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A
Configuration of display cases in typical supermarkets

According to Walker et al. [19], supermarket display cases can have four different designs, as described below and illustrated in Figure A.1.

- Tub: usually considered for storage and display of frozen food and meats, it operates at a uniform temperature and possesses a low product storage volume per square meter of sales area, though requiring the least amount of cooling load per meter of any case type;
- Open-front multi-deck: using an upright cabinet and shelves, it presents the largest storage volume per square meter of floor area, however refrigeration requirements are extremely high due to the entraining of ambient air in the curtain passing over the opening of the case;
- Glass door reach-in: often utilized for frozen foods, and presenting glass doors over the opening of the case equipped with antisweat electric heaters, it has refrigeration loads normally smaller than those of the multi-deck, but greater than those of the tub;
- Single-deck or service: commonly employed for display of fresh meat products in the deli and meat departments of supermarkets, it is equipped with sliding doors in the back for access by serving people, besides the glass front to show the products to customers.

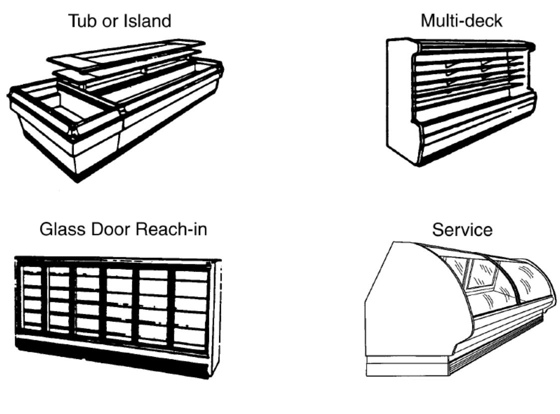

Figure A.1: Types of supermarket display cases, from Walker et al. [19].

B
Algorithms in thermodynamic models

Hereafter, the methodology associated to the determination of T_{cond} as a function of (P_{cond} and ΔP), P_{evap} in terms of (T_{evap} and ΔP), P_{cond} as a function of (T_{cond} andΔP), and P_{evap} in terms of (T_{evap} and $\Delta P, h_{in}$) is described and detailed for further understanding.

1. Mean condensation pressure in terms of mean condensation temperature and condenser pressure drop, $P_{cond}\left(T_{cond}, \Delta P\right)$

   The following procedure returns the mean condensation pressure when the mean condensation temperature and the condenser pressure drop are input variables. This method is applied for the Pumped CO_2 refrigerant condenser.

   In order to successfully execute the method, auxiliary temporal variables are considered. They are the following: pressure at bubble point, P_{bub}, pressure at dew point, P_{dew}, temperature at bubble point, T_{bub}, and temperature at dew point, T_{dew}.

   Below, the procedure is described in 5 simple steps:

   (a) Evaluating input parameters

$$T_{med} = T_{cd,rf} \tag{B.1}$$

$$\Delta P = \Delta P_{cd,rf} \tag{B.2}$$

$$\Delta P_{max} = 1.0 \tag{B.3}$$

$$\wp = 0.001 \tag{B.4}$$

   (b) Obtaining a value for parameter P_{init}

$$P_{bub} = \underline{P}\left(x = 0, T_{med}\right) \tag{B.5}$$

$$P_{dew} = \underline{P}\left(x = 1, T_{med}\right) \tag{B.6}$$

$$P_{init} = \frac{P_{bub} + P_{dew}}{2} \tag{B.7}$$

(c) Obtaining a first value for parameter T_{med01}, based on P_{init}

$$P_{med01} = P_{init} \tag{B.8}$$

$$T_{bub} = \underline{T}\left(x = 0, P_{med01} - \frac{\Delta P}{2}\right) \tag{B.9}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med01} + \frac{\Delta P}{2}\right) \tag{B.10}$$

$$T_{med01} = \frac{T_{bub} + T_{dew}}{2} \tag{B.11}$$

(d) Starting the iteration process (loop) to correct the value of parameter P_{med01}

