

27

Term Projects (4): Heat Transfer

- 27.1 Wilson's Method
- 27.2 Heat Exchanger Network I
- 27.3 Heat Exchanger Network II
- 27.4 Heat Exchanger Network III

Term Project 27.1

Wilson's Method

There is a laboratory procedure for evaluating the *outside* film coefficient, h_o , for a double pipe unit. Wilson's method [1] is a graphical technique for evaluating this coefficient. The inside coefficient, h_i , is a function of the Reynolds and Prandtl numbers via the Dittus – Boelter equation [2,3]; i.e.,

$$h_i = f(\text{Re}^{0.8} \text{Pr}^{0.3}) \quad (27.1)$$

A series of experiments can be carried out on a double pipe exchanger where all conditions are held relatively constant except for the velocity (V) of the cooling (in this case) inner stream. Therefore, for the proposed experiment:

$$h_i = f(\text{Re}^{0.8}) = f(V^{0.8}) = f(\dot{m}); \text{Re} = DV\rho/\mu \quad (27.2)$$

or, in equation form,

$$h_i = aV^{0.8} \quad (27.3)$$

where a is a constant. Equation (27.3) can be substituted into the overall coefficient equation

$$\frac{1}{h_o A_o} = R_o + R_w + R_i \quad (27.4)$$

where R_o = outside resistance

R_w = wall resistance

R_i = inside resistance

so that [2]

$$\frac{1}{U_o A_o} = \frac{1}{h_o A_o} + \frac{\Delta x}{k A_{lm}} + \frac{1}{a V^{0.8} A_i} \quad (27.5)$$

Data can be taken at varying velocities. By plotting $1/U_o A_o$ versus $1/V^{0.8}$, a straight line should be obtained since the first two terms of Equation (27.5)

are constants. The intercept of this line corresponds to an infinite velocity where the inside resistance is zero. Thus,

$$\left(\frac{1}{U_o A_o} \right)_{\text{intercept}} = \frac{1}{h_o A_o} + \frac{\Delta x}{k A_{\text{lm}}} \quad (27.6)$$

The second term on the right-hand side is known and/or can be calculated and h_o can then be evaluated from the intercept; details on this calculational scheme are provided in an illustrative example provided by Theodore [3], fouling coefficient, h_o , can be predicted or is negligible. Note that the fouling resistance is normally included in the intercept value.

Based on the above analysis, you have been requested to develop a similar-type procedure to evaluate the inside heat transfer coefficient in a shell-and-tube (tube-and-bundle) heat exchanger. Also describe the experimental equipment and method to be employed.

Term Project 27.2

Heat Exchanger Network I

In many chemical and petrochemical plants there are cold streams that must be heated and hot streams that must be cooled. Rather than use steam to do all the heating and cooling water to do all the cooling, it is often advantageous to have some of the hot streams heat the cold ones.

Highly interconnected networks of exchangers can save a great deal of energy in a chemical plant. The more interconnected they are, however, the harder the plant is to control, start-up and shut-down. Often auxiliary heat sources and cooling sources must be included in the plant design in order to ensure that the plant can operate smoothly.

A plant has three streams to be heated and three streams to be cooling. Cooling water (90°F supply, 155°F return) and steam (saturated at 250 psia) are available. Devise a network of heat exchangers that will make full use of heating and cooling streams against each other, using utilities only if necessary.

The three streams to be heated are provided in Table 27.1

The three streams to be cooled are provided in Table 27.2

The reader is referred to Illustrative Open-ended Problem 2 in Chapter 6 for calculations related to the above streams.

There are many possible combinations of interconnected heat exchangers that will work. Detailed cost analyses would be needed to determine which one was best. For each exchanger in the network, one needs to make sure that the duties on each side are equal and that there are no *temperature crossovers*. These occur when the stream being cooled is colder than the lowest temperature of the stream being heated at some point in the exchanger. This is (of course) forbidden by the second law of thermodynamics [6,7].

Table 27.1 Heated Stream

Stream	Flowrate, lb/h	c_p , Btu/lb·F	T_{in} , °F	T_{out} , °F
1	50,000	0.65	70	300
2	60,000	0.58	120	310
3	80,000	0.78	90	250

Table 27.2 Cooled Stream

Stream	Flowrate, lb/h	c_p , Btu/lb·F	T_{in} , °F	T_{out} , °F
4	60,000	0.70	420	120
5	40,000	0.52	300	100
6	35,000	0.60	240	90

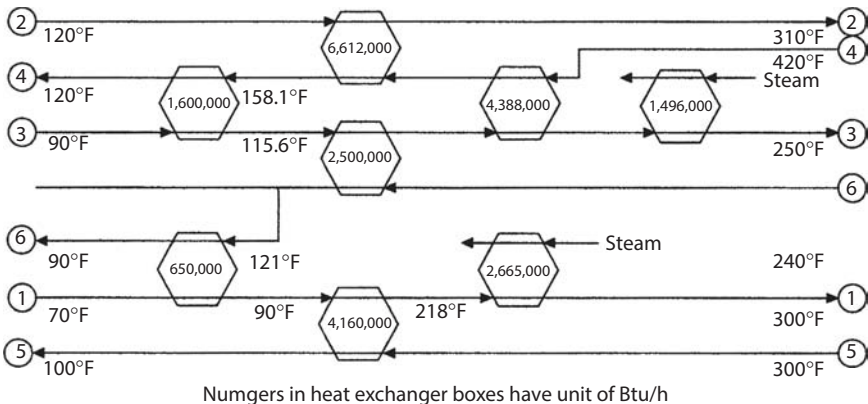


Figure 27.1 Kauffman's [4] heat exchanger network.

