

An example of sizing of a heat exchanger in which a stream undergoes both a phase change and temperature change in the vapor and/or liquid

In order to estimate the cost of a heat exchanger, it is necessary to know the type of heat exchanger, the pressures involved, the material of construction, and, normally, the heat exchange area.¹ Estimation of the heat exchange area A is simple when either a phase change or a temperature change occurs in both streams.² Then $A = Q/UF\Delta T_{avg}$, where Q is the heat transferred, U is the overall heat transfer coefficient (which can be estimated via heuristics³), F is the correction factor for deviation from countercurrent or cocurrent flow, $\Delta T_{avg} \approx \Delta T_{lm}$ is the average temperature difference between the two streams throughout the exchanger, and ΔT_{lm} is the log-mean temperature difference between the two streams at the ends of the exchanger.

The situation is much more complex when one or both streams undergo both a phase change (evaporation or condensation) and a temperature change in vapor and/or liquid. There are two problems:

1. ΔT_{avg} is no longer approximated satisfactorily by ΔT_{lm} . There can even be a temperature cross within the exchanger for some end temperatures, which is clearly impossible. While a simulator such as HYSYS can correctly calculate ΔT_{avg} ,⁴ it generally cannot handle the second problem.
2. As shown in heuristics³, U changes dramatically when boiling or condensation is taking place, and is quite different for gases and liquids

In order to simulate such a heat exchanger, one must separate it into two or more fictitious exchangers in which both phases in each experiences only a phase change or temperature change, and not both.

To exemplify the procedure for such a simulation, we consider heat exchanger E-100 in the maleic anhydride fluidized bed simulation.⁵ Figure 1 shows the temperature variation inside the exchanger, which can be divided into three parts where the following are taking place:

1. The temperature of liquid butane is increasing, while the high-pressure steam finishes condensing. At the end of this section the butane is saturated, at a temperature such that its vapor pressure equals the pressure.
2. Liquid butane is boiling, while the high-pressure steam is condensing. At the end of this section, all of the butane has evaporated to saturated vapor.
3. The temperature of the butane vapor is increasing, while the high-pressure steam is condensing.

Tables 1 and 2 show the behavior of P , H , vapour fraction and UA (actually $Q/\Delta T_{avg}$) throughout the heat exchanger. We will use these to specify conditions for the 3 fictitious

¹ <http://people.clarkson.edu/~wilcox/Design/refcosts.htm>

² <http://people.clarkson.edu/~wilcox/Design/hxequns.doc>

³ <http://people.clarkson.edu/~wilcox/Design/HeatExch.htm>

⁴ <http://people.clarkson.edu/~wilcox/Design/hxsizing.htm>

⁵ <http://people.clarkson.edu/~wilcox/Design/FB-react.doc>

heat exchangers used to find the correct A, corresponding to the three regions in the actually exchanger.

