The grid diagram as guidance for synthesizing the heat exchanger network

Example from Castillo et al.

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Case 9 ï Example from Castillo

Case 9 is an example from Castillo et al. (1998), also treated by Ravagnani et al. (2008). The data set is given in Table 9.1. For easy assessment, a temperature scale in °C was used.

Table 9.1

Tsupply °C	Ttarget °C	Heat kW	U*f kW/K,m²	Descript. -	mcp kW/K
840	40	3991.52	1.5	H1	4.9894
76	45	145.20	1.5	H2	4.6840
50	40	7.72	1.5	H3	0.7720
180	77	62.80	1.5	H4	0.6097
180	179	292.70	0.8	H5	292.70
90	45	137.97	1.5	H6	3.0660
24	25	329.80	0.8	C1	329.80
25	70	24.22	1.5	C2	0.5383
35	122	324.25	1.5	C3	3.7270
90	180	54.87	1.5	C4	0.6097
180	181	2581.10	0.8	C5	2581.1
20	40	1323.64	0.8	Cooling	
50	230	250.80	1.0	BFW 30.0 bar	
230	240	591.06	1.5	Steam 30.0 bar	

Area Cost = 9094 + 485 $A^{0.81}$
Hot utility cost (230°C) = 110 /kW,year
Cold utility cost = 15 /kW,year
Steam credit = 110 /kW,year (enthalpy above 230°C)

The example is a threshold problem requiring cooling only, as illustrated by Composite Curves and Grand Composite in Fig. 9.1 and Fig. 9.2,

The impact of the differences in heat transfer values is negligible. Target cost is 141 859 with an area of 63.13 m².

The shape of the composite curves would suggest to looking into the hot and cold streams at the 180°C temperature level. If adjustment of the levels in view of direct integration is not possible, then a heat pump would be conceivable. Another measure would be to generate MP steam to valorize the high temperature waste heat (Grand Composite Fig. 9.3). Even with the apparently small heat loads, more than 1.0 t/h of steam could be generated; this will be analyzed in a second step.

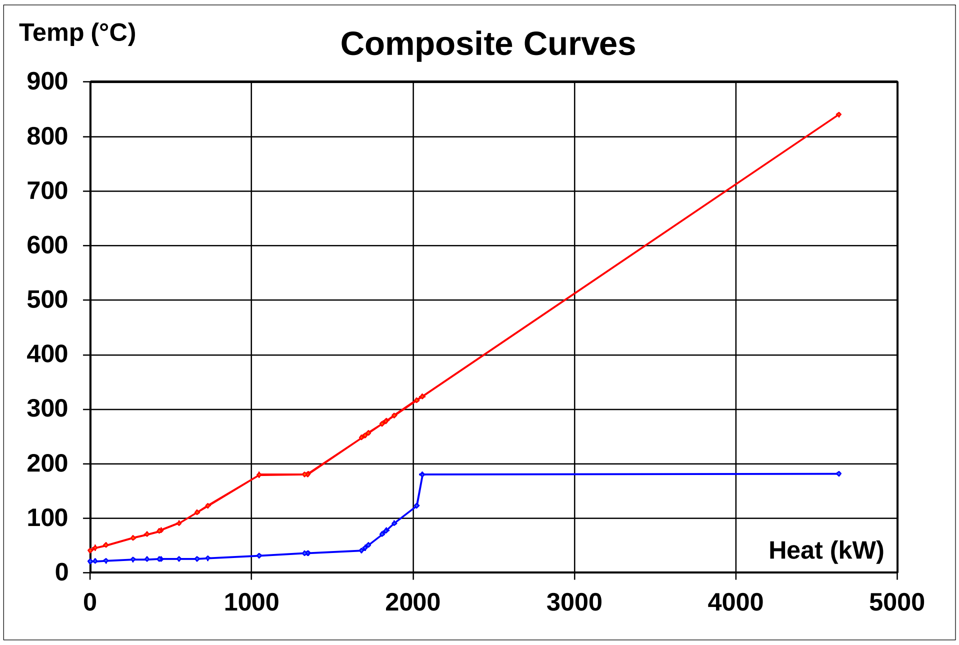

Fig. 9.1

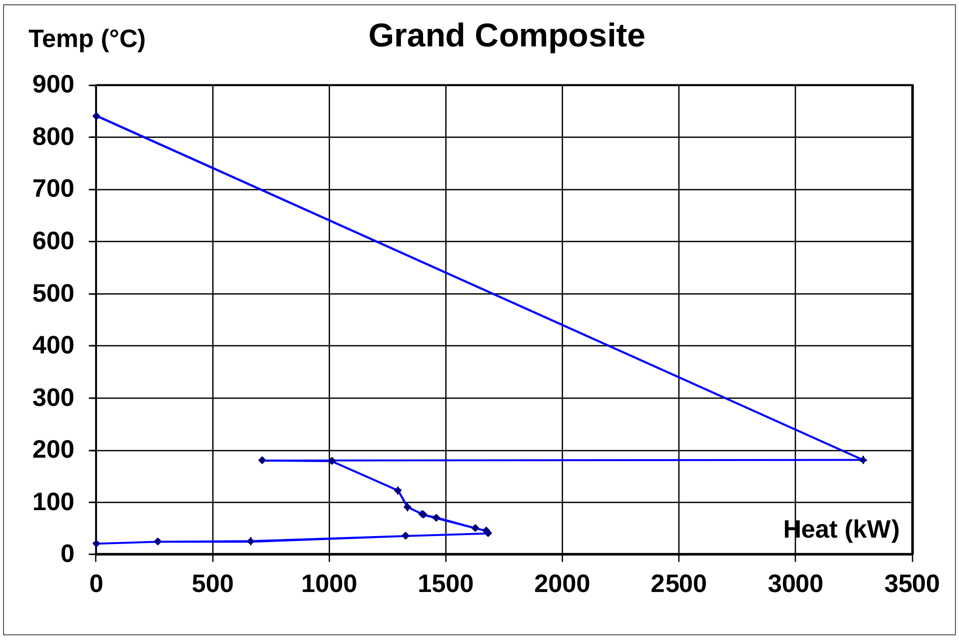

Fig. 9.2

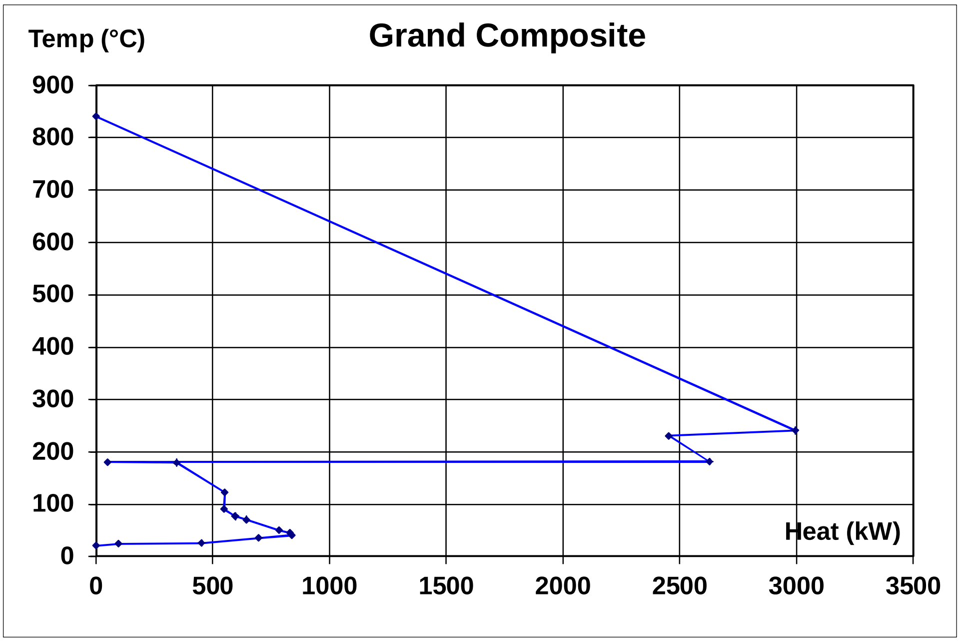

Fig. 9.3

For solving the problem, Ravagnani used a technique called Particle Swarm Optimization and produced a network that was marginally better than the network of Castillo, albeit with two stream splits. With the techniques applied here, further marginal improvements were obtained with networks with and without stream splits.