Comment: Since this and the next two term projects are concerned with the general subject of heat exchanger networks, Kauffman's solution [4] is provided in Figure 27.1. There are, of course, other solutions. Your assignment is to provide another solution.

Term Project 27.3

Heat Exchanger Network II

Any discussion of energy conservation above leads to an important second-law consideration—energy has “quality” as well as quantity. Because work is 100% convertible to heat whereas the reverse situation is not true, work is a more valuable form of energy than heat. Although it is not as obvious, it can also be shown through second law arguments that heat also has “quality” in terms of the temperature at which it is discharged from a system. The higher the temperature, the greater the possible energy transformation into work. Thus, thermal energy stored at high temperatures is generally more useful to society than that available at lower temperatures. While there is an immense quantity of energy stored in rivers and oceans, for example, its present availability to society for performing useful tasks is quite low. This implies, as noted above, that thermal energy loses some of its “quality” or is degraded when it is transferred by means of heat transfer from one temperature to a lower one. Other forms of energy degradation include energy transformation due to frictional effects and electrical resistance. Such effects are highly undesirable if the use of energy for practical purposes is to be maximized [8–10].

The second law provides a means of measuring this energy degradation through a thermodynamic term referred to as *entropy* and it is the second law (of thermodynamics) that serves to define this important property. It is normally designated as S with units of energy per absolute temperature (e.g., Btu/°R or cal/K). Furthermore, entropy calculations can provide quantitative information on the “quality” of energy and energy degradation [9,10].

There are a number of other phenomena that cannot be explained by the first law of conservation of energy. It is the second law of thermodynamics that provides an understanding and analysis of these diverse effects. However, among these considerations, it is the second law that can allow the measuring of the aforementioned “quality” of energy, including its effect on the design and performance of heat exchangers.

One of the areas where the aforementioned meaningful energy conservation measures can be realized is in the design and specification of process

(operating) conditions for heat exchangers. This can be best accomplished by the inclusion of second law principles in the analysis. The quantity of heat recovered in an exchanger is not alone in influencing size and cost. As the energy temperature difference driving force (LMTD) in the exchanger approaches zero, the “quality” heat recovered increases [11,12].

Most heat exchangers are designed with the requirements/specification that the temperature difference between the hot and cold fluid be at all times positive and be at least 20°F. This temperature difference or driving force is referred to by some as the *approach temperature*. However, the corresponding entropy change is also related to the driving force, with large temperature difference driving forces resulting in large irreversibilities and the associated large entropy changes [11,12].

The individual designing a heat exchanger is faced with two choices. He/she may decide to design with a large LMTD that results in both a more compact (smaller area) design and large entropy increase that is accompanied by the loss of “quality” energy. Alternately, a design with a small driving force results in both a larger heat exchanger and a smaller entropy change/larger recovery of “quality” energy [11,12].

Refer to the previous term project (27.2) on heat exchanger networks. Solve the problem if the network of exchangers must be such that the *entropy* increase in the proposed network is minimized

The reader should consider reviewing second law principles presented in Part II, Chapters 4 and 6.

Term Project 27.4

Heat Exchanger Network III

Refer to the two previous term projects concerned with heat exchanger networks [13,14].

1. *Outline* how to solve the first problem if the heat exchanger cost is a function of the heat exchanger area. The network should be such that the total cost of the resulting network is *minimized*. In effect, the economics involved are to be included with the outline to the solution.
2. *Outline* how to solve the two previous problems so that the network’s entropy increase *and* the network’s cost are *minimized*. Is there a unique solution? Justify your answer to this question. If there is not a unique solution, *outline* how a practicing chemical engineer could arrive at a *reasonable* solution to the problem.

References

1. E. Wilson, *Trans, ASME*, 34, 47, New York City, NY, 1915.
2. R. Perry, and D. Green, (editors), *Perry's Chemical Engineers' Handbook*, 7th edition, McGraw-Hill, New York City, NY, 1997.
3. L. Theodore, *Heat Transfer for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2011.
4. M. Theodore and L. Theodore, *Introduction to Environmental Management*, CRC Press/Taylor & Francis Group, Boca Raton, FL, 2009.
5. J. Smith, H. Van Ness, and M. Abbott, *Chemical Engineering Thermodynamics*, 6th edition, McGraw-Hill, New York City, NY, 2001.
6. L. Theodore and J. Reynolds, *Thermodynamics*, A Theodore Tutorial, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1994.
7. L. Theodore, F. Ricci, and T. VanVliet, *Thermodynamics for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2009.
8. L. Theodore, *Heat Transfer for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2011.
9. D. Kauffman, *Process Synthesis and Design*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1992.
10. L. Theodore, *Heat Transfer for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2011.
11. L. Theodore, F. Ricci, and T. VanVliet, *Thermodynamics for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2009.
12. L. Theodore, *Chemical Engineering: The Essential Reference*, McGraw-Hill, New York City, NY, 2014.
13. L. Theodore, F. Ricci, and T. VanVliet, *Thermodynamics for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2009.
14. L. Theodore, *Heat Transfer for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2011.