Heat exchanger network design based on physical principles and heuristics

Case 17 ï A new benchmark for the 10SP1 literature case

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The 10SP1 example was first presented by Pho and Lapidus in 1973. It comprises five hot and five cold streams and one cold utility. Data are given in Table 17.1.

Table 17.1

Tsupply °C	Ttarget °C	Heat kW	U*f kW/m²,K	Description -
160	93	588.93	1.704	H1
249	138	1171.05	1.704	H2
271	149	1532.32	1.704	H3
227	66	2377.97	1.704	H4
199	66	2358.09	1.704	H5
82	177	1641.60	1.704	C1
93	205	1556.80	1.704	C2
38	221	1544.52	1.704	C3
60	160	762.00	1.704	C4
116	222	644.48	1.704	C5
38	82	1878.96	1.704	Cooling

Cold utility = 18.12 EUR/kW,year
HEX cost formula = 145.63 x Area^ 0.60 EUR/year

Composite curves are shown in Figure 17.1.

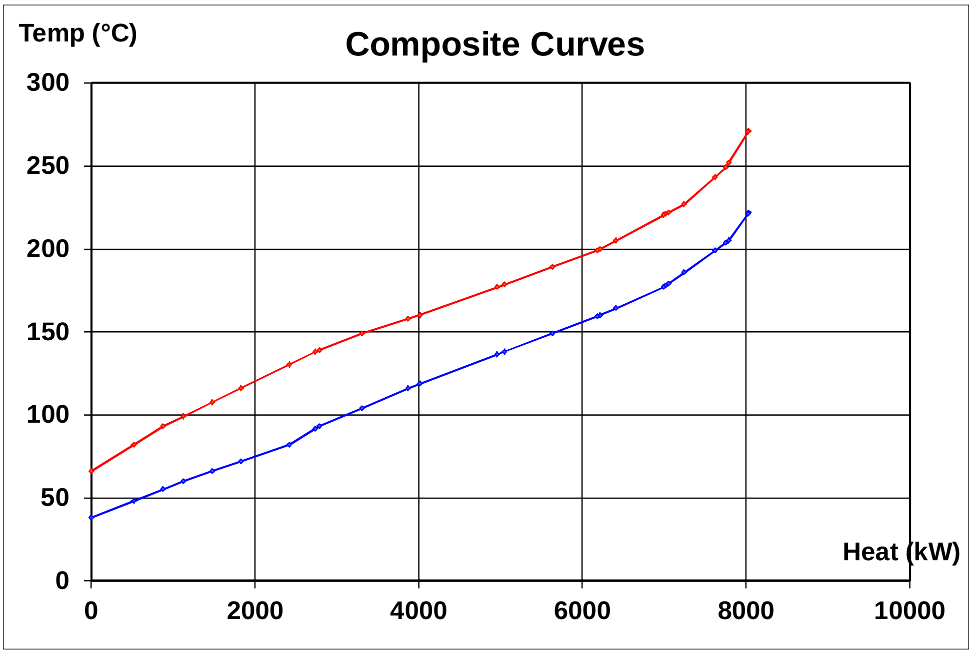


Figure 17.1

The data set leads to a threshold problem with a smallest DeltaT of 28 K at the cold side caused by the cold utility. There is, however, also a process pinch with a DeltaT of 39.65 K caused by hot stream H5; this becomes more visible in the diagram of the shifted composite curves set up without the cold utility in Figure 17.2.

The area target is 229.18 m², the cost target in the assumption of one single system with 10 units is 43582 EUR.

The curves are nearly parallel over most of the integration range with a DeltaT of 40 K to 50 K (Figure 17.3); in view of the design, the problem can be treated as a pinched problem with the pinch for the overall system caused by hot stream H5.

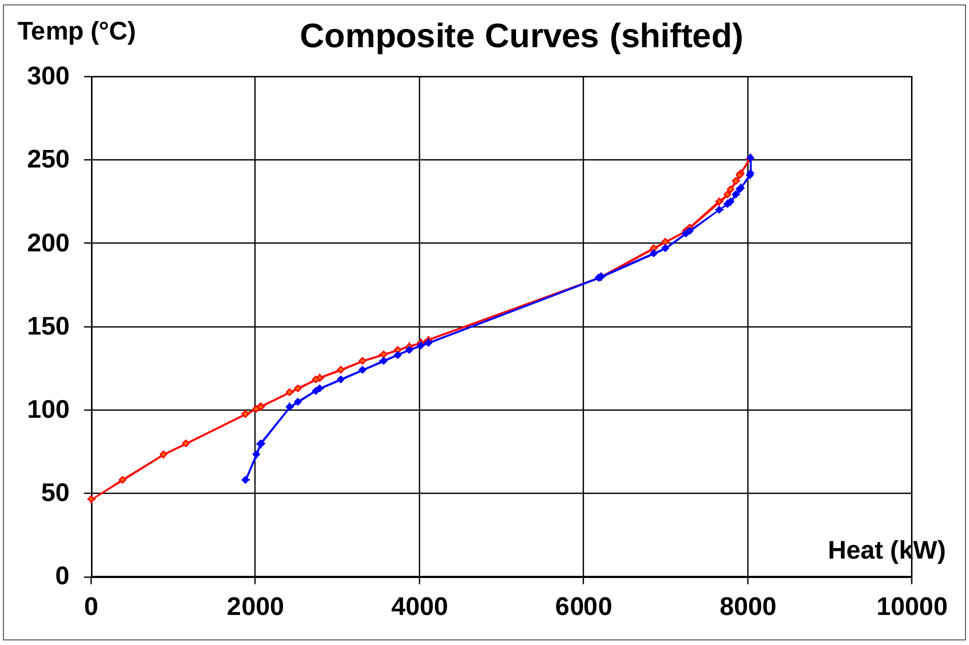


Figure 17.2

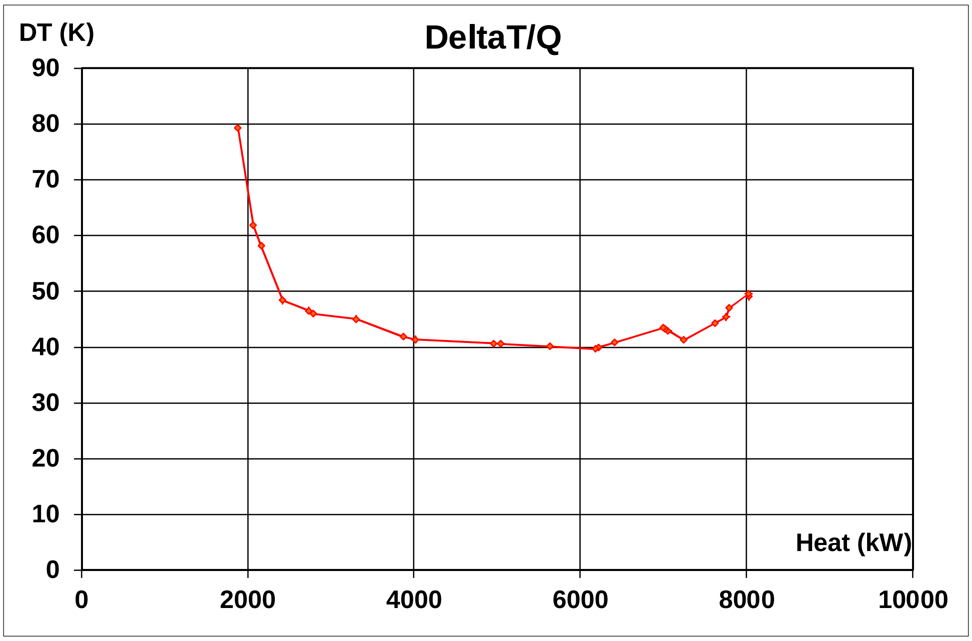


Figure 17.3

The network is developed following pinch design rules in combination with heuristic expert rules based on physical principles rather than on a purely mathematical approach. Analysis of the stream characteristics and of the resulting grid diagram is of primary importance.