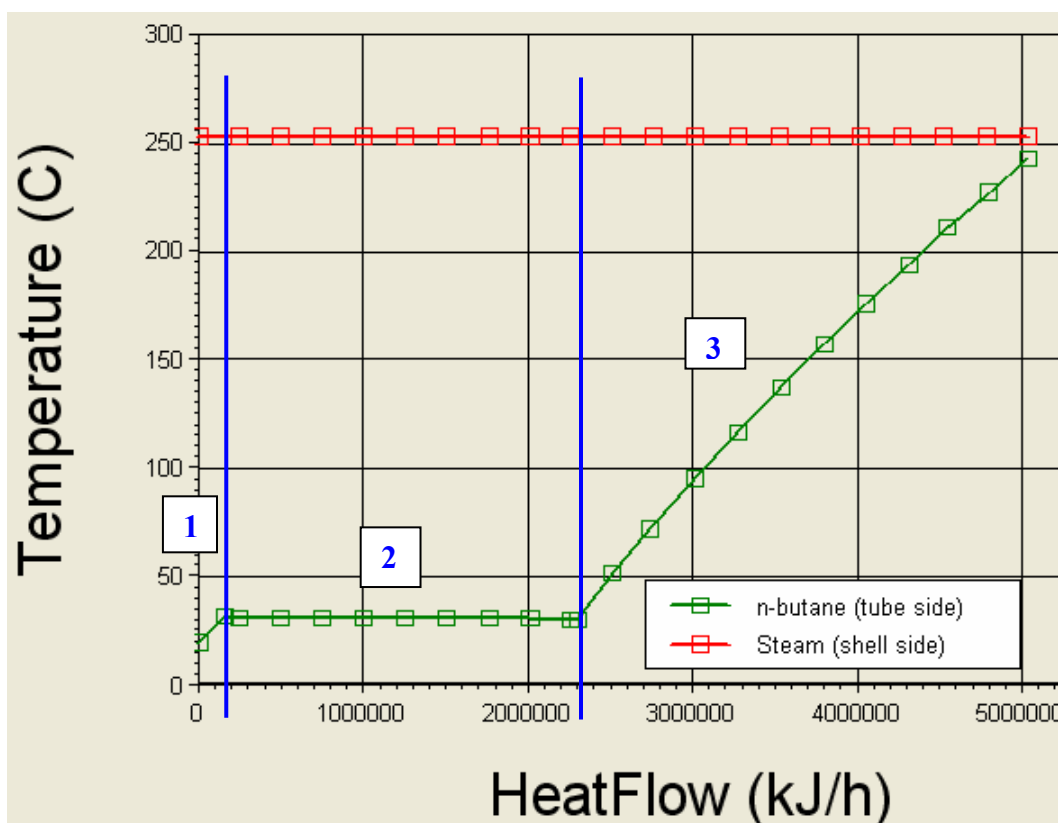


Figure 1. Temperature versus heat flow in the n-butane heat exchanger, E-100.

Table 1. Variation of properties in the n-butane stream (shell side) in E-100.

| Temperature [C] | Pressure [kPa] | Enthalpy [kJ/kgmole] | Heat Flow [kJ/h] | Vapour Frac. | Phase Mass Frac. | Cummulative UA [kJ/C-h] |
|-----------------|----------------|----------------------|------------------|--------------|------------------|-------------------------|
| 1 | 20.0447 | 300.0000 | -148211.6239 | 0.0000 | 0.0000 | 0.0000 |
| | 31.7218 | 299.3299 | -146555.8768 | 168886.1973 | 0.0000 | 743.2465 |
| 2 | 31.6837 | 299.0000 | -145740.7708 | 252027.0090 | 0.0390 | 1118.6627 |
| | 31.5723 | 298.0000 | -143269.9178 | 504054.0180 | 0.1572 | 2256.2712 |
| | 31.4576 | 297.0000 | -140799.0648 | 756081.0270 | 0.2754 | 3393.2642 |
| | 31.3424 | 296.0000 | -138328.2118 | 1008108.0361 | 0.3935 | 4529.6280 |
| | 31.2283 | 295.0000 | -135857.3587 | 1260135.0451 | 0.5116 | 5665.3769 |
| | 31.1148 | 294.0000 | -133386.5057 | 1512162.0541 | 0.6296 | 6800.5052 |
| | 31.0006 | 293.0000 | -130915.6527 | 1764189.0631 | 0.7475 | 7935.0083 |
| | 30.8847 | 292.0000 | -128444.7996 | 2016216.0721 | 0.8654 | 9068.8914 |
| | 30.7698 | 291.0000 | -125973.9466 | 2268243.0811 | 0.9832 | 10202.1475 |
| | 30.7530 | 290.8569 | -125621.9416 | 2304147.5916 | 1.0000 | 10363.5427 |
| 3 | 51.4547 | 290.0000 | -123503.0936 | 2520270.0902 | 1.0000 | 11383.2001 |
| | 72.1397 | 289.0967 | -121271.2173 | 2747921.4672 | 1.0000 | 12573.5359 |
| | 95.2856 | 288.0323 | -118641.1845 | 3016184.8156 | 1.0000 | 14158.4261 |
| | 117.1184 | 286.9776 | -116035.2218 | 3281993.0084 | 1.0000 | 15969.4100 |
| | 137.7530 | 285.9368 | -113463.4508 | 3544313.6499 | 1.0000 | 18058.9880 |
| | 157.3691 | 284.9086 | -110922.9739 | 3803442.3018 | 1.0000 | 20517.5728 |
| | 176.0987 | 283.8925 | -108412.3039 | 4059530.6373 | 1.0000 | 23488.5182 |
| | 194.0358 | 282.8886 | -105931.7867 | 4312543.3959 | 1.0000 | 27219.3726 |
| | 211.2394 | 281.8980 | -103484.2922 | 4562187.8341 | 1.0000 | 32196.6511 |
| | 227.7216 | 280.9241 | -101077.9039 | 4807639.4382 | 1.0000 | 39605.2569 |
| 243.0000 | 280.0000 | -98794.5633 | 5040540.1803 | 1.0000 | 53470.1879 | |

