93766
−8	217.08	0.0007571	0.092352	41.03	184.64	225.67	41.19	204.52	245.72	0.16498	0.77130	0.93629
−6	234.44	0.0007608	0.085802	43.66	183.13	226.80	43.84	203.07	246.91	0.17489	0.76008	0.93497
−4	252.85	0.0007646	0.079804	46.31	181.61	227.92	46.50	201.60	248.10	0.18476	0.74896	0.93372
−2	272.36	0.0007684	0.074304	48.96	180.08	229.04	49.17	200.11	249.28	0.19459	0.73794	0.93253
0	293.01	0.0007723	0.069255	51.63	178.53	230.16	51.86	198.60	250.45	0.20439	0.72701	0.93139
2	314.84	0.0007763	0.064612	54.30	176.97	231.27	54.55	197.07	251.61	0.21415	0.71616	0.93031
4	337.90	0.0007804	0.060338	56.99	175.39	232.38	57.25	195.51	252.77	0.22387	0.70540	0.92927
6	362.23	0.0007845	0.056398	59.68	173.80	233.48	59.97	193.94	253.91	0.23356	0.69471	0.92828
8	387.88	0.0007887	0.052762	62.39	172.19	234.58	62.69	192.35	255.04	0.24323	0.68410	0.92733
10	414.89	0.0007930	0.049403	65.10	170.56	235.67	65.43	190.73	256.16	0.25286	0.67356	0.92641
12	443.31	0.0007975	0.046295	67.83	168.92	236.75	68.18	189.09	257.27	0.26246	0.66308	0.92554
14	473.19	0.0008020	0.043417	70.57	167.26	237.83	70.95	187.42	258.37	0.27204	0.65266	0.92470
16	504.58	0.0008066	0.040748	73.32	165.58	238.90	73.73	185.73	259.46	0.28159	0.64230	0.92389
18	537.52	0.0008113	0.038271	76.08	163.88	239.96	76.52	184.01	260.53	0.29112	0.63198	0.92310

TABLE A–11

Saturated refrigerant-134a—Temperature table (*Continued*)

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
20	572.07	0.0008161	0.035969	78.86	162.16	241.02	79.32	182.27	261.59	0.30063	0.62172	0.92234
22	608.27	0.0008210	0.033828	81.64	160.42	242.06	82.14	180.49	262.64	0.31011	0.61149	0.92160
24	646.18	0.0008261	0.031834	84.44	158.65	243.10	84.98	178.69	263.67	0.31958	0.60130	0.92088
26	685.84	0.0008313	0.029976	87.26	156.87	244.12	87.83	176.85	264.68	0.32903	0.59115	0.92018
28	727.31	0.0008366	0.028242	90.09	155.05	245.14	90.69	174.99	265.68	0.33846	0.58102	0.91948
30	770.64	0.0008421	0.026622	92.93	153.22	246.14	93.58	173.08	266.66	0.34789	0.57091	0.91879
32	815.89	0.0008478	0.025108	95.79	151.35	247.14	96.48	171.14	267.62	0.35730	0.56082	0.91811
34	863.11	0.0008536	0.023691	98.66	149.46	248.12	99.40	169.17	268.57	0.36670	0.55074	0.91743
36	912.35	0.0008595	0.022364	101.55	147.54	249.08	102.33	167.16	269.49	0.37609	0.54066	0.91675
38	963.68	0.0008657	0.021119	104.45	145.58	250.04	105.29	165.10	270.39	0.38548	0.53058	0.91606
40	1017.1	0.0008720	0.019952	107.38	143.60	250.97	108.26	163.00	271.27	0.39486	0.52049	0.91536
42	1072.8	0.0008786	0.018855	110.32	141.58	251.89	111.26	160.86	272.12	0.40425	0.51039	0.91464
44	1130.7	0.0008854	0.017824	113.28	139.52	252.80	114.28	158.67	272.95	0.41363	0.50027	0.91391
46	1191.0	0.0008924	0.016853	116.26	137.42	253.68	117.32	156.43	273.75	0.42302	0.49012	0.91315
48	1253.6	0.0008996	0.015939	119.26	135.29	254.55	120.39	154.14	274.53	0.43242	0.47993	0.91236
52	1386.2	0.0009150	0.014265	125.33	130.88	256.21	126.59	149.39	275.98	0.45126	0.45941	0.91067
56	1529.1	0.0009317	0.012771	131.49	126.28	257.77	132.91	144.38	277.30	0.47018	0.43863	0.90880
60	1682.8	0.0009498	0.011434	137.76	121.46	259.22	139.36	139.10	278.46	0.48920	0.41749	0.90669
65	1891.0	0.0009750	0.009950	145.77	115.05	260.82	147.62	132.02	279.64	0.51320	0.39039	0.90359
70	2118.2	0.0010037	0.008642	154.01	108.14	262.15	156.13	124.32	280.46	0.53755	0.36227	0.89982
75	2365.8	0.0010372	0.007480	162.53	100.60	263.13	164.98	115.85	280.82	0.56241	0.33272	0.89512
80	2635.3	0.0010772	0.006436	171.40	92.23	263.63	174.24	106.35	280.59	0.58800	0.30111	0.88912
85	2928.2	0.0011270	0.005486	180.77	82.67	263.44	184.07	95.44	279.51	0.61473	0.26644	0.88117
90	3246.9	0.0011932	0.004599	190.89	71.29	262.18	194.76	82.35	277.11	0.64336	0.22674	0.87010
95	3594.1	0.0012933	0.003726	202.40	56.47	258.87	207.05	65.21	272.26	0.67578	0.17711	0.85289
100	3975.1	0.0015269	0.002630	218.72	29.19	247.91	224.79	33.58	258.37	0.72217	0.08999	0.81215