i. Obtaining a value for parameter T_{med02}, based on P_{med01} and ΔP_{max}

$$P_{med02} = P_{med01} + \frac{\Delta P_{max}}{20} \tag{B.12}$$

$$T_{bub} = \underline{T}\left(x = 0, P_{med02} - \frac{\Delta P}{2}\right) \tag{B.13}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med02} + \frac{\Delta P}{2}\right) \tag{B.14}$$

$$T_{med02} = \frac{T_{bub} + T_{dew}}{2} \tag{B.15}$$

ii. Obtaining a new value for parameter P_{med01}, based on results for a and b

$$a = \frac{P_{med02} - P_{med01}}{T_{med02} - T_{med01}} \tag{B.16}$$

$$b = P_{med01} - a \cdot T_{med01} \tag{B.17}$$

$$P_{med01} = a \cdot T_{med} + b \tag{B.18}$$

iii. Re-evaluating parameter T_{med01} and comparing its result with the mean condensation temperature

$$T_{bub} = \underline{T}\left(x = 0, P_{med01} - \frac{\Delta P}{2}\right) \tag{B.19}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med01} + \frac{\Delta P}{2}\right) \tag{B.20}$$

$$T_{med01} = \frac{T_{bub} + T_{dew}}{2} \tag{B.21}$$

$$\Im = |T_{med} - T_{med01}| \tag{B.22}$$

(e) Exiting the iteration process (loop) or re-entering it to further correct the value of parameter P_{med01}

i. If 5 iterations have already been executed OR if the error $\Im$ is less than or equal to tolerance $\wp$, exit the loop and evaluate parameter P_{med}

$$P_{med} = P_{med01} \tag{B.23}$$

ii. Otherwise, re-enter the iteration process, step (d), in order to obtain a better value for parameter P_{med01}

(f) Evaluating the average condensation pressure

$$P_{cd,ref} = P_{med} \tag{B.24}$$

2. Mean condensation temperature as a function of mean condensation pressure and condenser pressure drop, $T_{cond}\ (P_{cond}, \Delta P)$.

The following procedure returns the mean condensation temperature when the mean condensation pressure and the condenser pressure drop are input variables. This method is applied for the Pumped CO_2 secondary fluid condenser.

This procedure is considerably simpler, requiring solely two steps, as below (recall that the pressure drop at the condenser for the secondary fluid is null, as the receiver pressure is constant; however, the algorithm can be used for any value of pressure drop, as it considers the existence of pressure difference).

In order to successfully execute the method, auxiliary variables are considered once again. They are the following: temperature at bubble point, T_{bub}, and temperature at dew point, T_{dew}.

(a) Evaluating input parameters

$$P_{med} = P_{cd,sf} \tag{B.25}$$

$$\Delta P = \Delta P_{cd,sf} \tag{B.26}$$

(b) Obtaining a value for parameter T_{med}

$$T_{bub} = \underline{T}\ \left(x = 0, P_{med} - \frac{\Delta P}{2}\right) \tag{B.27}$$

$$T_{dew} = \underline{T}\ \left(x = 1, P_{med} + \frac{\Delta P}{2}\right) \tag{B.28}$$

$$T_{med} = \frac{T_{bub} + T_{dew}}{2} \tag{B.29}$$

(c) Evaluating the average condensation temperature

$$T_{cd,sf} = T_{med} \tag{B.30}$$

3. Mean evaporation pressure as a function of mean evaporation temperature, evaporator pressure drop and enthalpy at evaporator inlet, $P_{evap}\left(T_{evap}, \Delta P, h_{in}\right)$.

   The following procedure returns the mean evaporating pressure when the mean evaporating temperature, the evaporator pressure drop and the enthaply at evaporator inlet are previously known parameters. This method is applied for the Pumped CO_2 refrigerant evaporator.

   In order to successfully execute the method, auxiliary temporal variables are used. They are: pressure at bubble point, P_{bub}, pressure at dew point, P_{dew}, temperature at inlet, T_{00}, and temperature at dew point, T_{dew}.