The biggest challenge in heat exchanger network synthesis is the complexity related to the size of the problem in combination with the objective of achieving a minimum number of units in view of minimizing cost. If a process stream can be ticked-off at the start, then the complexity of the task is reduced by an order of magnitude.

The process stream with the biggest heat load can never be ticked-off with another process stream; however, it can be a good candidate for ticking-off the biggest counterpart. This leads to the first query:

- Query 1: check whether the biggest hot stream is an appropriate candidate to tick-off the biggest cold stream without violating pinch design rules and vice versa.

Whilst the process stream with the biggest heat load can never be ticked-off itself with another process stream, the likelihood that the process stream with the lowest heat load can be ticked-off is quite high; this leads to the second query:

- Query 2: check whether the smallest (or a small) process stream can be ticked-off without violating pinch design rules

In case of parallel composite curves, the driving force diagram will suggest matches between streams with preferably (almost) equal heat capacity flowrates (mcp’s) in the parallel section; this leads to the third query:

- Query 3: check whether matches are possible between streams with similar mcp’s in parallel sections of the composite curves.

In view of avoiding stream splitting at the pinch and achieving a minimum number of units, it is advantageous to tick-off streams that are crossing the pinch; this leads to the fourth query:

- Query 4: check whether matches are possible between streams crossing the pinch without violating pinch design rules.

The important pinch design rules to be considered are:

- No heat transfer across the process pinch (or as little as possible);
- Do not give away driving force.

Several matches are possible responding to several queries and also combinations of matches are possible. After accepting one or two or more compatible matches, the remaining problem can be analysed in view of remaining cost and available driving force. The remaining area and cost targets, together with the area and cost already spent on the envisaged matches give a good indication of the final result to be expected, this information can be used to prioritize particular combinations in an early stage, prior to finalizing the integral network. Less attractive combinations can be eliminated in an early stage.

After implementation of the matches, the remaining problem will have been reduced to a manageable number of streams which can easily be solved following a tick-off procedure. The resulting network can be fine-tuned with regard to the stream split ratio, if any, and the ultimate position of the smallest heat exchangers whilst maintaining the main structure of the network.

The procedure leads to results, the best of which are summarized in Table 17.2 and compared with published networks. For networks with stream splits, several networks have been developed that are better than the best published. For networks without stream split, the two best networks published so far were also identified.

The networks mentioned in Table 17.2 are shown in Figure 17.4 through Figure 17.13.

Table 17.2

Cases	First matches	Area (m^2)	Cost ('000)	Splits
Original data set - targeting		229.18	43.582	
With stream splits				
Case 1	H2-C2 & H4-C1	242.24	43.316	2
Case 2	H2-C4 & H4-C1	239.88	43.324	1
Case 3	H2-C4 & H4-C2	250.39	43.328	1
Case 4	H2-C3 & H4-C1	244.74	43.338	1
Case 5	H2-C3 & H4-C2	251.02	43.349	1
Without stream splits				
Case 6	H2-C3 & H4-C1	246.95	43.393 (1)	0
Case 7	H2-C3 & H4-C2	260.61	43.411 (2)	0
Case 8	H2-C3 & H5-C1	260.20	43.437	0
Case 9	H2-C3 & H3-C5 & H4-C2	252.93	43.450	0
Case 10	H2-C3 & H3-C2 & H4-C5	266.62	43.611	0
Published results				
Lin & Miller (2004)			43.329	4
Pettersson (2008)			43.331	3
Gupta, Ghosh (2010)			43.342	1
Huang, Karimi (2013)			43.359	1
Zhao, Yin, Huo (2013)			43.429	1
Flower & Linnhoff (1978)			43.934	0
Papoulias, Grossmnn (1983)			43.934	0
Lewin et al. (1998)			43.752	0
Pariyani et al. (2006)			43.439	0
Yerramsetty, Murty (2008)			43.538	0
(1) He, Cui (2013)			43.393	0
(2) Peng, Cui (2015)			43.411	0