Base Case ï tick-off procedure

In view of the large driving forces and the small heat loads with an overweight of fixed cost, expectedly only a network with the minimum number of units would qualify as a valuable candidate.

On the basis of the heat balance, a cooler on hot stream H1 is mandatory with a minimum load of 677.27 kW; if that cooler is imposed then all other hot streams shall be fully cooled down with coolers as shown in Fig.9.4, a network with a cost of 140 775.

Since the average temperature of cold stream C1 is lower than the average temperature of the cold utility, it will be advantageous to pick up the heat of utility cooled hot streams and to put it into cold stream C1; area and cost will drop. The sequence is determined by the position of the streams in the grid diagram. Once cold stream C1 is satisfied, this synthesis can be continued for the other cold streams in a sequence taking the (section of the) cold stream with the coldest supply temperature first; the resulting network is shown in Fig. 9.5 (cost 139 410).

An alternative would be to put all cooling on hot stream H1 right from the start and to integrate the other hot streams with the cold streams starting from the cold end pinch and applying the same sequence as before. The resulting network is identical with that obtained before.

In any case, the position of the streams in the grid diagram generated by the pinch analysis is determining the sequence of integration and is guiding the tick-off procedure successfully.

Base Case ï automated design procedure

The grid diagram can also be used as input for an initial design. If all cooling is concentrated on hot stream H1, the grid would be composed of 14 vertical integration bands (Table 9.3) which, using a simple LP program would result into a network with 25 exchangers plus 1 cooler (Fig.9.6). With incremental evolution, this network will automatically evolve into the network shown in Fig. 9.7 (cost 139 407). Merging bands in the grid diagram would lead to more stream splits which may further reduce the cost marginally. Removing the stream split on cold stream C1 in Fig. 9.7 would increase the cost to 139 419; consequently, the network of Fig. 9.5 is better, the only difference being the position of exchanger A4.

Base Case ï fine tuning

The network in Fig. 9.5 without steam splits is considered as the best network so far; further improvements by fine tuning and acceptance of stream splits as shown in the final networks in Fig.9.8 through Fig. 9.10 remain marginal.

Heat recovery case

Also the case with heat recovery by steam generation has been analyzed. It is possible to generate 1.16 t/h of 30 bar steam and to reduce the annual cost with more than 35 %. Application of the same procedures as in the base case leads to the networks as shown in Fig. 9.11 through Fig. 9.13. It should be noted, however, that the heat recovery will create a process pinch that will have to be taken into account when defining the sequences.

The results for the different cases can be compared in Table 9.2.

Only networks with one single cooler on hot stream H1 were retained. However, additional coolers can be accepted on various hot streams with only a very small cost penalty. A (very) large number of networks can be developed with a cost below target; this is the consequence of the degression exponent in the area cost function that works out favorably for very unequal heat exchanger areas.

Table 9.2

		Castillo	Ravagnani	This research			
# of Stream splits	-	(?)	2	2	1	0	target
Area	m^2	(?)	66.18	64.78	64.80	64.59	63.13
TotalCost	'000/y	141.55	140.14	139.40	139.40	139.41	141.86
With steam recovery							
Area	m^2			93.47	93.50	95.73	93.06
Cost	'000/y			152.88	152.88	153.41	156.94
Steam credit	'000/y			65.02	65.02	65.02	65.02
Net cost	'000/y			87.86	87.87	88.39	91.92

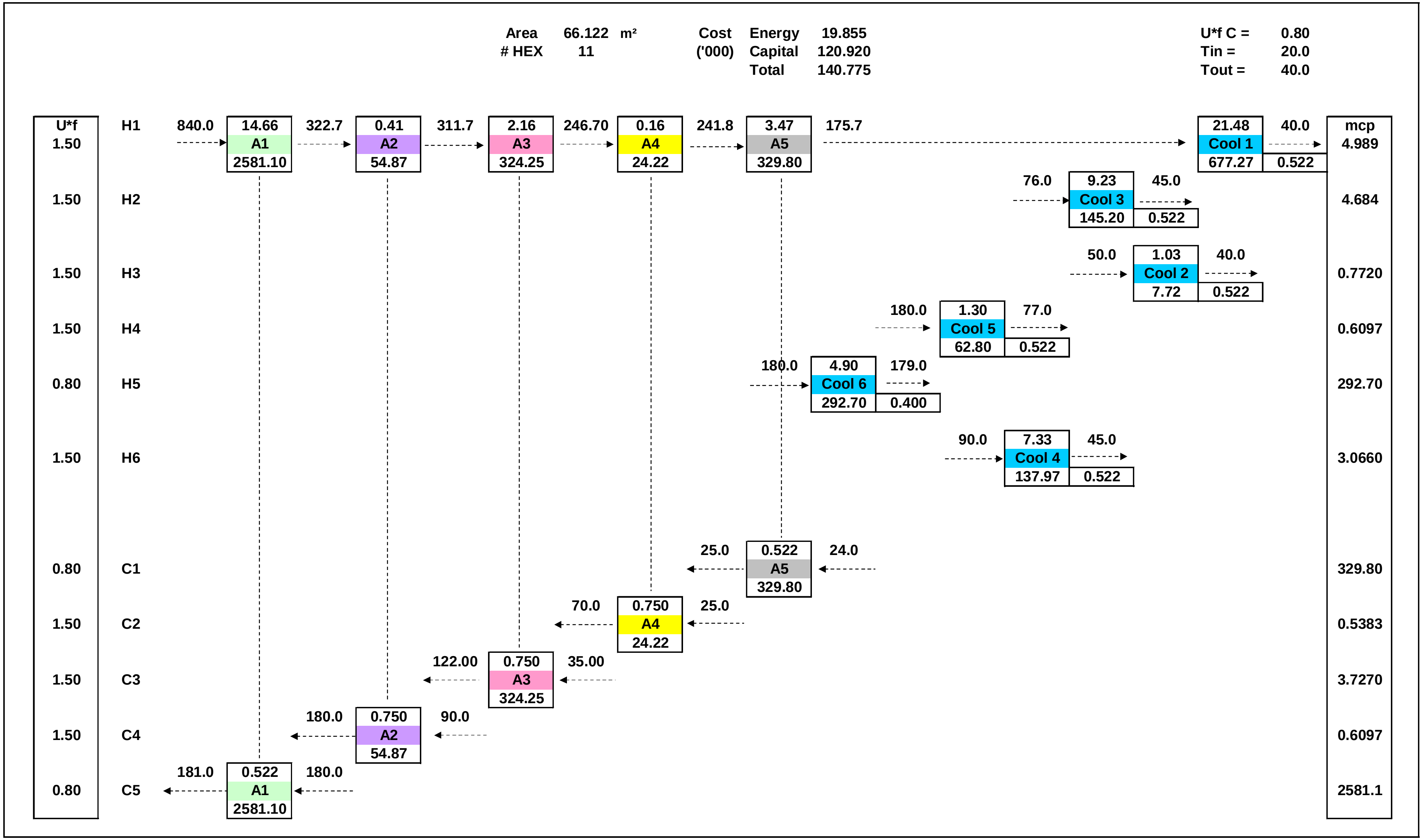
Area 66.122 m²
HEX 11
Cost ('000)
Energy 19.855
Capital 120.920
Total 140.775
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
1.50 H1 840.0 14.66 A1 2581.10 322.7 0.41 A2 54.87 311.7 2.16 A3 324.25 246.70 0.16 A4 24.22 241.8 3.47 A5 329.80 175.7 21.48 Cool 1 677.27 40.0 0.522 4.989
1.50 H2 76.0 9.23 Cool 3 145.20 45.0 0.522 4.684
1.50 H3 50.0 1.03 Cool 2 7.72 40.0 0.522 0.7720
1.50 H4 180.0 1.30 Cool 5 62.80 77.0 0.522 0.6097
0.80 H5 180.0 4.90 Cool 6 292.70 179.0 0.400 292.70
1.50 H6 90.0 7.33 Cool 4 137.97 45.0 0.522 3.0660
0.80 C1 25.0 0.522 A5 329.80 24.0 329.80
1.50 C2 70.0 0.750 A4 24.22 25.0 0.5383
1.50 C3 122.00 0.750 A3 324.25 35.00 3.7270
1.50 C4 180.0 0.750 A2 54.87 90.0 0.6097
0.80 C5 181.0 0.522 A1 2581.10 180.0 2581.1