   Below we describe the procedure in 5 simple steps:

   (a) Evaluating input parameters

$$T_{med} = T_{ev,ref} \tag{B.31}$$

$$\Delta P = \Delta P_{ev,ref} \tag{B.32}$$

$$\Delta P_{max} = 1.0 \tag{B.33}$$

$$\wp = 0.001 \tag{B.34}$$

   (b) Obtaining a value for parameter P_{init}

$$P_{bub} = \underline{P}\left(x = 0, T_{med}\right) \tag{B.35}$$

$$P_{dew} = \underline{P}\left(x = 1, T_{med}\right) \tag{B.36}$$

$$P_{init} = \frac{P_{bub} + P_{dew}}{2} \tag{B.37}$$

   (c) Obtaining a first value for parameter T_{med01}, based on P_{init}

$$P_{med01} = P_{init} \tag{B.38}$$

$$T_{00} = \underline{T}\left(h_{in}, P_{med01} + \frac{\Delta P}{2}\right) \tag{B.39}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med01} - \frac{\Delta P}{2}\right) \tag{B.40}$$

$$T_{med01} = \frac{T_{00} + T_{dew}}{2} \tag{B.41}$$

(d) Starting the iteration process (loop) to correct the value of parameter P_{med01}

i. Obtaining a value for parameter T_{med02}, based on P_{med01} and ΔP_{max}

$$P_{med02} = P_{med01} + \frac{\Delta P_{max}}{20} \tag{B.42}$$

$$T_{00} = \underline{T}\left(h_{in}, P_{med02} + \frac{\Delta P}{2}\right) \tag{B.43}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med02} - \frac{\Delta P}{2}\right) \tag{B.44}$$

$$T_{med02} = \frac{T_{00} + T_{dew}}{2} \tag{B.45}$$

ii. Obtaining a new value for parameter P_{med01}, based on results for a and b

$$a = \frac{P_{med02} - P_{med01}}{T_{med02} - T_{med01}} \tag{B.46}$$

$$b = P_{med01} - a \cdot T_{med01} \tag{B.47}$$

$$P_{med01} = a \cdot T_{med} + b \tag{B.48}$$

iii. Re-evaluating parameter T_{med01} and comparing its result with the mean evaporating temperature

$$T_{00} = \underline{T}\left(h_{In}, P_{med01} + \frac{\Delta P}{2}\right) \tag{B.49}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med01} - \frac{\Delta P}{2}\right) \tag{B.50}$$

$$T_{med01} = \frac{T_{00} + T_{dew}}{2} \tag{B.51}$$

$$\Im = |T_{med} - T_{med01}| \tag{B.52}$$

(e) Exiting the iteration process (loop) or re-entering it to further correct the value of parameter P_{med01}

i. If 5 iterations have already been executed OR if the error $\Im$ is less than or equal to tolerance $\wp$, exit the loop and evaluate parameter P_{med}

$$P_{med} = P_{med01} \tag{B.53}$$

ii. Otherwise, re-enter the iteration process, step (d), in order to obtain a better value for parameter P_{med01}

(f) Evaluating the average evaporating pressure

$$P_{ev,ref} = P_{med} \tag{B.54}$$

4. Mean evaporating pressure as a function of mean evaporating temperature and evaporator pressure drop, $P_{evap}\left(T_{evap}, \Delta P\right)$.

   The following procedure returns the mean evaporating pressure when the mean evaporating temperature and the evaporator pressure drop are input variables. This method is applied for the Pumped CO_2 secondary fluid evaporator.

   Additionally, auxiliary temporal variables are considered as well. They are the following: pressure at bubble point, P_{bub}, pressure at dew point, P_{dew}, temperature at bubble point, T_{bub}, and temperature at dew point, T_{dew}.