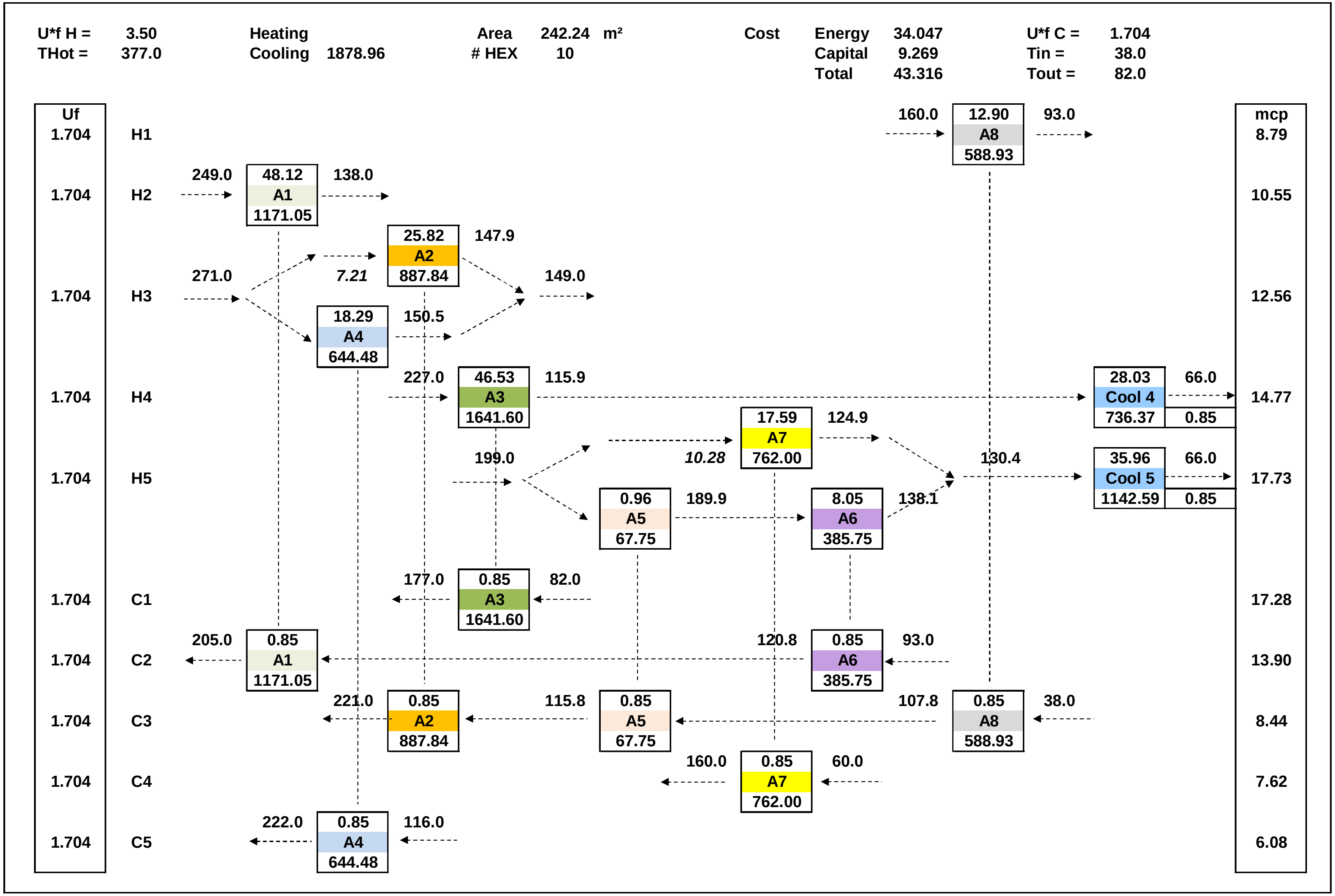

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 242.24 m²
HEX 10
Cost
Energy 34.047
Capital 9.269
Total 43.316
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
1.704 H1 8.79
1.704 H2 10.55
1.704 H3 12.56
1.704 H4 14.77
1.704 H5 17.73
1.704 C1 17.28
1.704 C2 13.90
1.704 C3 8.44
1.704 C4 7.62
1.704 C5 6.08
160.0 12.90 A8 588.93 93.0
249.0 48.12 A1 1171.05 138.0
25.82 A2 887.84 147.9
7.21
271.0
149.0
18.29 A4 644.48 150.5
227.0 46.53 A3 1641.60 115.9
28.03 Cool 4 736.37 66.0 0.85
17.59 A7 762.00 124.9
10.28
199.0
130.4
35.96 Cool 5 1142.59 66.0 0.85
0.96 A5 67.75 189.9
8.05 A6 385.75 138.1
177.0 0.85 A3 1641.60 82.0
205.0 0.85 A1 1171.05
120.8 0.85 A6 385.75 93.0
221.0 0.85 A2 887.84 115.8
0.85 A5 67.75
107.8 0.85 A8 588.93 38.0
160.0 0.85 A7 762.00 60.0
222.0 0.85 A4 644.48 116.0

Figure 17.4

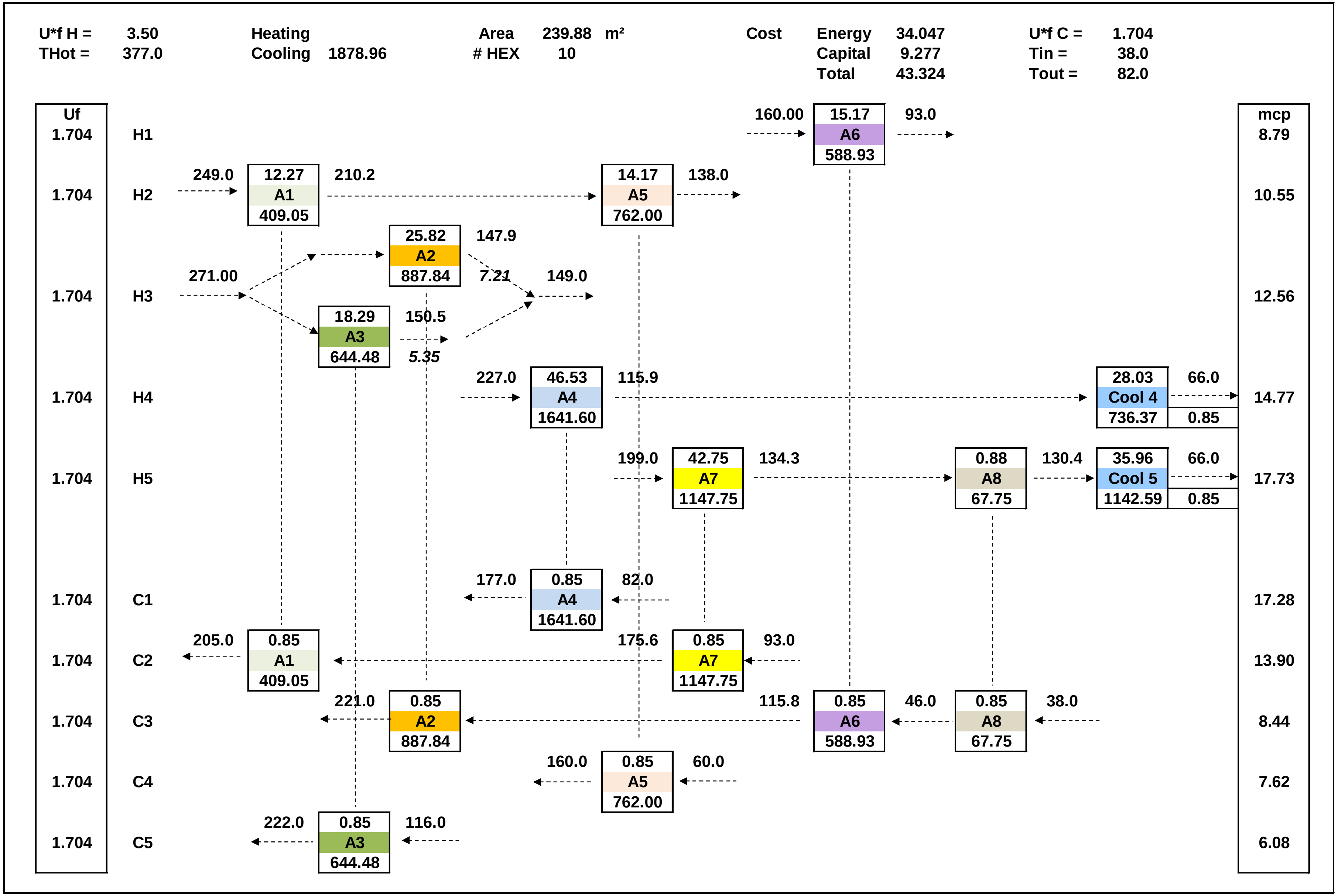

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 239.88 m²
HEX 10
Cost
Energy 34.047
Capital 9.277
Total 43.324
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
1.704 H1 8.79
1.704 H2 10.55
1.704 H3 12.56
1.704 H4 14.77
1.704 H5 17.73
1.704 C1 17.28
1.704 C2 13.90
1.704 C3 8.44
1.704 C4 7.62
1.704 C5 6.08
160.00 15.17 A6 588.93 93.0
249.0 12.27 A1 409.05 210.2
14.17 A5 762.00 138.0
25.82 A2 887.84 147.9
271.00
7.21
149.0
18.29 A3 644.48 150.5
5.35
227.0 46.53 A4 1641.60 115.9
28.03 Cool 4 736.37 66.0 0.85
199.0 42.75 A7 1147.75 134.3
0.88 A8 67.75 130.4
35.96 Cool 5 1142.59 66.0 0.85
177.0 0.85 A4 1641.60 82.0
205.0 0.85 A1 409.05
175.6 0.85 A7 1147.75 93.0
221.0 0.85 A2 887.84
115.8 0.85 A6 588.93 46.0
0.85 A8 67.75 38.0
160.0 0.85 A5 762.00 60.0
222.0 0.85 A3 644.48 116.0