Source: Tables A-11 through A-13 are generated using the Engineering Equation Solver (EES) software developed by S. A. Klein and F. L. Alvarado. The routine used in calculations is the R134a, which is based on the fundamental equation of state developed by R. Tillner-Roth and H.D. Baehr, "An International Standard Formulation for the Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (HFC-134a) for temperatures from 170 K to 455 K and Pressures up to 70 MPa," *J. Phys. Chem, Ref. Data*, Vol. 23, No. 5, 1994. The enthalpy and entropy values of saturated liquid are set to zero at −40°C (and −40°F).

TABLE A–12

Saturated refrigerant-134a—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007098	0.31121	3.798	205.32	209.12	3.841	223.95	227.79	0.01634	0.94807	0.96441
70	−33.87	0.0007144	0.26929	7.680	203.20	210.88	7.730	222.00	229.73	0.03267	0.92775	0.96042
80	−31.13	0.0007185	0.23753	11.15	201.30	212.46	11.21	220.25	231.46	0.04711	0.90999	0.95710
90	−28.65	0.0007223	0.21263	14.31	199.57	213.88	14.37	218.65	233.02	0.06008	0.89419	0.95427
100	−26.37	0.0007259	0.19254	17.21	197.98	215.19	17.28	217.16	234.44	0.07188	0.87995	0.95183
120	−22.32	0.0007324	0.16212	22.40	195.11	217.51	22.49	214.48	236.97	0.09275	0.85503	0.94779
140	−18.77	0.0007383	0.14014	26.98	192.57	219.54	27.08	212.08	239.16	0.11087	0.83368	0.94456
160	−15.60	0.0007437	0.12348	31.09	190.27	221.35	31.21	209.90	241.11	0.12693	0.81496	0.94190
180	−12.73	0.0007487	0.11041	34.83	188.16	222.99	34.97	207.90	242.86	0.14139	0.79826	0.93965
200	−10.09	0.0007533	0.099867	38.28	186.21	224.48	38.43	206.03	244.46	0.15457	0.78316	0.93773
240	−5.38	0.0007620	0.083897	44.48	182.67	227.14	44.66	202.62	247.28	0.17794	0.75664	0.93458
280	−1.25	0.0007699	0.072352	49.97	179.50	229.46	50.18	199.54	249.72	0.19829	0.73381	0.93210
320	2.46	0.0007772	0.063604	54.92	176.61	231.52	55.16	196.71	251.88	0.21637	0.71369	0.93006
360	5.82	0.0007841	0.056738	59.44	173.94	233.38	59.72	194.08	253.81	0.23270	0.69566	0.92836
400	8.91	0.0007907	0.051201	63.62	171.45	235.07	63.94	191.62	255.55	0.24761	0.67929	0.92691
450	12.46	0.0007985	0.045619	68.45	168.54	237.00	68.81	188.71	257.53	0.26465	0.66069	0.92535
500	15.71	0.0008059	0.041118	72.93	165.82	238.75	73.33	185.98	259.30	0.28023	0.64377	0.92400
550	18.73	0.0008130	0.037408	77.10	163.25	240.35	77.54	183.38	260.92	0.29461	0.62821	0.92282
600	21.55	0.0008199	0.034295	81.02	160.81	241.83	81.51	180.90	262.40	0.30799	0.61378	0.92177
650	24.20	0.0008266	0.031646	84.72	158.48	243.20	85.26	178.51	263.77	0.32051	0.60030	0.92081
700	26.69	0.0008331	0.029361	88.24	156.24	244.48	88.82	176.21	265.03	0.33230	0.58763	0.91994
750	29.06	0.0008395	0.027371	91.59	154.08	245.67	92.22	173.98	266.20	0.34345	0.57567	0.91912
800	31.31	0.0008458	0.025621	94.79	152.00	246.79	95.47	171.82	267.29	0.35404	0.56431	0.91835
850	33.45	0.0008520	0.024069	97.87	149.98	247.85	98.60	169.71	268.31	0.36413	0.55349	0.91762
900	35.51	0.0008580	0.022683	100.83	148.01	248.85	101.61	167.66	269.26	0.37377	0.54315	0.91692
950	37.48	0.0008641	0.021438	103.69	146.10	249.79	104.51	165.64	270.15	0.38301	0.53323	0.91624
1000	39.37	0.0008700	0.020313	106.45	144.23	250.68	107.32	163.67	270.99	0.39189	0.52368	0.91558
1200	46.29	0.0008934	0.016715	116.70	137.11	253.81	117.77	156.10	273.87	0.42441	0.48863	0.91303
1400	52.40	0.0009166	0.014107	125.94	130.43	256.37	127.22	148.90	276.12	0.45315	0.45734	0.91050
1600	57.88	0.0009400	0.012123	134.43	124.04	258.47	135.93	141.93	277.86	0.47911	0.42873	0.90784
1800	62.87	0.0009639	0.010559	142.33	117.83	260.17	144.07	135.11	279.17	0.50294	0.40204	0.90498
2000	67.45	0.0009886	0.009288	149.78	111.73	261.51	151.76	128.33	280.09	0.52509	0.37675	0.90184
2500	77.54	0.0010566	0.006936	166.99	96.47	263.45	169.63	111.16	280.79	0.57531	0.31695	0.89226
3000	86.16	0.0011406	0.005275	183.04	80.22	263.26	186.46	92.63	279.09	0.62118	0.25776	0.87894