   (a) Evaluating input parameters

$$T_{med} = T_{ev,sf} \tag{B.55}$$

$$\Delta P = \Delta P_{ev,sf} \tag{B.56}$$

$$\Delta P_{max} = 1.0 \tag{B.57}$$

$$\wp = 0.001 \tag{B.58}$$

   (b) Obtaining a value for parameter P_{init}

$$P_{bub} = \underline{P}\left(x = 0, T_{med}\right) \tag{B.59}$$

$$P_{dew} = \underline{P}\left(x = 1, T_{med}\right) \tag{B.60}$$

$$P_{init} = \frac{P_{bub} + P_{dew}}{2} \tag{B.61}$$

   (c) Obtaining a first value for parameter T_{med01}, based on P_{init}

$$P_{med01} = P_{init} \tag{B.62}$$

$$T_{bub} = \underline{T}\left(x = 0, P_{med01} + \frac{\Delta P}{2}\right) \tag{B.63}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med01} - \frac{\Delta P}{2}\right) \tag{B.64}$$

$$T_{med01} = \frac{T_{bub} + T_{dew}}{2} \tag{B.65}$$

   (d) Starting the iteration process (loop) to correct the value of parameter P_{med01}

i. Obtaining the value for parameter T_{med02}, based on P_{med01} and ΔP_{max}

$$P_{med02} = P_{med01} + \frac{\Delta P_{max}}{20} \tag{B.66}$$

$$T_{bub} = \underline{T}\left(x = 0, P_{med02} + \frac{\Delta P}{2}\right) \tag{B.67}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med02} - \frac{\Delta P}{2}\right) \tag{B.68}$$

$$T_{med02} = \frac{T_{bub} + T_{dew}}{2} \tag{B.69}$$

ii. Obtaining a new value for parameter P_{med01}, based on results for m and b

$$a = \frac{P_{med02} - P_{med01}}{T_{med02} - T_{med01}} \tag{B.70}$$

$$b = P_{med01} - a \cdot T_{med01} \tag{B.71}$$

$$P_{med01} = a \cdot T_{med} + b \tag{B.72}$$

iii. Re-evaluating parameter T_{med01} and comparing its result with the mean condensation temperature

$$T_{bub} = \underline{T}\left(x = 0, P_{med01} + \frac{\Delta P}{2}\right) \tag{B.73}$$

$$T_{dew} = \underline{T}\left(x = 1, P_{med01} - \frac{\Delta P}{2}\right) \tag{B.74}$$

$$T_{med01} = \frac{T_{bub} + T_{dew}}{2} \tag{B.75}$$

$$\Im = |T_{med} - T_{med01}| \tag{B.76}$$

(e) Exiting the iteration process (loop) or re-entering it to further correct the value of parameter P_{med01}

i. If 5 iterations have already been executed OR if the error $\Im$ is less than or equal to tolerance $\wp$, exit the loop and evaluate parameter P_{med}

$$P_{med} = P_{med01} \tag{B.77}$$

ii. Otherwise, re-enter the iteration process, step (d), in order to obtain a better value for parameter P_{med01}

(f) Evaluating the average evaporating pressure

$$P_{ev,sf} = P_{med} \tag{B.78}$$

C
Weather bin data

Table C.1: Weather bin data for Atlanta, USA [133].

Ambient temperature bin	Number of hours
35.0 — 37.8	9
32.2 — 35.0	56
29.4 — 32.2	196
26.7 — 29.4	758
23.9 — 26.7	768
21.1 — 23.9	1314
18.3 — 21.1	885
15.6 — 18.3	1027
12.8 — 15.6	790
10.0 — 12.8	673
7.2 — 10.0	641
4.4 — 7.2	436
1.7 — 4.4	560
−1.1 — 1.7	323
−3.9 — − 1.1	181
−6.7 — − 3.9	72
−9.4 — − 6.7	64
−12.2 — − 9.4	7
−15.0 — − 12.2	0
−17.8 — − 15.0	0
Total hours	8760

Table C.2: Weather bin data for Boulder, USA [133].

Ambient temperature bin	Number of hours
35.0 — 37.8	22
32.2 — 35.0	96
29.4 — 32.2	115
26.7 — 29.4	382
23.9 — 26.7	440
21.1 — 23.9	489
18.3 — 21.1	503
15.6 — 18.3	907
12.8 — 15.6	698
10.0 — 12.8	754
7.2 — 10.0	762
4.4 — 7.2	633
1.7 — 4.4	834
−1.1 — 1.7	717
−3.9 — − 1.1	611
−6.7 — − 3.9	251
−9.4 — − 6.7	201
−12.2 — − 9.4	130
−15.0 — − 12.2	89
−17.8 — − 15.0	126
Total hours	8760

Table C.3: Weather bin data for Manaus, Brazil [134].