Figure 17.5

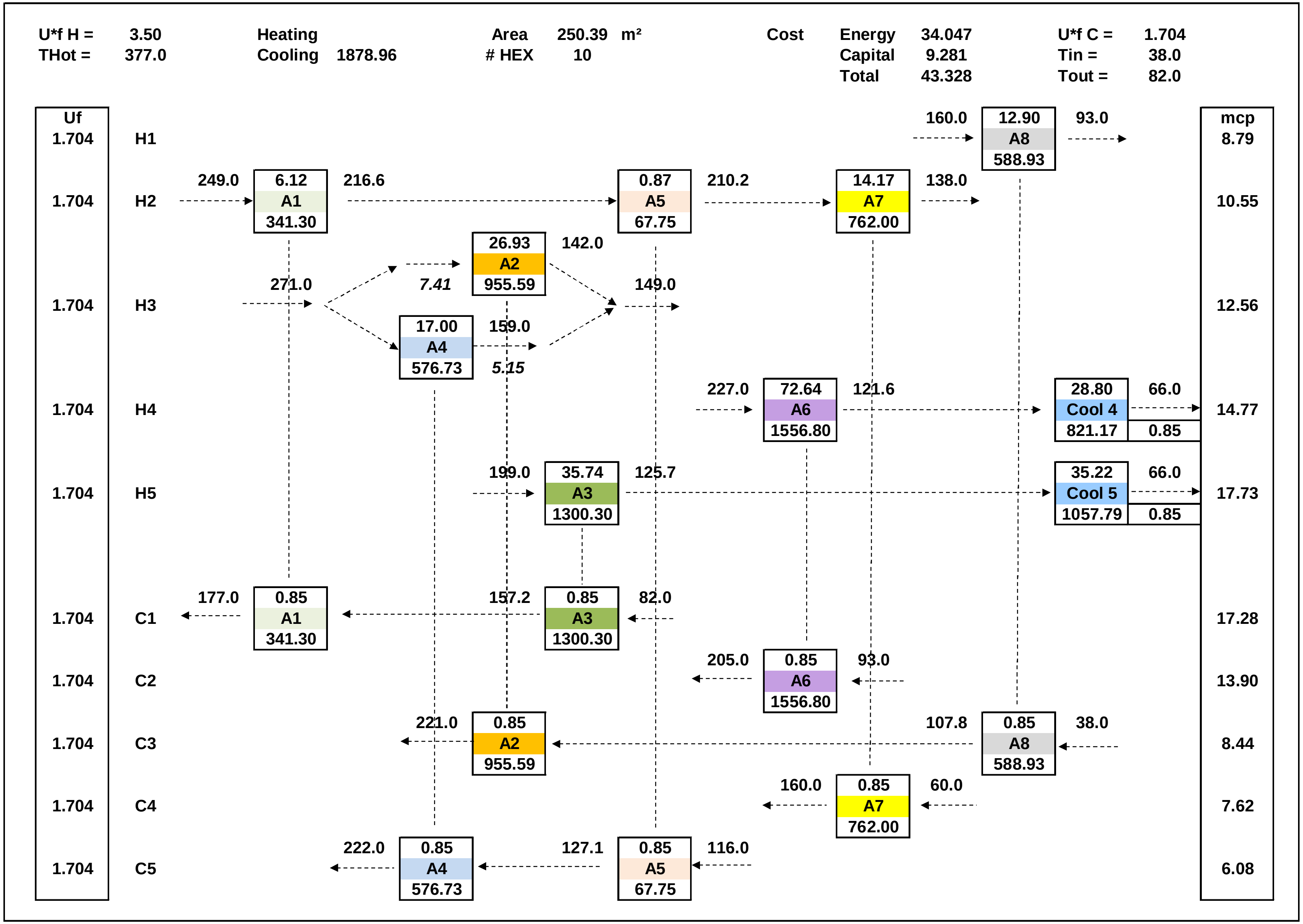

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 250.39 m²
HEX 10
Cost
Energy 34.047
Capital 9.281
Total 43.328
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
1.704 H1 8.79
1.704 H2 10.55
1.704 H3 12.56
1.704 H4 14.77
1.704 H5 17.73
1.704 C1 17.28
1.704 C2 13.90
1.704 C3 8.44
1.704 C4 7.62
1.704 C5 6.08
160.0 12.90 A8 588.93 93.0
249.0 6.12 A1 341.30 216.6
0.87 A5 67.75 210.2
14.17 A7 762.00 138.0
26.93 A2 955.59 142.0
7.41
271.0
149.0
17.00 A4 576.73 159.0
5.15
227.0 72.64 A6 1556.80 121.6
28.80 Cool 4 821.17 66.0 0.85
199.0 35.74 A3 1300.30 125.7
35.22 Cool 5 1057.79 66.0 0.85
177.0 0.85 A1 341.30
157.2 0.85 A3 1300.30 82.0
205.0 0.85 A6 1556.80 93.0
221.0 0.85 A2 955.59
107.8 0.85 A8 588.93 38.0
160.0 0.85 A7 762.00 60.0
222.0 0.85 A4 576.73
127.1 0.85 A5 67.75 116.0