Fig. 9.4

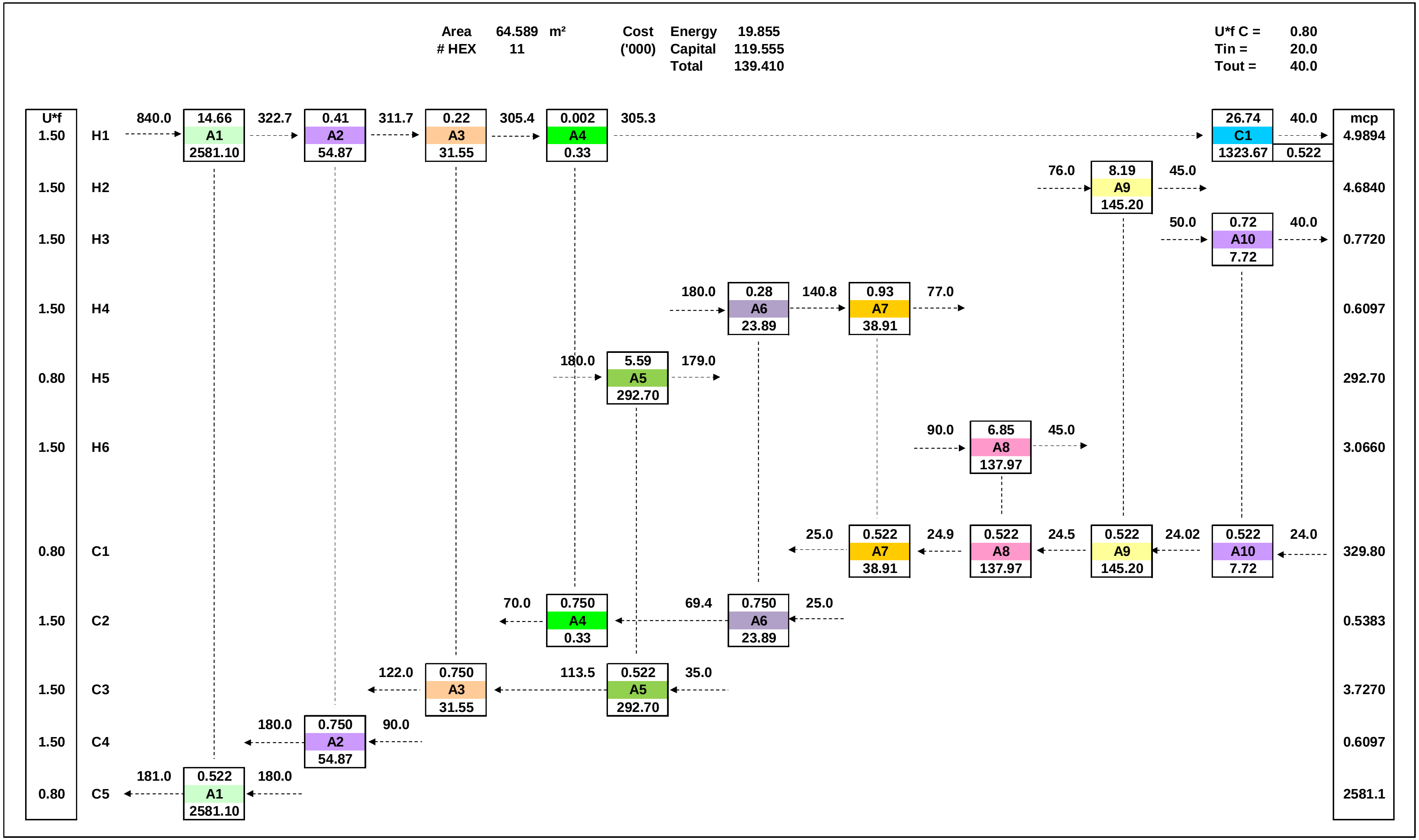
Area 64.589 m²
HEX 11
Cost ('000)
Energy 19.855
Capital 119.555
Total 139.410
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
1.50 H1 840.0 14.66 A1 2581.10 322.7 0.41 A2 54.87 311.7 0.22 A3 31.55 305.4 0.002 A4 0.33 305.3 26.74 C1 1323.67 40.0 0.522 4.9894
1.50 H2 76.0 8.19 A9 145.20 45.0 4.6840
1.50 H3 50.0 0.72 A10 7.72 40.0 0.7720
1.50 H4 180.0 0.28 A6 23.89 140.8 0.93 A7 38.91 77.0 0.6097
0.80 H5 180.0 5.59 A5 292.70 179.0 292.70
1.50 H6 90.0 6.85 A8 137.97 45.0 3.0660
0.80 C1 25.0 0.522 A7 38.91 24.9 0.522 A8 137.97 24.5 0.522 A9 145.20 24.02 0.522 A10 7.72 24.0 329.80
1.50 C2 70.0 0.750 A4 0.33 69.4 0.750 A6 23.89 25.0 0.5383
1.50 C3 122.0 0.750 A3 31.55 113.5 0.522 A5 292.70 35.0 3.7270
1.50 C4 180.0 0.750 A2 54.87 90.0 0.6097
0.80 C5 181.0 0.522 A1 2581.10 180.0 2581.1

Fig. 9.5

Table 9.3

Descript. -	1	2	3	4	5	6	7	8	9	10	11	12	13	14		mcp kW/K
H1	840.0	322.7	315.6	305.3												4.9894
H2												76.0	50.0	45.0		4.6840
H3													50.0	45.0	40.0	0.7720
H4				180.0	179.7	179.4	179.0	149.6	140.8	90.0	77.0					0.6097
H5				180.0	179.7	179.4	179.0									292.70
H6										90.0	77.0	76.0	50.0	45.0		3.0660
C1									25.0	24.9	24.8	24.8	24.1	24.01	24.0	329.80
C2						70.0	39.2	35.0	25.0							0.5383
C3			122.0	110.2	90.0	70.0	39.2	35.0								3.7270
C4		180.0	122.0	110.2	90.0											0.6097
C5	181.0	180.0														2581.10