TABLE A–13

Superheated refrigerant-134a

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.06 MPa (T_{sat} = −36.95°C)				P = 0.10 MPa (T_{sat} = −26.37°C)				P = 0.14 MPa (T_{sat} = −18.77°C)			
Sat.	0.31121	209.12	227.79	0.9644	0.19254	215.19	234.44	0.9518	0.14014	219.54	239.16	0.9446
−20	0.33608	220.60	240.76	1.0174	0.19841	219.66	239.50	0.9721				
−10	0.35048	227.55	248.58	1.0477	0.20743	226.75	247.49	1.0030	0.14605	225.91	246.36	0.9724
0	0.36476	234.66	256.54	1.0774	0.21630	233.95	255.58	1.0332	0.15263	233.23	254.60	1.0031
10	0.37893	241.92	264.66	1.1066	0.22506	241.30	263.81	1.0628	0.15908	240.66	262.93	1.0331
20	0.39302	249.35	272.94	1.1353	0.23373	248.79	272.17	1.0918	0.16544	248.22	271.38	1.0624
30	0.40705	256.95	281.37	1.1636	0.24233	256.44	280.68	1.1203	0.17172	255.93	279.97	1.0912
40	0.42102	264.71	289.97	1.1915	0.25088	264.25	289.34	1.1484	0.17794	263.79	288.70	1.1195
50	0.43495	272.64	298.74	1.2191	0.25937	272.22	298.16	1.1762	0.18412	271.79	297.57	1.1474
60	0.44883	280.73	307.66	1.2463	0.26783	280.35	307.13	1.2035	0.19025	279.96	306.59	1.1749
70	0.46269	288.99	316.75	1.2732	0.27626	288.64	316.26	1.2305	0.19635	288.28	315.77	1.2020
80	0.47651	297.41	326.00	1.2997	0.28465	297.08	325.55	1.2572	0.20242	296.75	325.09	1.2288
90	0.49032	306.00	335.42	1.3260	0.29303	305.69	334.99	1.2836	0.20847	305.38	334.57	1.2553
100	0.50410	314.74	344.99	1.3520	0.30138	314.46	344.60	1.3096	0.21449	314.17	344.20	1.2814
	P = 0.18 MPa (T_{sat} = −12.73°C)				P = 0.20 MPa (T_{sat} = −10.09°C)				P = 0.24 MPa (T_{sat} = −5.38°C)			
Sat.	0.11041	222.99	242.86	0.9397	0.09987	224.48	244.46	0.9377	0.08390	227.14	247.28	0.9346
−10	0.11189	225.02	245.16	0.9484	0.09991	224.55	244.54	0.9380				
0	0.11722	232.48	253.58	0.9798	0.10481	232.09	253.05	0.9698	0.08617	231.29	251.97	0.9519
10	0.12240	240.00	262.04	1.0102	0.10955	239.67	261.58	1.0004	0.09026	238.98	260.65	0.9831
20	0.12748	247.64	270.59	1.0399	0.11418	247.35	270.18	1.0303	0.09423	246.74	269.36	1.0134
30	0.13248	255.41	279.25	1.0690	0.11874	255.14	278.89	1.0595	0.09812	254.61	278.16	1.0429