Figure 17.6

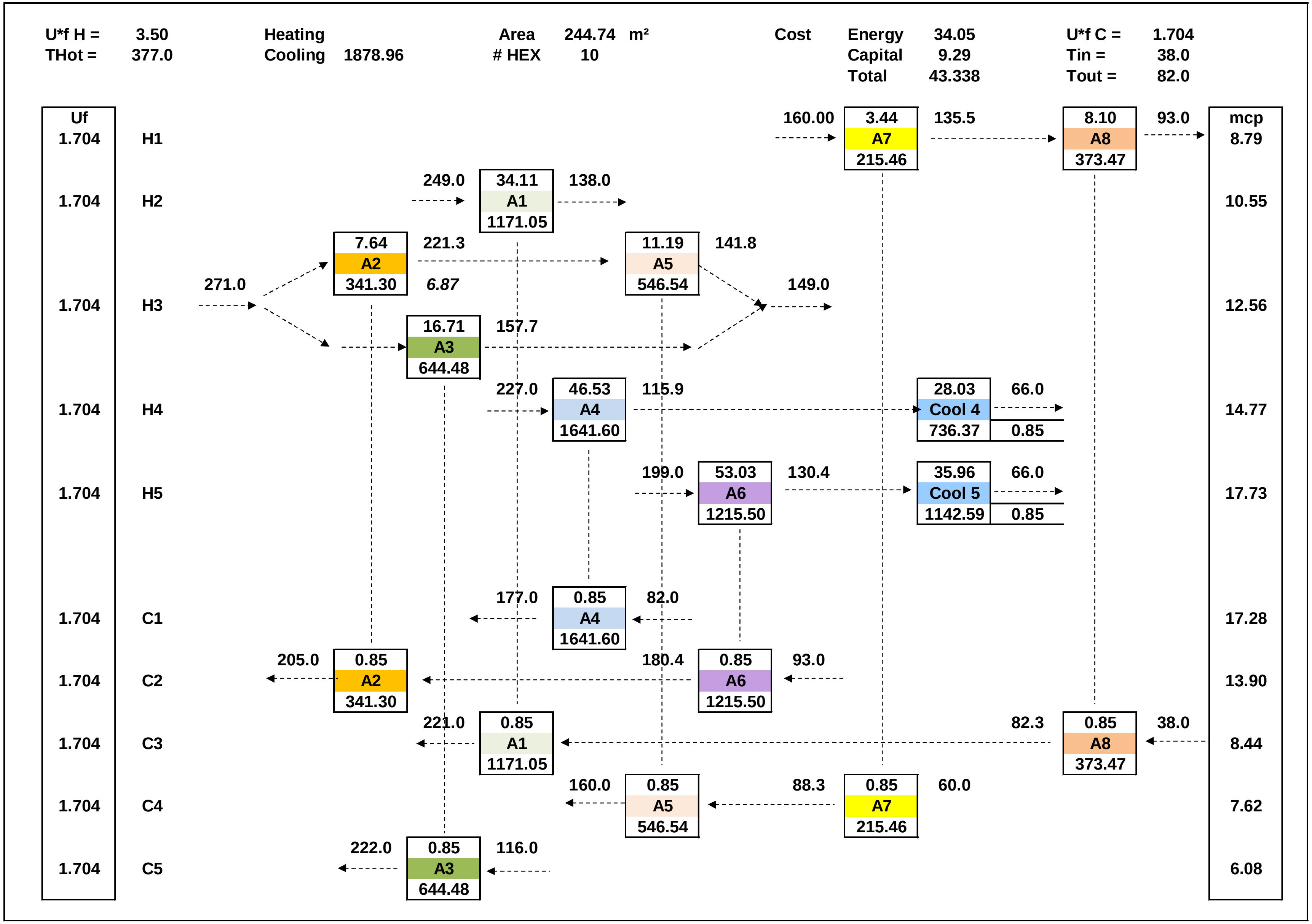

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 244.74 m²
HEX 10
Cost
Energy 34.05
Capital 9.29
Total 43.338
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
1.704 H1
1.704 H2
1.704 H3
1.704 H4
1.704 H5
1.704 C1
1.704 C2
1.704 C3
1.704 C4
1.704 C5
mcp
8.79
10.55
12.56
14.77
17.73
17.28
13.90
8.44
7.62
6.08
160.00
3.44 A7 215.46
135.5
8.10 A8 373.47
93.0
249.0
34.11 A1 1171.05
138.0
271.0
7.64 A2 341.30
221.3
6.87
11.19 A5 546.54
141.8
149.0
16.71 A3 644.48
157.7
227.0
46.53 A4 1641.60
115.9
28.03 Cool 4 736.37
66.0
0.85
199.0
53.03 A6 1215.50
130.4
35.96 Cool 5 1142.59
66.0
0.85
177.0
0.85 A4 1641.60
82.0
205.0
0.85 A2 341.30
180.4
0.85 A6 1215.50
93.0
221.0
0.85 A1 1171.05
82.3
0.85 A8 373.47
38.0
160.0
0.85 A5 546.54
88.3
0.85 A7 215.46
60.0
222.0
0.85 A3 644.48
116.0

Figure 17.7

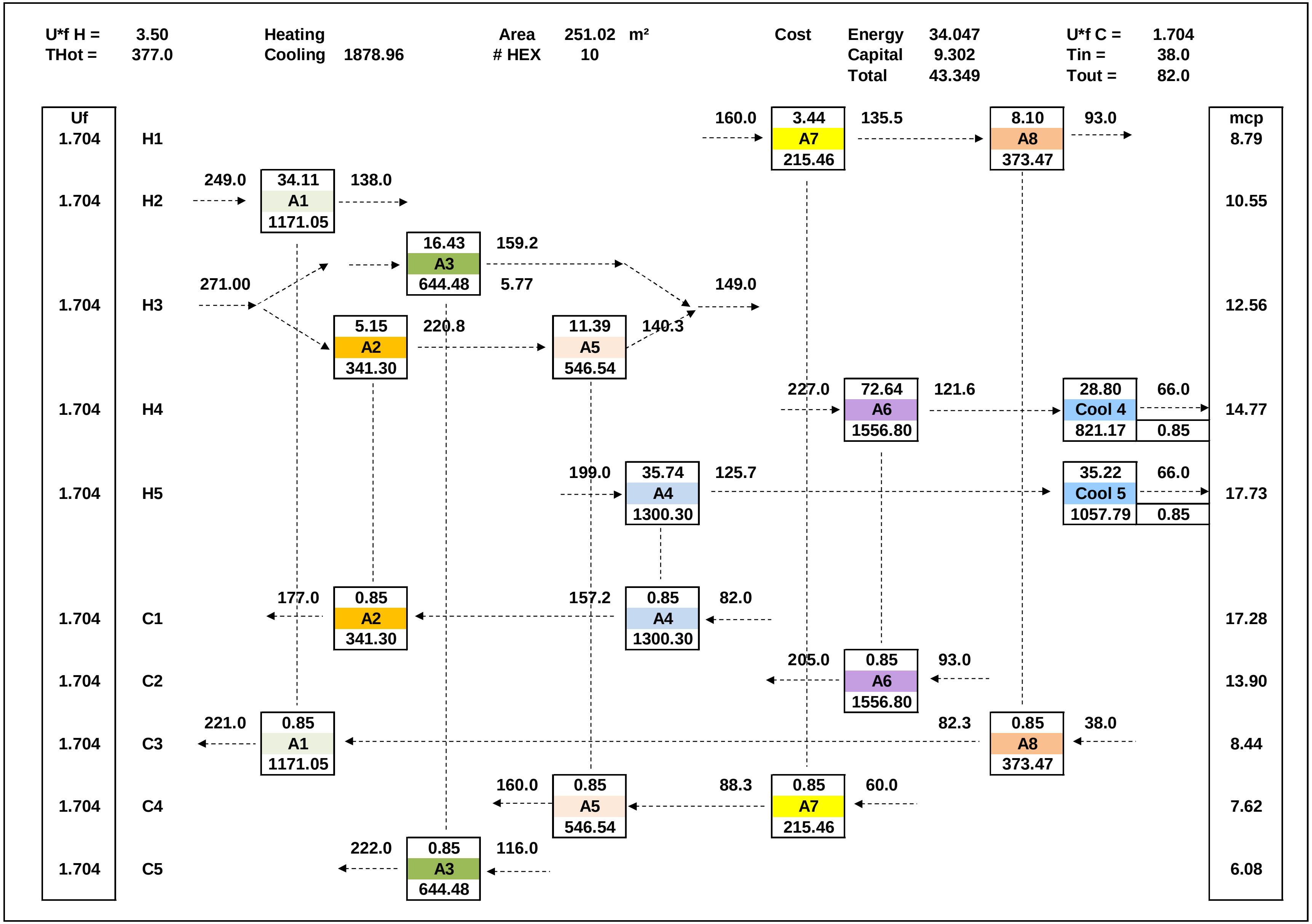

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 251.02 m²
HEX 10
Cost
Energy 34.047
Capital 9.302
Total 43.349
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
H1 H2 H3 H4 H5 C1 C2 C3 C4 C5
1.704
8.79 10.55 12.56 14.77 17.73 17.28 13.90 8.44 7.62 6.08
A1 A2 A3 A4 A5 A6 A7 A8
Cool 4
Cool 5