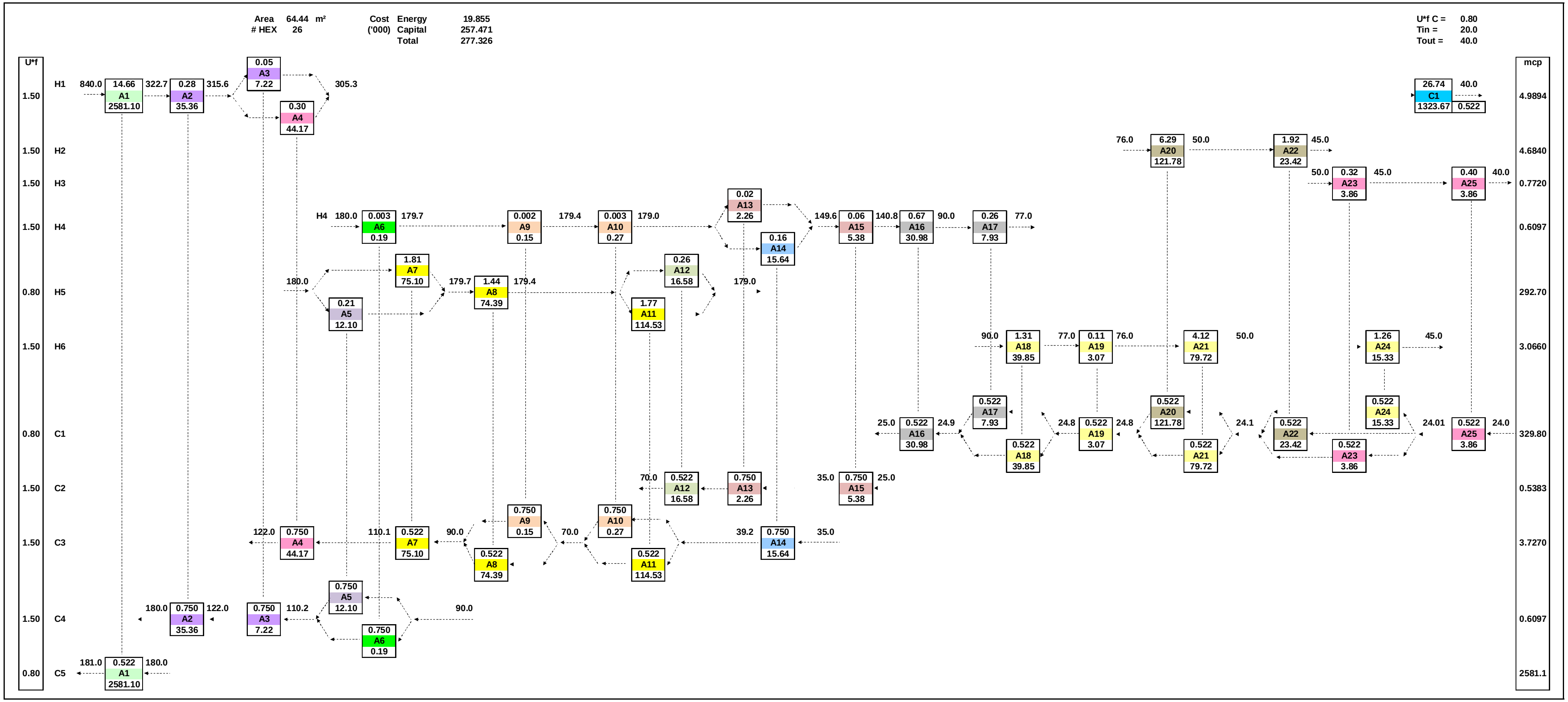
Area 64.44 m²
HEX 26
Cost ('000) Energy 19.855
Capital 257.471
Total 277.326
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
H1 1.50 4.9894
840.0 14.66 A1 2581.10 322.7 0.28 A2 35.36 315.6
0.05 A3 7.22
0.30 A4 44.17
305.3
26.74 C1 1323.67 0.522 40.0
H2 1.50 4.6840
76.0 6.29 A20 121.78 50.0 1.92 A22 23.42 45.0
H3 1.50 0.7720
50.0 0.32 A23 3.86 45.0 0.40 A25 3.86 40.0
H4 1.50 0.6097
H4 180.0 0.003 A6 0.19 179.7 0.002 A9 0.15 179.4 0.003 A10 0.27 179.0
0.02 A13 2.26
0.16 A14 15.64
149.6 0.06 A15 5.38 140.8 0.67 A16 30.98 90.0 0.26 A17 7.93 77.0
H5 0.80 292.70
180.0 1.81 A7 75.10 179.7 1.44 A8 74.39 179.4
0.21 A5 12.10
0.26 A12 16.58
1.77 A11 114.53
179.0
H6 1.50 3.0660
90.0 1.31 A18 39.85 77.0 0.11 A19 3.07 76.0 4.12 A21 79.72 50.0 1.26 A24 15.33 45.0
C1 0.80 329.80
0.522 A17 7.93
0.522 A20 121.78
0.522 A24 15.33
25.0 0.522 A16 30.98 24.9
0.522 A18 39.85
24.8 0.522 A19 3.07 24.8
0.522 A21 79.72
24.1
0.522 A22 23.42
0.522 A23 3.86
24.01 0.522 A25 3.86 24.0
C2 1.50 0.5383
70.0 0.522 A12 16.58 0.750 A13 2.26
35.0 0.750 A15 5.38 25.0
C3 1.50 3.7270
0.750 A9 0.15
0.750 A10 0.27
122.0 0.750 A4 44.17 110.1 0.522 A7 75.10 90.0
0.522 A8 74.39
70.0
0.522 A11 114.53
39.2 0.750 A14 15.64 35.0
C4 1.50 0.6097
0.750 A5 12.10
180.0 0.750 A2 35.36 122.0 0.750 A3 7.22 110.2
0.750 A6 0.19
90.0
C5 0.80 2581.1
181.0 0.522 A1 2581.10 180.0

Fig. 9.6

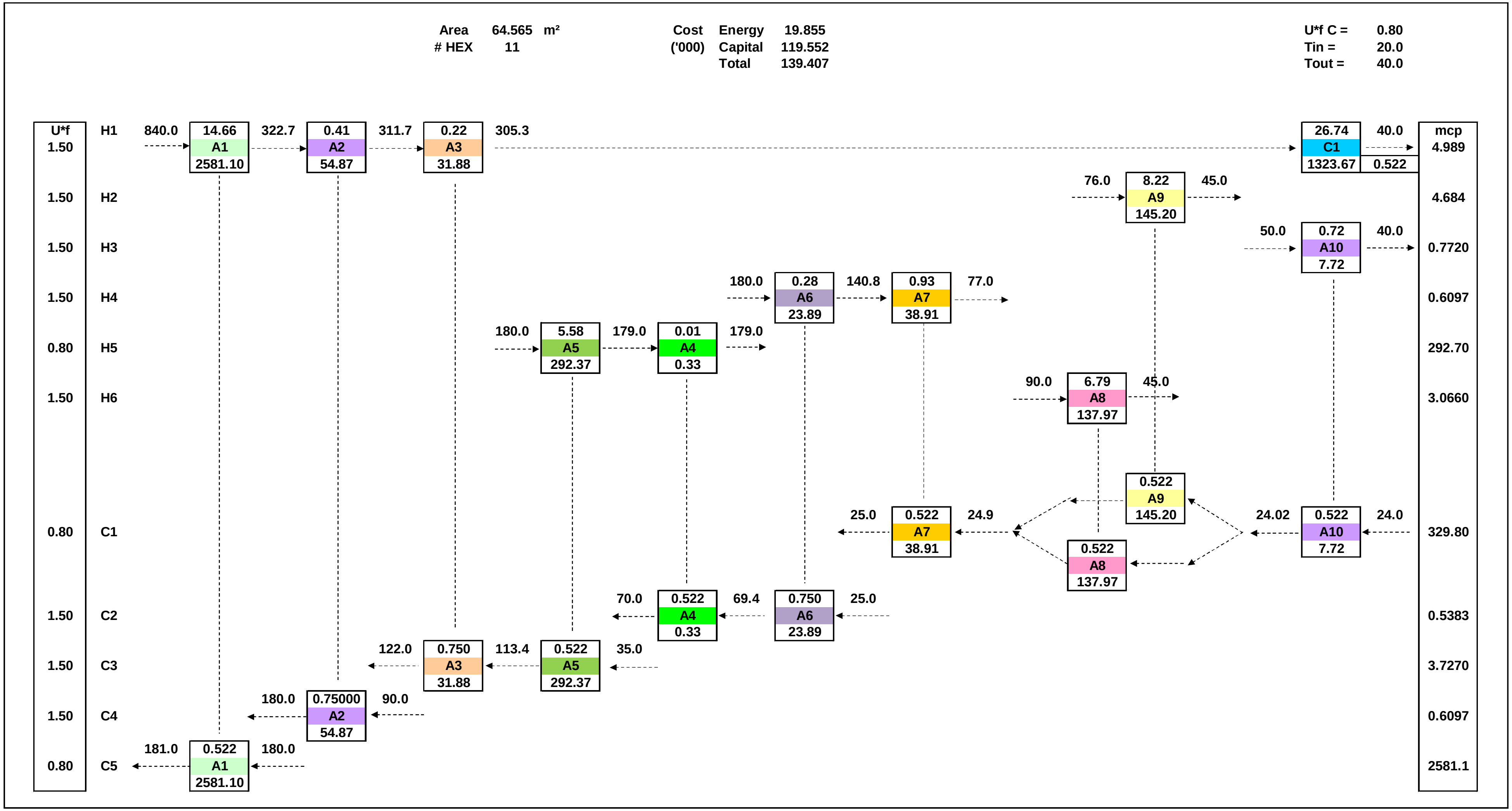
Area 64.565 m²
HEX 11
Cost ('000)
Energy 19.855
Capital 119.552
Total 139.407
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
1.50 H1
1.50 H2
1.50 H3
1.50 H4
0.80 H5
1.50 H6
0.80 C1
1.50 C2
1.50 C3
1.50 C4
0.80 C5
mcp
4.989
4.684
0.7720
0.6097
292.70
3.0660
329.80
0.5383
3.7270
0.6097
2581.1
840.0
14.66 A1 2581.10
322.7
0.41 A2 54.87
311.7
0.22 A3 31.88
305.3
26.74 C1 1323.67
40.0
0.522
76.0
8.22 A9 145.20
45.0
50.0
0.72 A10 7.72
40.0
180.0
0.28 A6 23.89
140.8
0.93 A7 38.91
77.0
180.0
5.58 A5 292.37
179.0
0.01 A4 0.33
179.0
90.0
6.79 A8 137.97
45.0
0.522 A9 145.20
25.0
0.522 A7 38.91
24.9
24.02
0.522 A10 7.72
24.0
0.522 A8 137.97
70.0
0.522 A4 0.33
69.4
0.750 A6 23.89
25.0
122.0
0.750 A3 31.88
113.4
0.522 A5 292.37
35.0
180.0
0.75000 A2 54.87
90.0
181.0
0.522 A1 2581.10
180.0