Table 2. Properties of the high-temperature steam in E-100.

| | Temperature [C] | Pressure [kPa] | Enthalpy [kJ/kgmole] | Heat Flow [kJ/h] | Vapour Frac. | Phase Mass Frac. | Cummulative UA [kJ/C-h] |
|---|-----------------|----------------|----------------------|------------------|--------------|------------------|-------------------------|
| 1 | 253.1576 | 4190.0000 | -267042.2593 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| | 253.1674 | 4190.5000 | -265512.0232 | 252027.0090 | 0.0500 | 0.0500 | 1118.6627 |
| | 253.1707 | 4191.0000 | -263981.7870 | 504054.0180 | 0.1000 | 0.1000 | 2256.2712 |
| | 253.1812 | 4191.5000 | -262451.5508 | 756081.0270 | 0.1499 | 0.1499 | 3393.2642 |
| 2 | 253.1863 | 4192.0000 | -260921.3146 | 1008108.0361 | 0.1999 | 0.1999 | 4529.6280 |
| | 253.1920 | 4192.5000 | -259391.0785 | 1260135.0451 | 0.2499 | 0.2499 | 5665.3769 |
| | 253.2013 | 4193.0000 | -257860.8423 | 1512162.0541 | 0.2999 | 0.2999 | 6800.5052 |
| | 253.2091 | 4193.5000 | -256330.6061 | 1764189.0631 | 0.3499 | 0.3499 | 7935.0083 |
| | 253.2142 | 4194.0000 | -254800.3700 | 2016216.0721 | 0.3999 | 0.3999 | 9068.8914 |
| | 253.2241 | 4194.5000 | -253270.1338 | 2268243.0811 | 0.4499 | 0.4499 | 10202.1475 |
| | 253.2313 | 4195.0000 | -251739.8976 | 2520270.0902 | 0.4999 | 0.4999 | 11383.2001 |
| | 253.2356 | 4195.5000 | -250209.6615 | 2772297.0992 | 0.5499 | 0.5499 | 12708.9244 |
| 3 | 253.2438 | 4196.0000 | -248679.4253 | 3024324.1082 | 0.5999 | 0.5999 | 14210.0636 |
| | 253.2521 | 4196.5000 | -247149.1891 | 3276351.1172 | 0.6499 | 0.6499 | 15928.0366 |
| | 253.2587 | 4197.0000 | -245618.9530 | 3528378.1262 | 0.6999 | 0.6999 | 17921.7683 |
| | 253.2651 | 4197.5000 | -244088.7168 | 3780405.1352 | 0.7499 | 0.7499 | 20279.5013 |
| | 253.2733 | 4198.0000 | -242558.4806 | 4032432.1443 | 0.7999 | 0.7999 | 23141.8209 |
| | 253.2812 | 4198.5000 | -241028.2445 | 4284459.1533 | 0.8499 | 0.8499 | 26753.1334 |
| | 253.2871 | 4199.0000 | -239498.0083 | 4536486.1623 | 0.9000 | 0.9000 | 31597.9294 |
| | 253.2935 | 4199.5000 | -237967.7721 | 4788513.1713 | 0.9500 | 0.9500 | 38875.5029 |
| | 253.3022 | 4200.0000 | -236437.5360 | 5040540.1803 | 1.0000 | 1.0000 | 53470.1879 |