Figure 17.8

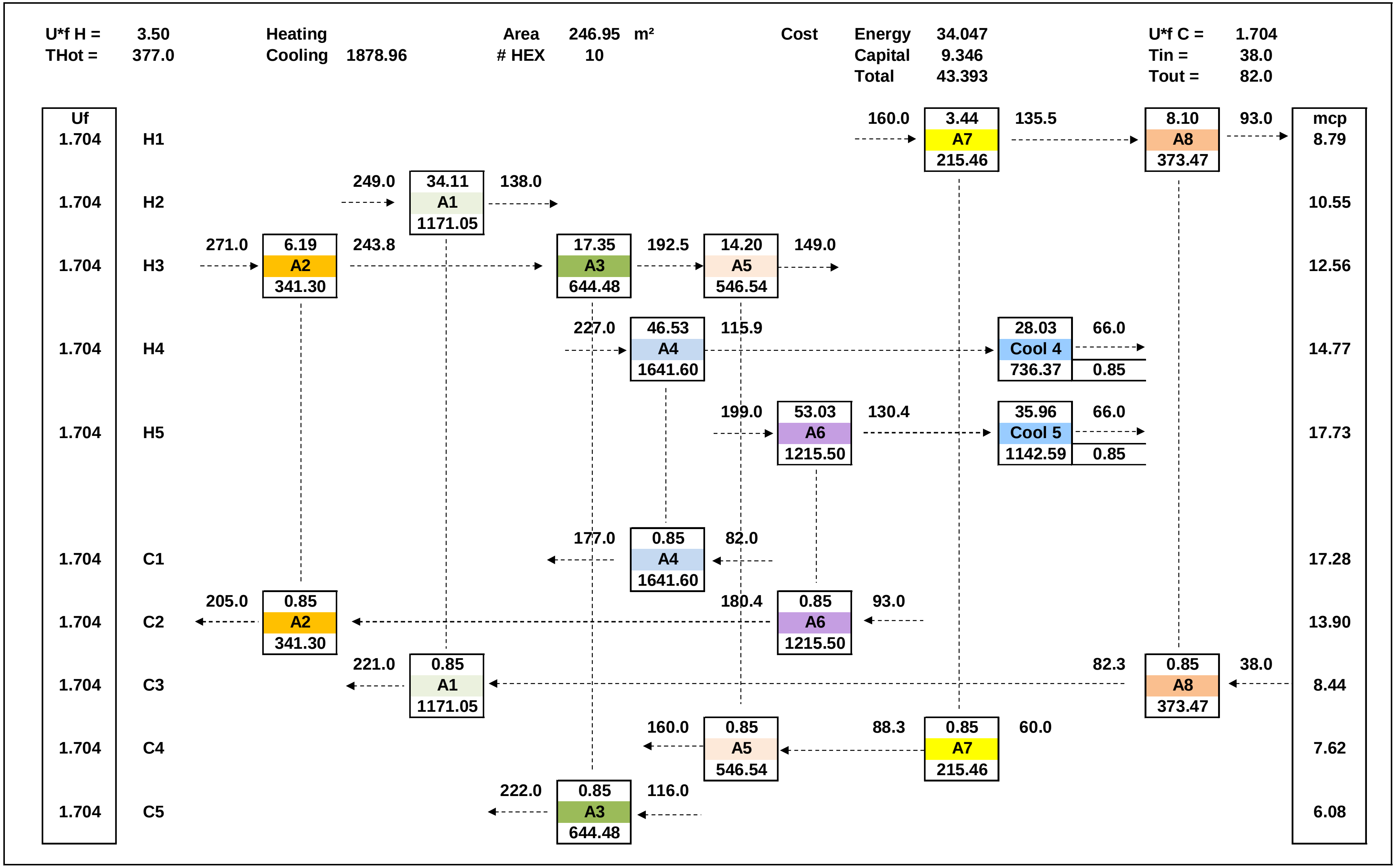
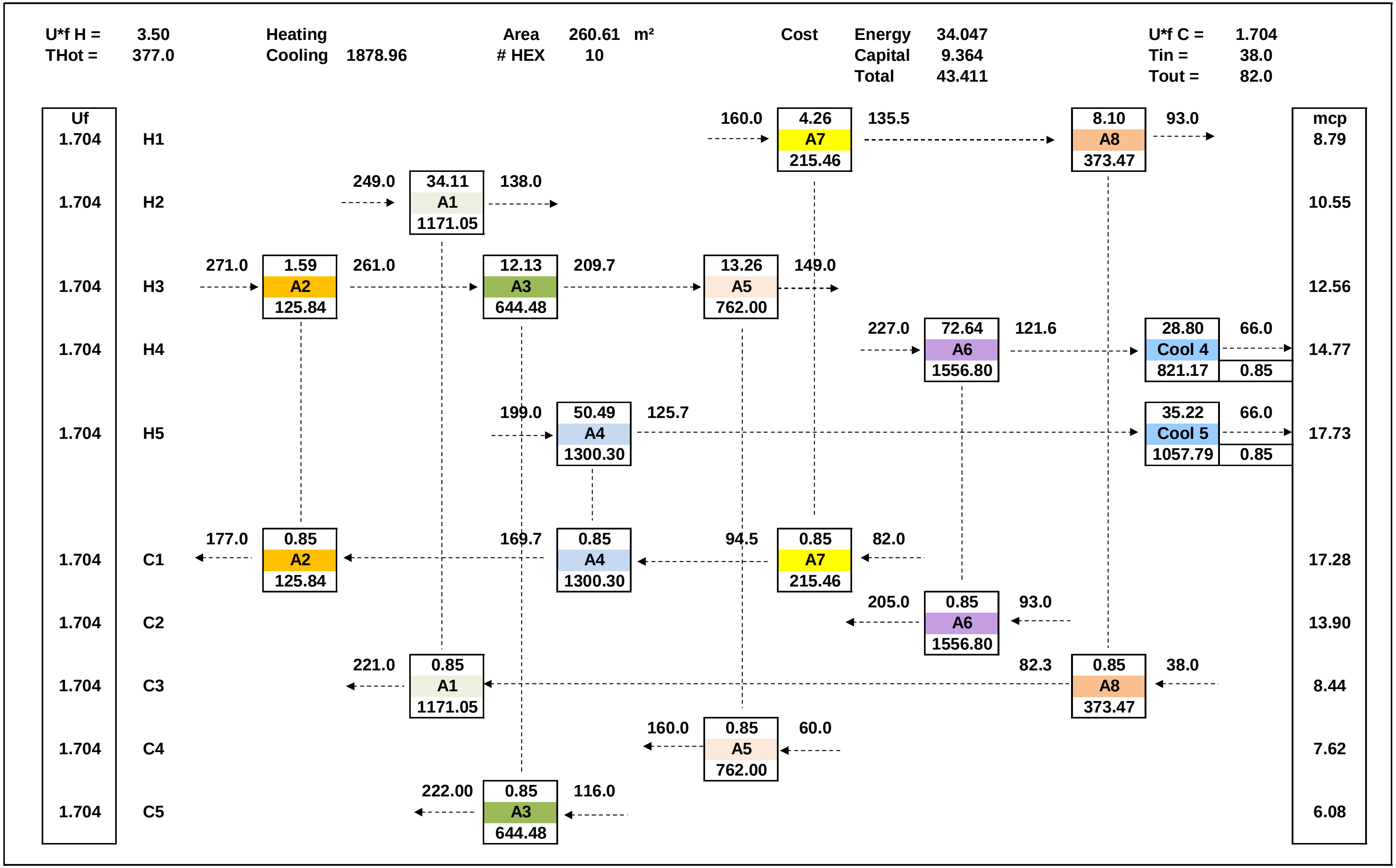

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 246.95 m²
HEX 10
Cost
Energy 34.047
Capital 9.346
Total 43.393
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
1.704 H1
1.704 H2
1.704 H3
1.704 H4
1.704 H5
1.704 C1
1.704 C2
1.704 C3
1.704 C4
1.704 C5
mcp
8.79
10.55
12.56
14.77
17.73
17.28
13.90
8.44
7.62
6.08
160.0
3.44
A7
215.46
135.5
8.10
A8
373.47
93.0
249.0
34.11
A1
1171.05
138.0
271.0
6.19
A2
341.30
243.8
17.35
A3
644.48
192.5
14.20
A5
546.54
149.0
227.0
46.53
A4
1641.60
115.9
28.03
Cool 4
736.37
66.0
0.85
199.0
53.03
A6
1215.50
130.4
35.96
Cool 5
1142.59
66.0
0.85
177.0
0.85
A4
1641.60
82.0
205.0
0.85
A2
341.30
180.4
0.85
A6
1215.50
93.0
221.0
0.85
A1
1171.05
82.3
0.85
A8
373.47
38.0
160.0
0.85
A5
546.54
88.3
0.85
A7
215.46
60.0
222.0
0.85
A3
644.48
116.0

Figure 17.9



U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 260.61 m²
HEX 10
Cost
Energy 34.047
Capital 9.364
Total 43.411
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
1.704 H1 8.79
1.704 H2 10.55
1.704 H3 12.56
1.704 H4 14.77
1.704 H5 17.73
1.704 C1 17.28
1.704 C2 13.90
1.704 C3 8.44
1.704 C4 7.62
1.704 C5 6.08
A1 34.11 1171.05
A2 1.59 125.84
A3 12.13 644.48
A4 50.49 1300.30
A5 13.26 762.00
A6 72.64 1556.80
A7 4.26 215.46
A8 8.10 373.47
Cool 4 28.80 821.17 0.85 66.0
Cool 5 35.22 1057.79 0.85 66.0