Ambient temperature bin	Number of hours
32.5 — 33.0	0
32.0 — 32.5	62
31.5 — 32.0	31
31.0 — 31.5	123
30.5 — 31.0	214
30.0 — 30.5	151
29.5 — 30.0	276
29.0 — 29.5	397
28.5 — 29.0	490
28.0 — 28.5	518
27.5 — 28.0	483
27.0 — 27.5	760
26.5 — 27.0	762
26.0 — 26.5	913
25.5 — 26.0	1245
25.0 — 25.5	1188
24.5 — 25.0	758
24.0 — 24.5	361
23.5 — 24.0	28
23.0 — 23.5	0
Total hours	8760

Table C.4: Weather bin data for Philadelphia, USA [133].

Ambient temperature bin	Number of hours
35.0 — 37.8	3
32.2 — 35.0	52
29.4 — 32.2	104
26.7 — 29.4	477
23.9 — 26.7	656
21.1 — 23.9	907
18.3 — 21.1	619
15.6 — 18.3	983
12.8 — 15.6	625
10.0 — 12.8	540
7.2 — 10.0	576
4.4 — 7.2	552
1.7 — 4.4	1067
−1.1 — 1.7	685
−3.9 — − 1.1	442
−6.7 — − 3.9	248
−9.4 — − 6.7	184
−12.2 — − 9.4	40
−15.0 — − 12.2	0
−17.8 — − 15.0	0
Total hours	8760

Table C.5: Weather bin data for Rio de Janeiro, Brazil [134].

Ambient temperature bin	Number of hours
29.5 — 30.0	0
29.0 — 29.5	62
28.5 — 29.0	174
28.0 — 28.5	397
27.5 — 28.0	270
27.0 — 27.5	239
26.5 — 27.0	329
26.0 — 26.5	450
25.5 — 26.0	482
25.0 — 25.5	636
24.5 — 25.0	738
24.0 — 24.5	644
23.5 — 24.0	734
23.0 — 23.5	550
22.5 — 23.0	641
22.0 — 22.5	519
21.5 — 22.0	400
21.0 — 21.5	459
20.5 — 21.0	304
20.0 — 20.5	273
19.5 — 20.0	151
19.0 — 19.5	153
18.5 — 19.0	155
18.0 — 18.5	0
Total hours	8760

Table C.6: Weather bin data for Stockholm, Sweden [135].

Ambient temperature bin	Number of hours
20.0 — 21.0	62
19.0 — 20.0	217
18.0 — 19.0	247
17.0 — 18.0	336
16.0 — 17.0	244
15.0 — 16.0	370
14.0 — 15.0	521
13.0 — 14.0	430
12.0 — 13.0	213
11.0 — 12.0	272
10.0 — 11.0	272
9.0 — 10.0	302
8.0 — 9.0	399
7.0 — 8.0	246
6.0 — 7.0	245
5.0 — 6.0	370
4.0 — 5.0	60
3.0 — 4.0	120
2.0 — 3.0	364
1.0 — 2.0	634
0.0 — 1.0	472
−1.0 — 0.0	419
−2.0 — − 1.0	860
−3.0 — − 2.0	434
−4.0 — − 3.0	651
Total hours	8760

D
COP and annual consumption results for thermodynamic models

Table D.1: Annual consumption (MWh/year) of supermarket refrigeration technologies operating with distinct refrigerants in different locations.