40	0.13741	263.31	288.05	1.0975	0.12322	263.08	287.72	1.0882	0.10193	262.59	287.06	1.0718
50	0.14230	271.36	296.98	1.1256	0.12766	271.15	296.68	1.1163	0.10570	270.71	296.08	1.1001
60	0.14715	279.56	306.05	1.1532	0.13206	279.37	305.78	1.1441	0.10942	278.97	305.23	1.1280
70	0.15196	287.91	315.27	1.1805	0.13641	287.73	315.01	1.1714	0.11310	287.36	314.51	1.1554
80	0.15673	296.42	324.63	1.2074	0.14074	296.25	324.40	1.1983	0.11675	295.91	323.93	1.1825
90	0.16149	305.07	334.14	1.2339	0.14504	304.92	333.93	1.2249	0.12038	304.60	333.49	1.2092
100	0.16622	313.88	343.80	1.2602	0.14933	313.74	343.60	1.2512	0.12398	313.44	343.20	1.2356
	P = 0.28 MPa (T_{sat} = −1.25°C)				P = 0.32 MPa (T_{sat} = 2.46°C)				P = 0.40 MPa (T_{sat} = 8.91°C)			
Sat.	0.07235	229.46	249.72	0.9321	0.06360	231.52	251.88	0.9301	0.051201	235.07	255.55	0.9269
0	0.07282	230.44	250.83	0.9362								
10	0.07646	238.27	259.68	0.9680	0.06609	237.54	258.69	0.9544	0.051506	235.97	256.58	0.9305
20	0.07997	246.13	268.52	0.9987	0.06925	245.50	267.66	0.9856	0.054213	244.18	265.86	0.9628
30	0.08338	254.06	277.41	1.0285	0.07231	253.50	276.65	1.0157	0.056796	252.36	275.07	0.9937
40	0.08672	262.10	286.38	1.0576	0.07530	261.60	285.70	1.0451	0.059292	260.58	284.30	1.0236
50	0.09000	270.27	295.47	1.0862	0.07823	269.82	294.85	1.0739	0.061724	268.90	293.59	1.0528
60	0.09324	278.56	304.67	1.1142	0.08111	278.15	304.11	1.1021	0.064104	277.32	302.96	1.0814
70	0.09644	286.99	314.00	1.1418	0.08395	286.62	313.48	1.1298	0.066443	285.86	312.44	1.1094
80	0.09961	295.57	323.46	1.1690	0.08675	295.22	322.98	1.1571	0.068747	294.53	322.02	1.1369
90	0.10275	304.29	333.06	1.1958	0.08953	303.97	332.62	1.1840	0.071023	303.32	331.73	1.1640
100	0.10587	313.15	342.80	1.2222	0.09229	312.86	342.39	1.2105	0.073274	312.26	341.57	1.1907
110	0.10897	322.16	352.68	1.2483	0.09503	321.89	352.30	1.2367	0.075504	321.33	351.53	1.2171
120	0.11205	331.32	362.70	1.2742	0.09775	331.07	362.35	1.2626	0.077717	330.55	361.63	1.2431
130	0.11512	340.63	372.87	1.2997	0.10045	340.39	372.54	1.2882	0.079913	339.90	371.87	1.2688
140	0.11818	350.09	383.18	1.3250	0.10314	349.86	382.87	1.3135	0.082096	349.41	382.24	1.2942