Figure 17.10

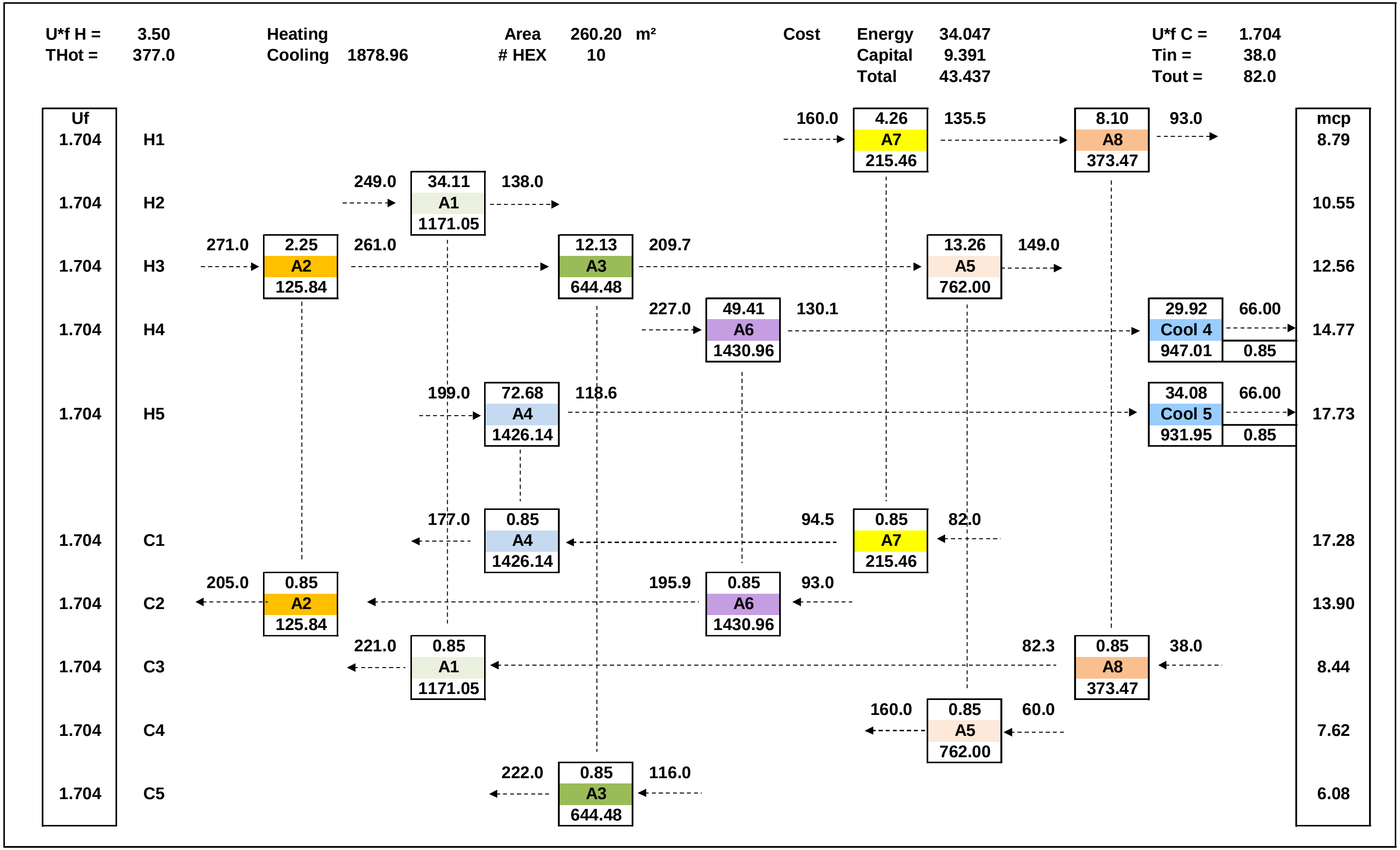

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 260.20 m²
HEX 10
Cost
Energy 34.047
Capital 9.391
Total 43.437
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
H1 1.704 8.79
H2 1.704 10.55
H3 1.704 12.56
H4 1.704 14.77
H5 1.704 17.73
C1 1.704 17.28
C2 1.704 13.90
C3 1.704 8.44
C4 1.704 7.62
C5 1.704 6.08
160.0 4.26 A7 215.46 135.5 8.10 A8 373.47 93.0
249.0 34.11 A1 1171.05 138.0
271.0 2.25 A2 125.84 261.0 12.13 A3 644.48 209.7 13.26 A5 762.00 149.0
227.0 49.41 A6 1430.96 130.1 29.92 Cool 4 947.01 66.00 0.85
199.0 72.68 A4 1426.14 118.6 34.08 Cool 5 931.95 66.00 0.85
177.0 0.85 A4 1426.14 94.5 0.85 A7 215.46 82.0
205.0 0.85 A2 125.84 195.9 0.85 A6 1430.96 93.0
221.0 0.85 A1 1171.05 82.3 0.85 A8 373.47 38.0
160.0 0.85 A5 762.00 60.0
222.0 0.85 A3 644.48 116.0