Location	System	R404A	R407A	R407F	HDR81	CO_2
Atlanta	DX	872.9	825.4	821.3	825.2	—
	Pumped CO_2	995.2	954.5	949.0	953.4	—
	CO_2 booster	—	—	—	—	1167
Boulder	DX	742.9	706.8	704.2	706.8	—
	Pumped CO_2	863.0	833.3	829.6	832.5	—
	CO_2 booster	—	—	—	—	931.2
Manaus	DX	1209	1125	1116	1125	—
	Pumped CO_2	1338	1262	1250	1260	—
	CO_2 booster	—	—	—	—	2107
Philadelphia	DX	782.3	743.4	740.4	743.3	—
	Pumped CO_2	903.7	870.7	866.5	869.8	—
	CO_2 booster	—	—	—	—	997.9
Rio de Janeiro	DX	1103	1034	1027	1034	—
	Pumped CO_2	1230	1168	1159	1166	—
	CO_2 booster	—	—	—	—	1617
Stockholm	DX	634.0	608.7	607.7	608.8	—
	Pumped CO_2	752.0	732.8	730.9	732.3	—
	CO_2 booster	—	—	—	—	714.8

Table D.2: COP of refrigeration technologies operating with distinct refrigerants in different locations.

Location	Ambient temp. (°C)	System	R404A	R407A	R407F	HDR81	CO_2
		DX	2.759	2.938	2.957	2.939	—
Atlanta	23.33	Pumped CO_2	2.471	2.595	2.615	2.599	—
		CO_2 booster	—	—	—	—	2.227
		DX	3.612	3.259	3.803	3.790	—
Boulder	15.61	Pumped CO_2	3.151	3.259	3.273	3.263	—
		CO_2 booster	—	—	—	—	3.017
		DX	2.532	2.712	2.733	2.714	—
Manaus	25.94	Pumped CO_2	2.283	2.413	2.435	2.418	—
		CO_2 booster	—	—	—	—	1.850
		DX	2.728	2.907	2.927	2.909	—
Philadelphia	23.67	Pumped CO_2	2.446	2.571	2.591	2.575	—
		CO_2 booster	—	—	—	—	2.201
		DX	2.616	2.796	2.816	2.797	—
Rio de Janeiro	24.94	Pumped CO_2	2.353	2.481	2.502	2.485	—
		CO_2 booster	—	—	—	—	2.074
		DX	3.447	3.625	3.639	3.625	—
Stockholm	16.89	Pumped CO_2	3.022	3.133	3.148	3.137	—
		CO_2 booster	—	—	—	—	2.868

E
LCCP, refrigerant charge and annual consumption results for lumped parameter model

Table E.1: Annual consumption (MWh/year) of experimental facility direct expansion refrigeration system operating with distinct refrigerants.

Min. condensing temp. (°C)	Temperature level	R404A	R407F	HDR21	HDR81
10	MT	19.52	19.98	19.60	19.46
	LT	30.52	28.29	28.39	27.87
21	MT	20.48	20.78	20.40	20.23
	LT	31.35	28.76	29.02	28.47

Table E.2: Refrigerant charge (kg) of experimental facility direct expansion refrigeration system operating with distinct refrigerants.

Min. condensing temp. (°C)	Temperature level	R404A	R407F	HDR21	HDR81
10	MT	1.769	1.502	1.482	1.466
	LT	1.456	1.237	1.256	1.224
21	MT	1.783	1.510	1.481	1.467
	LT	1.470	1.241	1.275	1.229

Table E.3: LCCP (ton CO_2) of experimental facility direct expansion refrigeration system operating with distinct refrigerants.

Min. condensing temp. (°C)	R404A	R407F	HDR21	HDR81
10	520.5	482.4	476.6	470.3
21	538.3	494.8	490.5	483.6

Table E.4: Annual consumption (MWh/year) of supermarket store direct expansion refrigeration system operating with distinct refrigerants.

Min. condensing temp. (°C)	Temperature level	R404A	R407F	HDR21	HDR81
10	MT	1181	1159	1338	1258
	LT	674.0	826.0	766.7	834.6
21	MT	1239	1236	1383	1303
	LT	719.0	864.3	796.3	873.4

Table E.5: LCCP (ton CO_2) of supermarket store direct expansion refrigeration system operating with distinct refrigerants.

Min. condensing temp. (°C)	R404A	R407F	HDR21	HDR81
10	29,488	24,210	24,069	24,100
21	30,492	25,330	24,803	24,922