Fig. 9.7

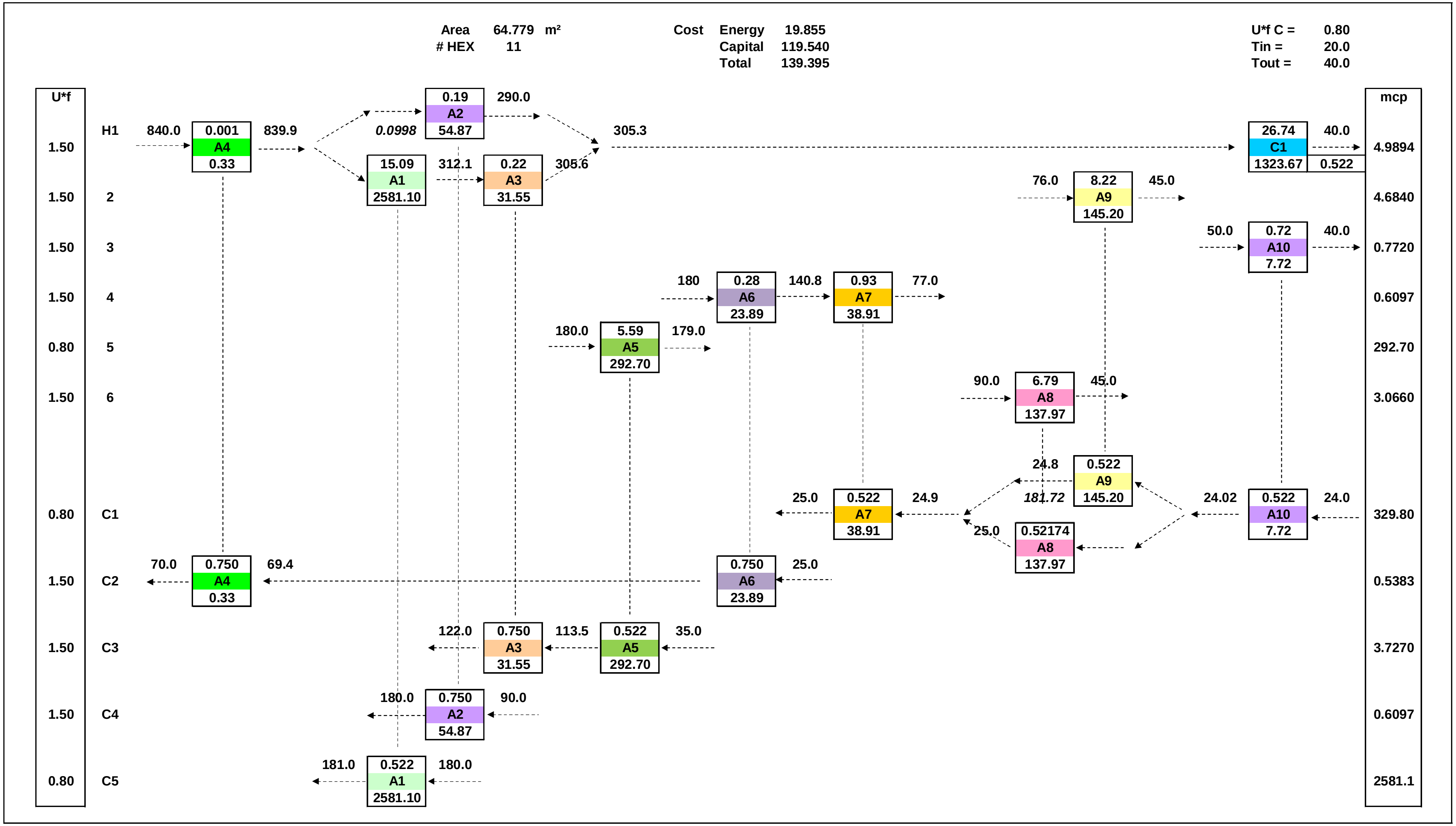
Area 64.779 m²
HEX 11
Cost Energy 19.855
Capital 119.540
Total 139.395
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
0.19
A2
54.87
290.0
H1
840.0
0.001
A4
0.33
839.9
0.0998
305.3
26.74
C1
1323.67
40.0
0.522
1.50
4.9894
15.09
A1
2581.10
312.1
0.22
A3
31.55
305.6
2
1.50
4.6840
76.0
8.22
A9
145.20
45.0
3
1.50
0.7720
50.0
0.72
A10
7.72
40.0
4
1.50
0.6097
180
0.28
A6
23.89
140.8
0.93
A7
38.91
77.0
5
0.80
292.70
180.0
5.59
A5
292.70
179.0
6
1.50
3.0660
90.0
6.79
A8
137.97
45.0
C1
0.80
329.80
24.8
0.522
A9
145.20
181.72
25.0
0.522
A7
38.91
24.9
24.02
0.522
A10
7.72
24.0
25.0
0.52174
A8
137.97
C2
1.50
0.5383
70.0
0.750
A4
0.33
69.4
0.750
A6
23.89
25.0
C3
1.50
3.7270
122.0
0.750
A3
31.55
113.5
0.522
A5
292.70
35.0
C4
1.50
0.6097
180.0
0.750
A2
54.87
90.0
C5
0.80
2581.1
181.0
0.522
A1
2581.10
180.0