Figure 17.11

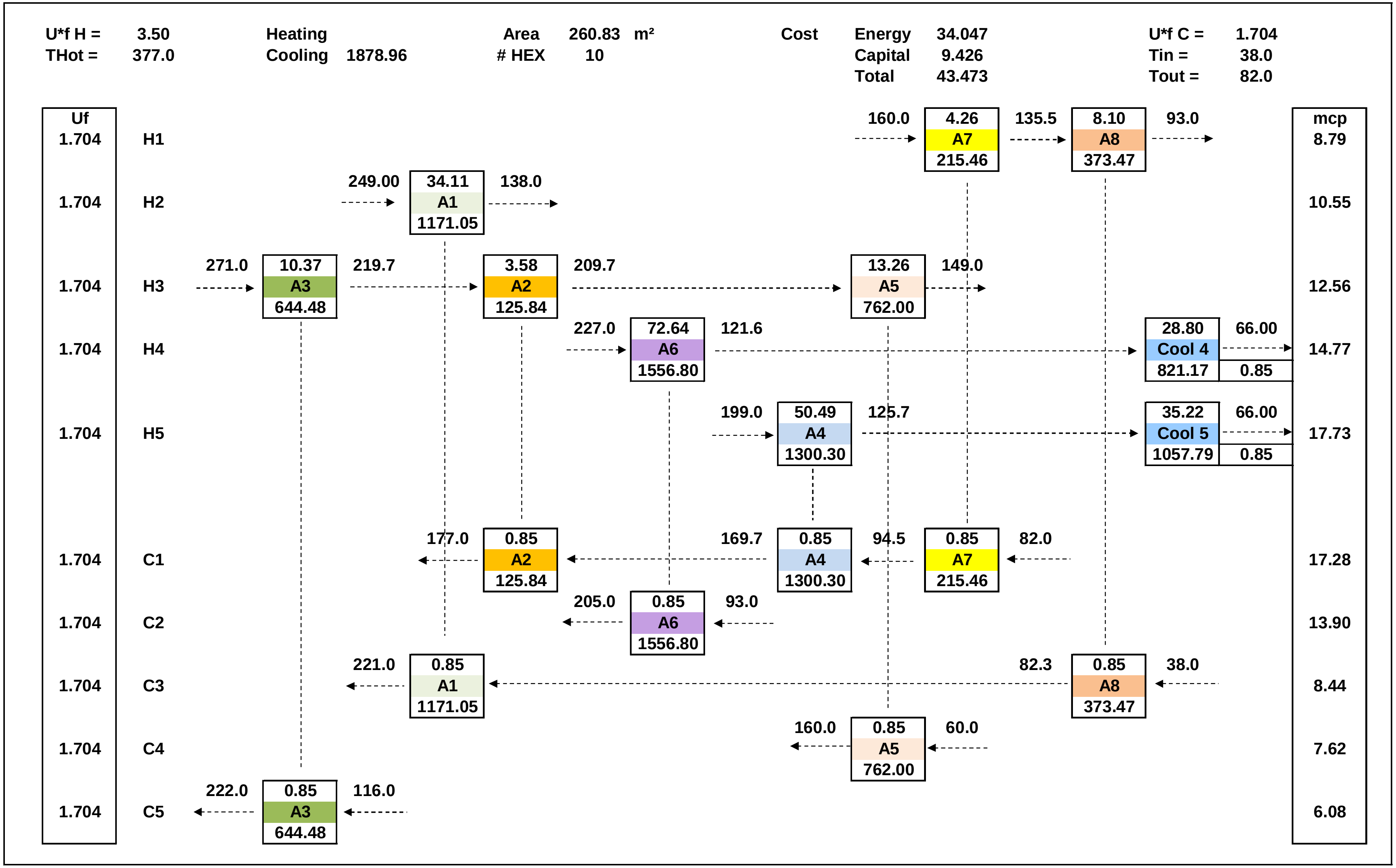

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 260.83 m²
HEX 10
Cost
Energy 34.047
Capital 9.426
Total 43.473
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
H1 1.704 8.79
160.0 4.26 A7 215.46 135.5 8.10 A8 373.47 93.0
H2 1.704 10.55
249.00 34.11 A1 1171.05 138.0
H3 1.704 12.56
271.0 10.37 A3 644.48 219.7 3.58 A2 125.84 209.7 13.26 A5 762.00 149.0
H4 1.704 14.77
227.0 72.64 A6 1556.80 121.6 28.80 Cool 4 821.17 66.00 0.85
H5 1.704 17.73
199.0 50.49 A4 1300.30 125.7 35.22 Cool 5 1057.79 66.00 0.85
C1 1.704 17.28
177.0 0.85 A2 125.84 169.7 0.85 A4 1300.30 94.5 0.85 A7 215.46 82.0
C2 1.704 13.90
205.0 0.85 A6 1556.80 93.0
C3 1.704 8.44
221.0 0.85 A1 1171.05 82.3 0.85 A8 373.47 38.0
C4 1.704 7.62
160.0 0.85 A5 762.00 60.0
C5 1.704 6.08
222.0 0.85 A3 644.48 116.0

Figure 17.12

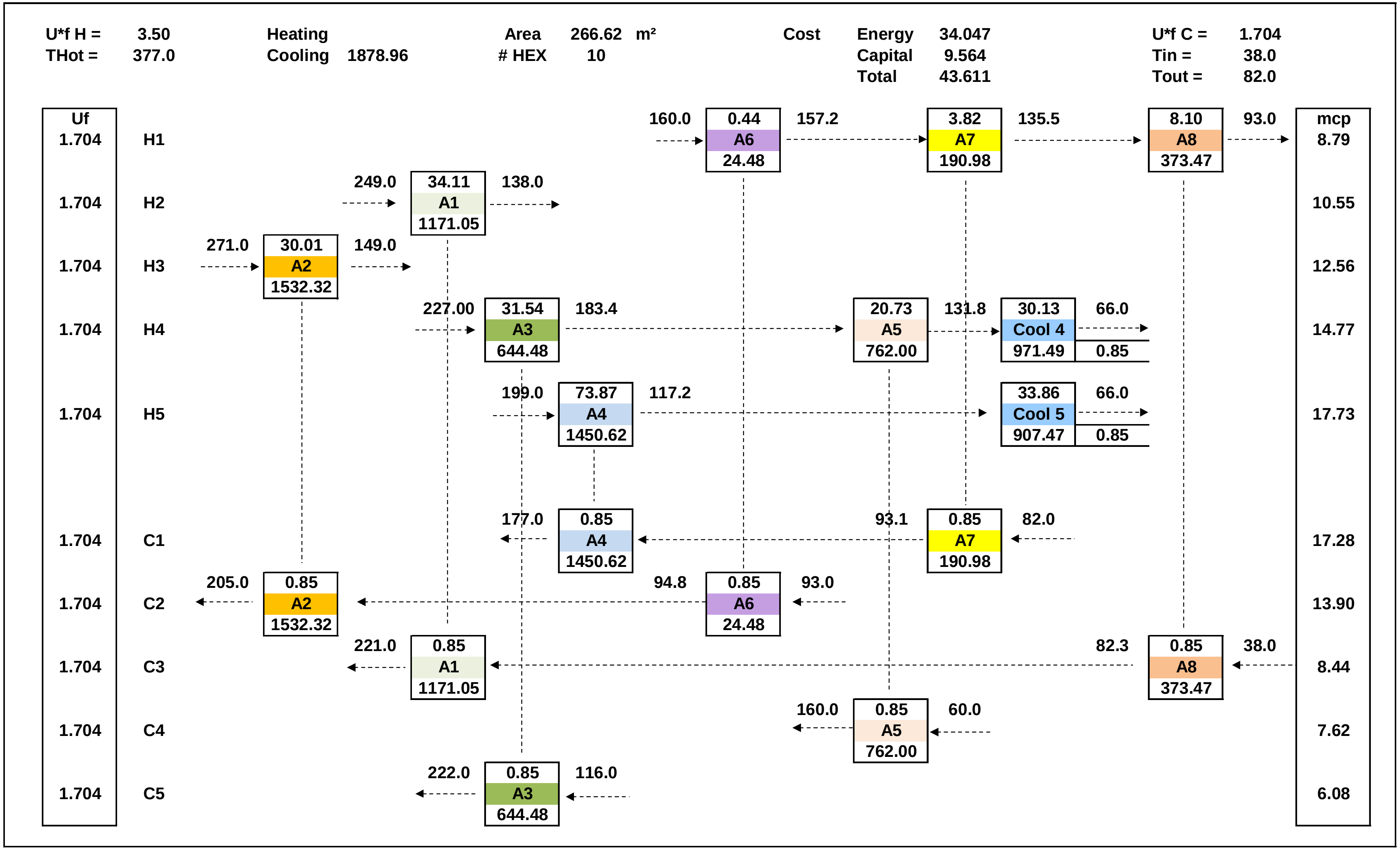

U*f H = 3.50
THot = 377.0
Heating
Cooling 1878.96
Area 266.62 m²
HEX 10
Cost
Energy 34.047
Capital 9.564
Total 43.611
U*f C = 1.704
Tin = 38.0
Tout = 82.0
Uf
mcp
H1
H2
H3
H4
H5
C1
C2
C3
C4
C5
1.704
8.79
10.55
12.56
14.77
17.73
17.28
13.90
8.44
7.62
6.08
160.0
0.44
A6
24.48
157.2
3.82
A7
190.98
135.5
8.10
A8
373.47
93.0
249.0
34.11
A1
1171.05
138.0
271.0
30.01
A2
1532.32
149.0
227.00
31.54
A3
644.48
183.4
20.73
A5
762.00
131.8
30.13
Cool 4
971.49
66.0
0.85
199.0
73.87
A4
1450.62
117.2
33.86
Cool 5
907.47
177.0
93.1
82.0
205.0
94.8
221.0
82.3
38.0
160.0
60.0
222.0
116.0

Figure 17.13