TABLE A–13

Superheated refrigerant-134a (*Continued*)

T °C	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K
	P = 0.50 MPa (T_{sat} = 15.71°C)				P = 0.60 MPa (T_{sat} = 21.55°C)				P = 0.70 MPa (T_{sat} = 26.69°C)			
Sat.	0.041118	238.75	259.30	0.9240	0.034295	241.83	262.40	0.9218	0.029361	244.48	265.03	0.9199
20	0.042115	242.40	263.46	0.9383								
30	0.044338	250.84	273.01	0.9703	0.035984	249.22	270.81	0.9499	0.029966	247.48	268.45	0.9313
40	0.046456	259.26	282.48	1.0011	0.037865	257.86	280.58	0.9816	0.031696	256.39	278.57	0.9641
50	0.048499	267.72	291.96	1.0309	0.039659	266.48	290.28	1.0121	0.033322	265.20	288.53	0.9954
60	0.050485	276.25	301.50	1.0599	0.041389	275.15	299.98	1.0417	0.034875	274.01	298.42	1.0256
70	0.052427	284.89	311.10	1.0883	0.043069	283.89	309.73	1.0705	0.036373	282.87	308.33	1.0549
80	0.054331	293.64	320.80	1.1162	0.044710	292.73	319.55	1.0987	0.037829	291.80	318.28	1.0835
90	0.056205	302.51	330.61	1.1436	0.046318	301.67	329.46	1.1264	0.039250	300.82	328.29	1.1114
100	0.058053	311.50	340.53	1.1705	0.047900	310.73	339.47	1.1536	0.040642	309.95	338.40	1.1389
110	0.059880	320.63	350.57	1.1971	0.049458	319.91	349.59	1.1803	0.042010	319.19	348.60	1.1658
120	0.061687	329.89	360.73	1.2233	0.050997	329.23	359.82	1.2067	0.043358	328.55	358.90	1.1924
130	0.063479	339.29	371.03	1.2491	0.052519	338.67	370.18	1.2327	0.044688	338.04	369.32	1.2186
140	0.065256	348.83	381.46	1.2747	0.054027	348.25	380.66	1.2584	0.046004	347.66	379.86	1.2444
150	0.067021	358.51	392.02	1.2999	0.055522	357.96	391.27	1.2838	0.047306	357.41	390.52	1.2699
160	0.068775	368.33	402.72	1.3249	0.057006	367.81	402.01	1.3088	0.048597	367.29	401.31	1.2951
	P = 0.80 MPa (T_{sat} = 31.31°C)				P = 0.90 MPa (T_{sat} = 35.51°C)				P = 1.00 MPa (T_{sat} = 39.37°C)			
Sat.	0.025621	246.79	267.29	0.9183	0.022683	248.85	269.26	0.9169	0.020313	250.68	270.99	0.9156
40	0.027035	254.82	276.45	0.9480	0.023375	253.13	274.17	0.9327	0.020406	251.30	271.71	0.9179
50	0.028547	263.86	286.69	0.9802	0.024809	262.44	284.77	0.9660	0.021796	260.94	282.74	0.9525
60	0.029973	272.83	296.81	1.0110	0.026146	271.60	295.13	0.9976	0.023068	270.32	293.38	0.9850
70	0.031340	281.81	306.88	1.0408	0.027413	280.72	305.39	1.0280	0.024261	279.59	303.85	1.0160
80	0.032659	290.84	316.97	1.0698	0.028630	289.86	315.63	1.0574	0.025398	288.86	314.25	1.0458
90	0.033941	299.95	327.10	1.0981	0.029806	299.06	325.89	1.0860	0.026492	298.15	324.64	1.0748