Fig. 9.8

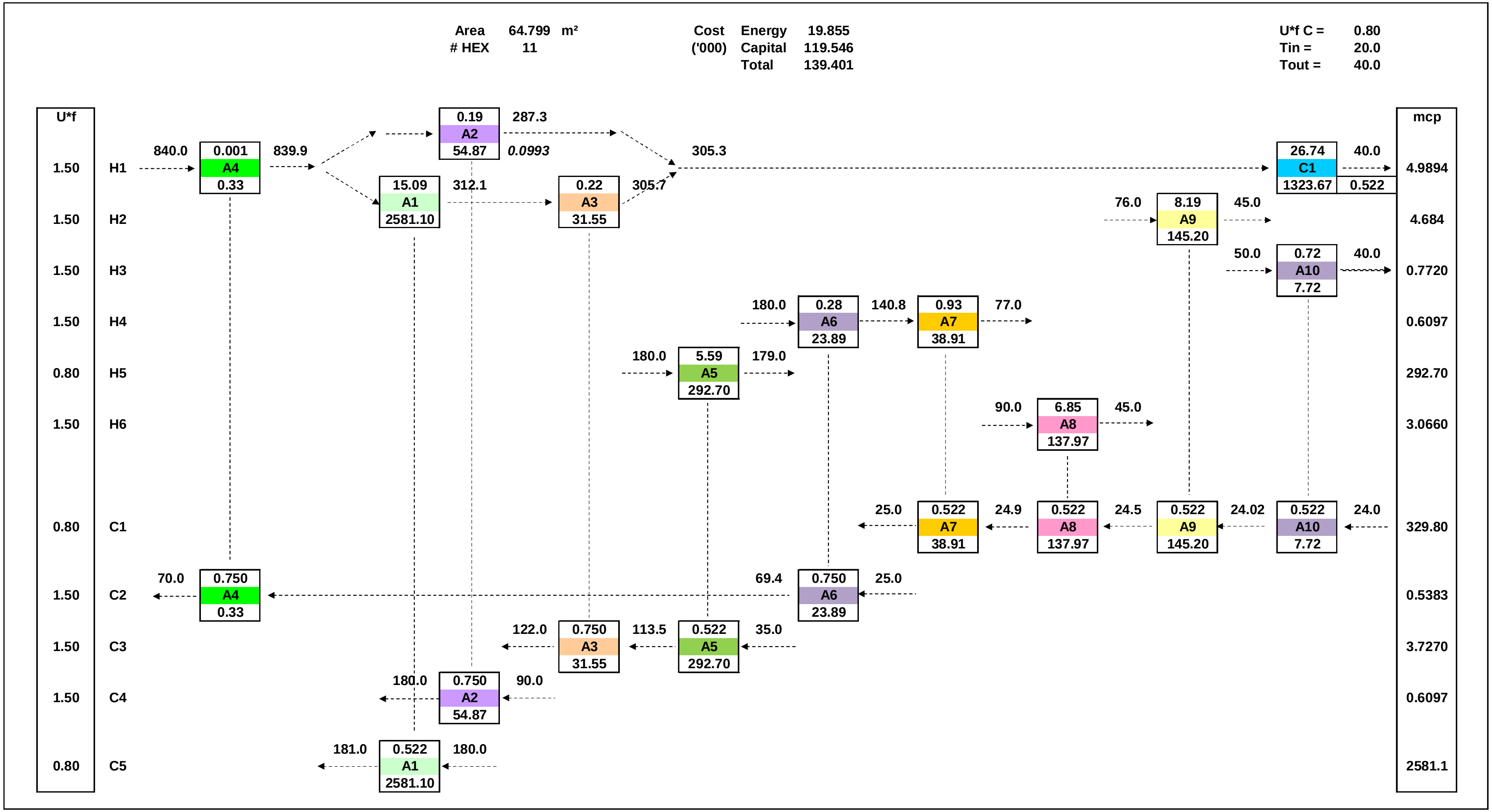
Area 64.799 m²
HEX 11
Cost ('000)
Energy 19.855
Capital 119.546
Total 139.401
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
1.50 H1 4.9894
1.50 H2 4.684
1.50 H3 0.7720
1.50 H4 0.6097
0.80 H5 292.70
1.50 H6 3.0660
0.80 C1 329.80
1.50 C2 0.5383
1.50 C3 3.7270
1.50 C4 0.6097
0.80 C5 2581.1
840.0
0.001
A4
0.33
839.9
0.19
A2
54.87
287.3
0.0993
15.09
A1
2581.10
312.1
0.22
A3
31.55
305.7
305.3
26.74
C1
1323.67
40.0
0.522
76.0
8.19
A9
145.20
45.0
50.0
0.72
A10
7.72
40.0
180.0
0.28
A6
23.89
140.8
0.93
A7
38.91
77.0
180.0
5.59
A5
292.70
179.0
90.0
6.85
A8
137.97
45.0
25.0
0.522
A7
38.91
24.9
0.522
A8
137.97
24.5
0.522
A9
145.20
24.02
0.522
A10
7.72
24.0
70.0
0.750
A4
0.33
69.4
0.750
A6
23.89
25.0
122.0
0.750
A3
31.55
113.5
0.522
A5
292.70
35.0
180.0
0.750
A2
54.87
90.0
181.0
0.522
A1
2581.10
180.0

Fig. 9.9

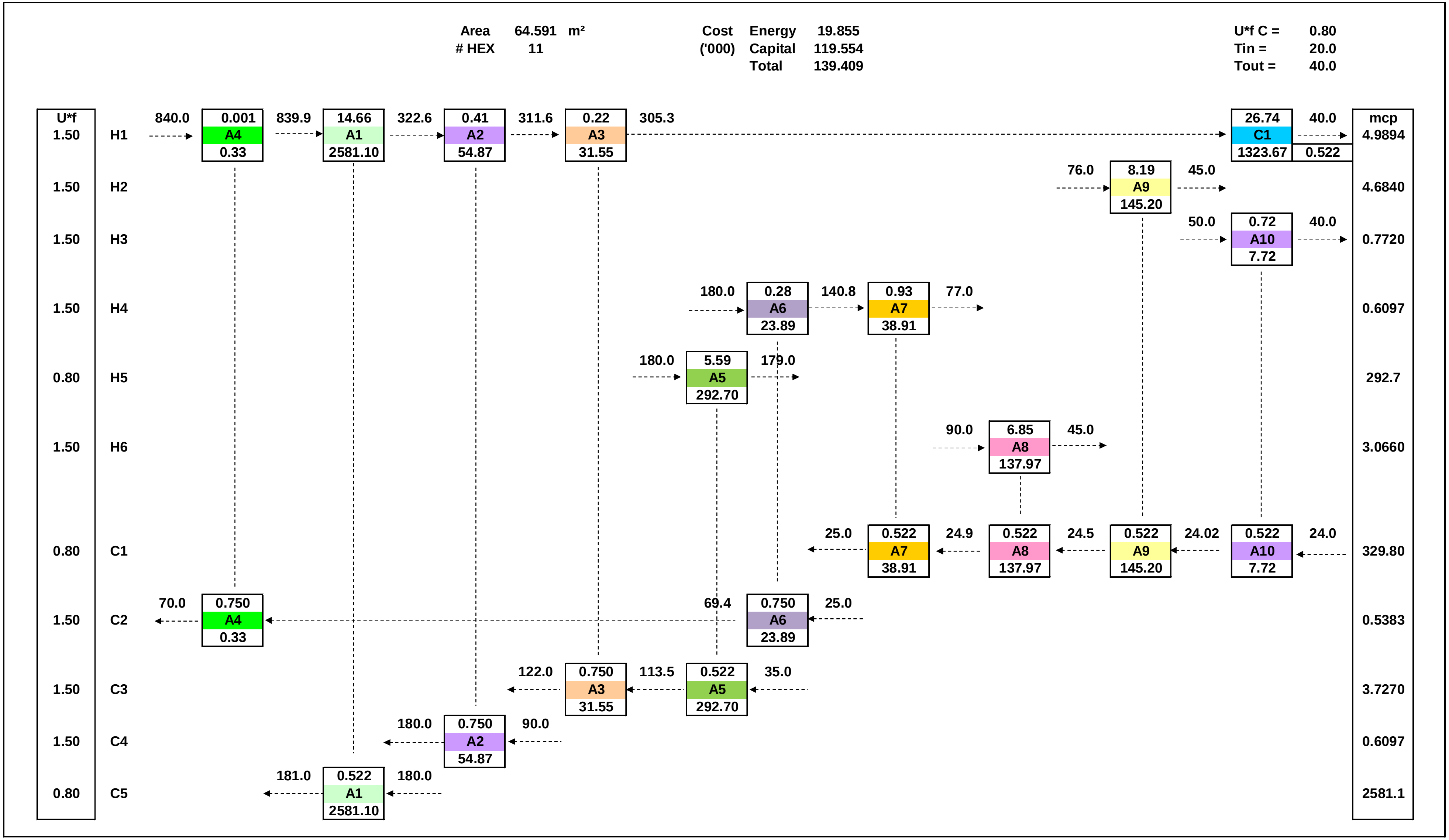
Area 64.591 m²
HEX 11
Cost ('000)
Energy 19.855
Capital 119.554
Total 139.409
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
1.50 H1 4.9894
840.0
0.001 A4 0.33
839.9
14.66 A1 2581.10
322.6
0.41 A2 54.87
311.6
0.22 A3 31.55
305.3
26.74 C1 1323.67
40.0
0.522
1.50 H2 4.6840
76.0
8.19 A9 145.20
45.0
1.50 H3 0.7720
50.0
0.72 A10 7.72
40.0
1.50 H4 0.6097
180.0
0.28 A6 23.89
140.8
0.93 A7 38.91
77.0
0.80 H5 292.7
180.0
5.59 A5 292.70
179.0
1.50 H6 3.0660
90.0
6.85 A8 137.97
45.0
0.80 C1 329.80
25.0
0.522 A7 38.91
24.9
0.522 A8 137.97
24.5
0.522 A9 145.20
24.02
0.522 A10 7.72
24.0
1.50 C2 0.5383
70.0
0.750 A4 0.33
69.4
0.750 A6 23.89
25.0
1.50 C3 3.7270
122.0
0.750 A3 31.55
113.5
0.522 A5 292.70
35.0
1.50 C4 0.6097
180.0
0.750 A2 54.87
90.0
0.80 C5 2581.1
181.0
0.522 A1 2581.10
180.0