Use the procedure below, which will result in something like Figure 2. Basically, to get ready convergence you will add in the butane streams from left to right, and then the high-pressure steam streams from right to left. You must take particular care with specifications, to avoid conflicts or overspecification.

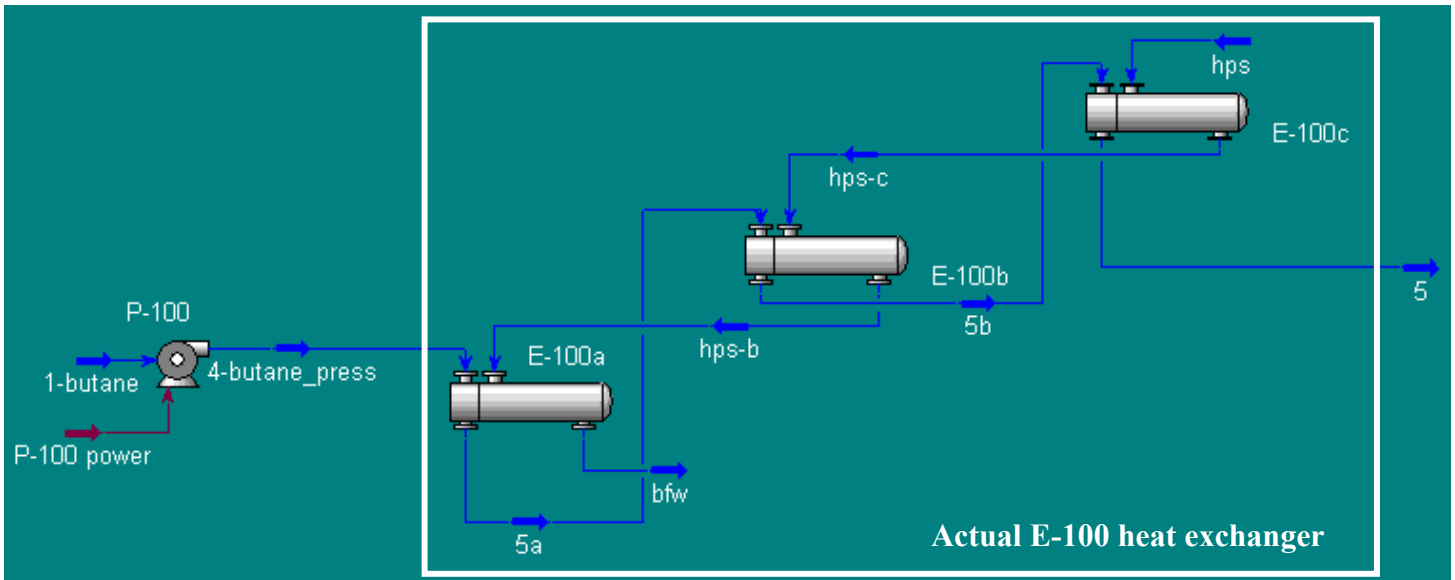


Figure 2. Simulation of E-100 using three fictitious heat exchangers, with liquid butane being heated in the first, boiling in the second, and the vapor being heated in the third.

1. From the simulation of the maleic anhydride plant, read the mass flow rate of the high pressure steam passing through E-100. (2967 kg/h).
2. Enter the three fictitious heat exchangers. Right click on each and change the icon, if desired.
3. Connect stream 4 as the tube inlet of E-100a, and stream 5a as its outlet. **DO NOT CONNECT THE STEAM LINES YET.** On the Design Parameters page, select

Exchanger Design (Weighted). On the Worksheet page, set the pressure of stream 5a to that at the boundary between region 1 and 2 in Table 2. Set its vapour fraction to 0 (saturated liquid).