100	0.035193	309.15	337.30	1.1258	0.030951	308.34	336.19	1.1140	0.027552	307.51	335.06	1.1031
110	0.036420	318.45	347.59	1.1530	0.032068	317.70	346.56	1.1414	0.028584	316.94	345.53	1.1308
120	0.037625	327.87	357.97	1.1798	0.033164	327.18	357.02	1.1684	0.029592	326.47	356.06	1.1580
130	0.038813	337.40	368.45	1.2061	0.034241	336.76	367.58	1.1949	0.030581	336.11	366.69	1.1846
140	0.039985	347.06	379.05	1.2321	0.035302	346.46	378.23	1.2210	0.031554	345.85	377.40	1.2109
150	0.041143	356.85	389.76	1.2577	0.036349	356.28	389.00	1.2467	0.032512	355.71	388.22	1.2368
160	0.042290	366.76	400.59	1.2830	0.037384	366.23	399.88	1.2721	0.033457	365.70	399.15	1.2623
170	0.043427	376.81	411.55	1.3080	0.038408	376.31	410.88	1.2972	0.034392	375.81	410.20	1.2875
180	0.044554	386.99	422.64	1.3327	0.039423	386.52	422.00	1.3221	0.035317	386.04	421.36	1.3124
	P = 1.20 MPa (T_{sat} = 46.29°C)				P = 1.40 MPa (T_{sat} = 52.40°C)				P = 1.60 MPa (T_{sat} = 57.88°C)			
Sat.	0.016715	253.81	273.87	0.9130	0.014107	256.37	276.12	0.9105	0.012123	258.47	277.86	0.9078
50	0.017201	257.63	278.27	0.9267								
60	0.018404	267.56	289.64	0.9614	0.015005	264.46	285.47	0.9389	0.012372	260.89	280.69	0.9163
70	0.019502	277.21	300.61	0.9938	0.016060	274.62	297.10	0.9733	0.013430	271.76	293.25	0.9535
80	0.020529	286.75	311.39	1.0248	0.017023	284.51	308.34	1.0056	0.014362	282.09	305.07	0.9875
90	0.021506	296.26	322.07	1.0546	0.017923	294.28	319.37	1.0364	0.015215	292.17	316.52	1.0194
100	0.022442	305.80	332.73	1.0836	0.018778	304.01	330.30	1.0661	0.016014	302.14	327.76	1.0500
110	0.023348	315.38	343.40	1.1118	0.019597	313.76	341.19	1.0949	0.016773	312.07	338.91	1.0795
120	0.024228	325.03	354.11	1.1394	0.020388	323.55	352.09	1.1230	0.017500	322.02	350.02	1.1081
130	0.025086	334.77	364.88	1.1664	0.021155	333.41	363.02	1.1504	0.018201	332.00	361.12	1.1360
140	0.025927	344.61	375.72	1.1930	0.021904	343.34	374.01	1.1773	0.018882	342.05	372.26	1.1632
150	0.026753	354.56	386.66	1.2192	0.022636	353.37	385.07	1.2038	0.019545	352.17	383.44	1.1900
160	0.027566	364.61	397.69	1.2449	0.023355	363.51	396.20	1.2298	0.020194	362.38	394.69	1.2163
170	0.028367	374.78	408.82	1.2703	0.024061	373.75	407.43	1.2554	0.020830	372.69	406.02	1.2421
180	0.029158	385.08	420.07	1.2954	0.024757	384.10	418.76	1.2807	0.021456	383.11	417.44	1.2676

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