Fig. 9.10

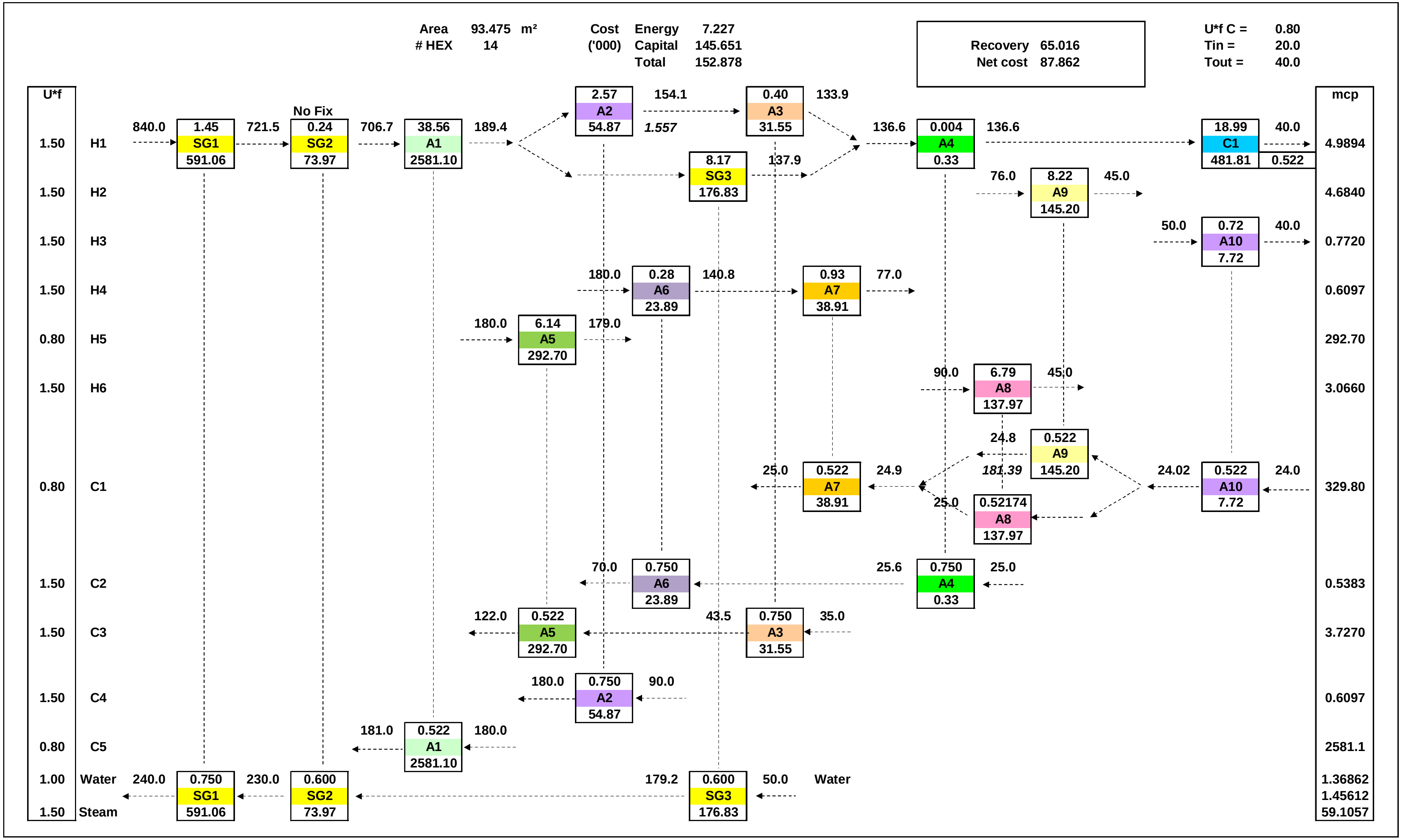
Area 93.475 m²
HEX 14
Cost ('000)
Energy 7.227
Capital 145.651
Total 152.878
Recovery 65.016
Net cost 87.862
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
1.50 H1 4.9894
1.50 H2 4.6840
1.50 H3 0.7720
1.50 H4 0.6097
0.80 H5 292.70
1.50 H6 3.0660
0.80 C1 329.80
1.50 C2 0.5383
1.50 C3 3.7270
1.50 C4 0.6097
0.80 C5 2581.1
1.00 Water 1.36862
1.50 Steam 1.45612
59.1057
840.0
1.45 SG1 591.06
721.5
No Fix
0.24 SG2 73.97
706.7
38.56 A1 2581.10
189.4
2.57 A2 54.87
154.1
1.557
0.40 A3 31.55
133.9
8.17 SG3 176.83
137.9
136.6
0.004 A4 0.33
136.6
18.99 C1 481.81
0.522
40.0
76.0
8.22 A9 145.20
45.0
50.0
0.72 A10 7.72
40.0
180.0
0.28 A6 23.89
140.8
0.93 A7 38.91
77.0
180.0
6.14 A5 292.70
179.0
90.0
6.79 A8 137.97
45.0
24.8
0.522 A9 145.20
181.39
25.0
0.522 A7 38.91
24.9
25.0
0.52174 A8 137.97
24.02
0.522 A10 7.72
24.0
70.0
0.750 A6 23.89
25.6
0.750 A4 0.33
25.0
122.0
0.522 A5 292.70
43.5
0.750 A3 31.55
35.0
180.0
0.750 A2 54.87
90.0
181.0
0.522 A1 2581.10
180.0
240.0
0.750 SG1 591.06
230.0
0.600 SG2 73.97
179.2
0.600 SG3 176.83
50.0
Water

Fig. 9.11

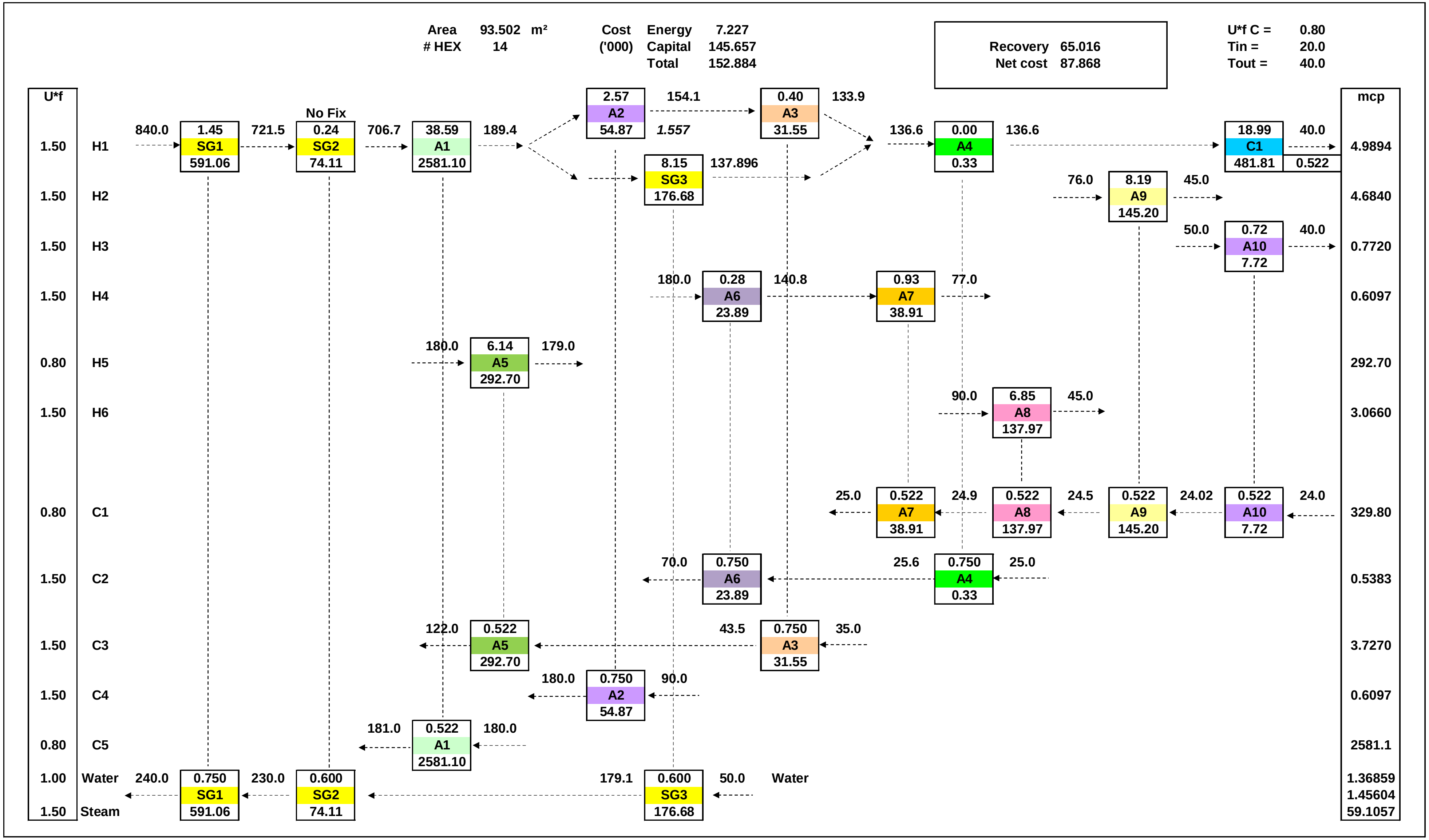
Area 93.502 m²
HEX 14
Cost ('000)
Energy 7.227
Capital 145.657
Total 152.884
Recovery 65.016
Net cost 87.868
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
1.50 H1 4.9894
1.50 H2 4.6840
1.50 H3 0.7720
1.50 H4 0.6097
0.80 H5 292.70
1.50 H6 3.0660
0.80 C1 329.80
1.50 C2 0.5383
1.50 C3 3.7270
1.50 C4 0.6097
0.80 C5 2581.1
1.00 Water 1.36859
1.50 Steam 1.45604
59.1057
840.0
1.45 SG1 591.06
721.5
No Fix
0.24 SG2 74.11
706.7
38.59 A1 2581.10
189.4
2.57 A2 54.87
154.1
1.557
0.40 A3 31.55
133.9
8.15 SG3 176.68
137.896
136.6
0.00 A4 0.33
136.6
18.99 C1 481.81
0.522
40.0
76.0
8.19 A9 145.20
45.0
50.0
0.72 A10 7.72
40.0
180.0
0.28 A6 23.89
140.8
0.93 A7 38.91
77.0
180.0
6.14 A5 292.70
179.0
90.0
6.85 A8 137.97
45.0
25.0
0.522 A7 38.91
24.9
0.522 A8 137.97
24.5
0.522 A9 145.20
24.02
0.522 A10 7.72
24.0
70.0
0.750 A6 23.89
25.6
0.750 A4 0.33
25.0
122.0
0.522 A5 292.70
43.5
0.750 A3 31.55
35.0
180.0
0.750 A2 54.87
90.0
181.0
0.522 A1 2581.10
180.0
240.0
0.750 SG1 591.06
230.0
0.600 SG2 74.11
179.1
0.600 SG3 176.68
50.0
Water