4. Connect stream 5a to the tube-side inlet of E-100b, and stream 5b as its outlet. **DO NOT CONNECT THE STEAM LINES YET.** On the Design Parameters page, select Exchanger Design (Weighted). On the Worksheet page, set the pressure of stream 5b to that at the boundary between region 2 and 3 in Table 2, and its vapour fraction to 1 (saturated vapor).
5. Connect stream 5b to the tube-side inlet of E-100c, and stream 5 as its outlet. On the Design Parameters page, select Exchanger Design (Weighted). On the Worksheet page, set the outlet pressure and temperature of stream 5 to those in the bottom row of Table 2.
6. All of the butane streams should now have converged. If not, figure out why and fix it. If so, you are ready to add the steam lines, from right to left.
7. Connect hps to the shell-side inlet of E-100c and hps-c to its outlet. Change the basis for the shell side to basis-2 (for water and the ASME or NBS steam fluid package). On Worksheet Composition, specify the hps as mole fraction 1 of water. On Worksheet Conditions set the P of hps to that shown in the bottom row of Table 3, its vapour fraction to 1, and its mass flow rate to 2967 kg/h. E-100c should now converge.
8. Connect hps-c to the shell-side inlet of E-100b and hps-b to its outlet. Change the basis for the shell side to basis-2. On the Worksheet set the pressure for hps-b to that between regions 2 and 3 of Table 3. E-100b should now converge.
9. Connect hps-b to the shell-side inlet of E-100a and bfw to its outlet. Change the basis for the shell side to basis-2. On the Worksheet set the pressure for bfw to that in the top row of Table 3. If you did everything right, everything should converge and the vapour fraction should be 0 for the bfw.
10. Compare the UA for each fictitious heat exchanger with that for that part of the real exchanger, obtainable via the cumulative UA values in the last column of Table 1 or 2.
11. Calculate the areas of the three fictitious heat exchanger using the methods of <http://people.clarkson.edu/~wilcox/Design/hxsizing.htm>. Add these together to get the total area of E-100.

The HYSYS workbook for this simulation is shown below.

Table 3. Resulting HYSYS workbook. Data in blue are specified, those in black calculated by HYSYS.

| Name | 1-butane | 4-butane_press | 5 | 5a | 5b | bfw | hps | hps-b | hps-c |
|-----------------------|------------|----------------|------------|------------|------------|------------|------------|------------|------------|
| Vapour Fraction | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.03 | 0.46 |
| Temperature [C] | 20 | 20 | 243 | 32 | 31 | 253 | 253 | 253 | 253 |
| Pressure [kPa] | 253 | 300 | 280 | 299 | 291 | 4.19e+03 | 4.20e+03 | 4.19e+03 | 4.20e+03 |
| Heat Flow [kJ/h] | -1.51e+007 | -1.51e+007 | -1.01e+007 | -1.49e+007 | -1.28e+007 | -4.40e+007 | -3.89e+007 | -4.38e+007 | -4.17e+007 |
| Mass Flow [kg/h] | 5929 | 5929 | 5929 | 5929 | 5929 | 2967 | 2967 | 2967 | 2967 |
| Molar Flow [kgmole/h] | 102 | 102 | 102 | 102 | 102 | 165 | 165 | 165 | 165 |
| (n-Butane) [kgmole/h] | 102 | 102 | 102 | 102 | 102 | xxx | xxx | xxx | xxx |
| (Oxygen) [kgmole/h] | 0 | 0 | 0 | 0 | 0 | xxx | xxx | xxx | xxx |
| (Nitrogen) [kgmole/h] | 0 | 0 | 0 | 0 | 0 | xxx | xxx | xxx | xxx |
| (H2O) [kgmole/h] | 0 | 0 | 0 | 0 | 0 | 165 | 165 | 165 | 165 |