Fig. 9.12

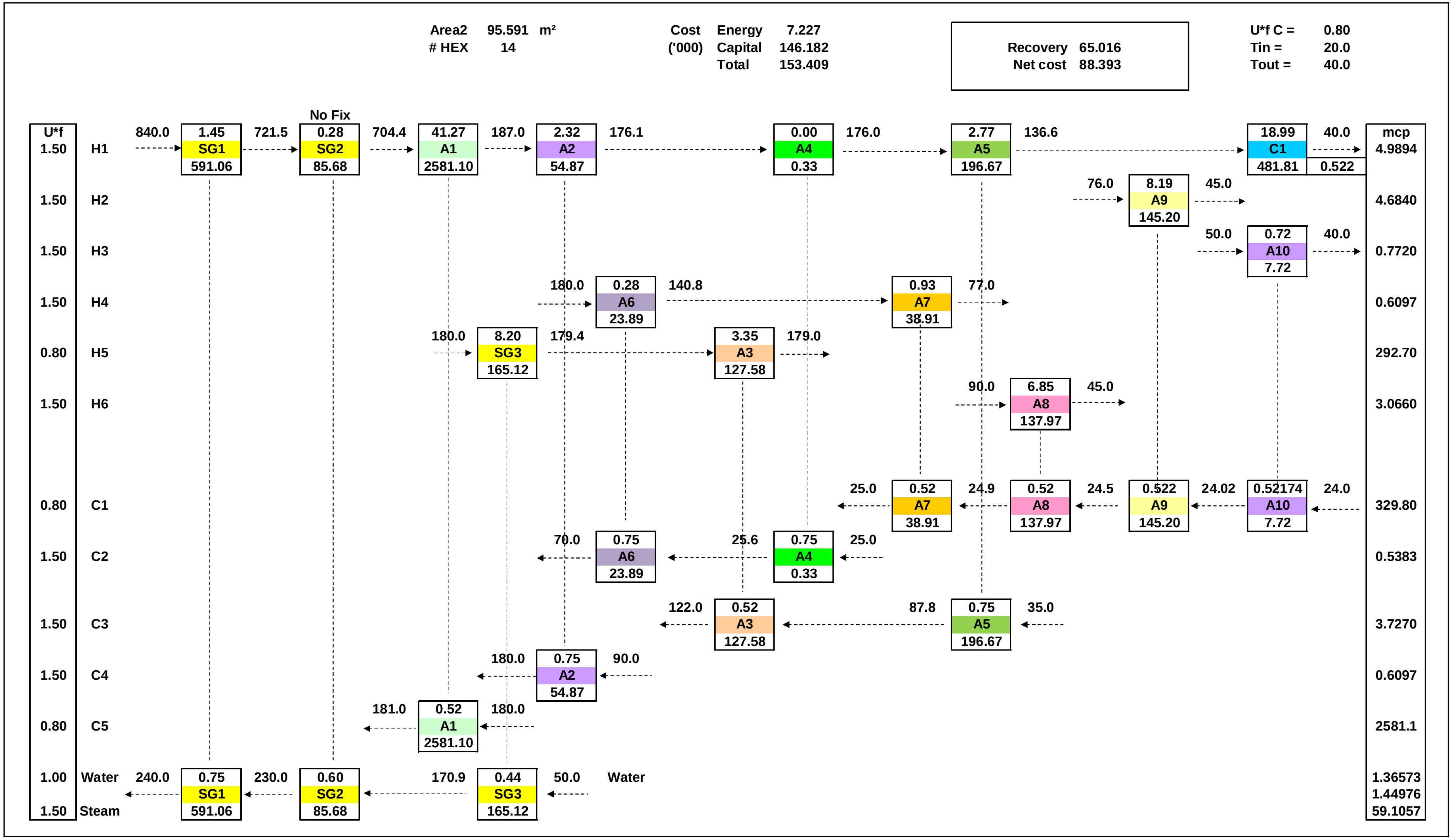
Area2 95.591 m²
HEX 14
Cost ('000)
Energy 7.227
Capital 146.182
Total 153.409
Recovery 65.016
Net cost 88.393
U*f C = 0.80
Tin = 20.0
Tout = 40.0
U*f
mcp
No Fix
1.50 H1 840.0 1.45 SG1 591.06 721.5 0.28 SG2 85.68 704.4 41.27 A1 2581.10 187.0 2.32 A2 54.87 176.1 0.00 A4 0.33 176.0 2.77 A5 196.67 136.6 18.99 C1 481.81 40.0 0.522 4.9894
1.50 H2 76.0 8.19 A9 145.20 45.0 4.6840
1.50 H3 50.0 0.72 A10 7.72 40.0 0.7720
1.50 H4 180.0 0.28 A6 23.89 140.8 0.93 A7 38.91 77.0 0.6097
0.80 H5 180.0 8.20 SG3 165.12 179.4 3.35 A3 127.58 179.0 292.70
1.50 H6 90.0 6.85 A8 137.97 45.0 3.0660
0.80 C1 25.0 0.52 A7 38.91 24.9 0.52 A8 137.97 24.5 0.522 A9 145.20 24.02 0.52174 A10 7.72 24.0 329.80
1.50 C2 70.0 0.75 A6 23.89 25.6 0.75 A4 0.33 25.0 0.5383
1.50 C3 122.0 0.52 A3 127.58 87.8 0.75 A5 196.67 35.0 3.7270
1.50 C4 180.0 0.75 A2 54.87 90.0 0.6097
0.80 C5 181.0 0.52 A1 2581.10 180.0 2581.1
1.00 Water 240.0 0.75 SG1 591.06 230.0 0.60 SG2 85.68 170.9 0.44 SG3 165.12 50.0 Water 1.36573
1.50 Steam 1.44976
59.1057

Fig. 9.13