

Energy Conservation: Heat Transfer Design Considerations Using Thermodynamic Principles

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Abstract

Environmental concerns involving conservation of energy issues gained increasing prominence during and immediately after the OPEC oil embargo of 1973. In addition, global population growth has led to an increasing demand for energy. Although the use of energy has resulted in great benefits, the environmental and human health impact of this energy use has become a concern. One of the keys to reducing and/or eliminating this problem will be achieved through what has come to be referred to as meaningful energy conservation.

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.

The law of conservation of energy is defined by many as the first law of thermodynamics. Its application allows calculations of energy relationships associated with various processes. Both a qualitative and quantitative review of entropy and the second law are presented in this paper. This is followed by a section titled “The Heat Exchanger Dilemma” that examines the interrelationship of entropy with heat exchanger design and optimization. The paper concludes with four Illustrative Examples.

It is concluded that from a “conservation of energy” perspective, second law considerations mandate its inclusion in heat exchanger applications with appropriate economic considerations. Both the cost of the exchanger and the economic factors associated with the “quality” of the recovered energy must be included in any meaningful optimization study and/or analysis.

Introduction

This paper describes the results of a recent thermodynamic study conducted by chemical engineering students at Manhattan College. During the study, the students learned about the interrelationship between two

principal subject areas of chemical engineering: thermodynamics and heat transfer. The educational outcome of this research project provided the students with a better understanding of how the two disciplines simultaneously affect design applications. These concepts can be used when the student is given a task to design an applicable heat exchanger in the work field or an academic environment.

The law of conservation of energy is defined by many as the first law of thermodynamics. Its application allows calculations of energy relationships associated with various processes. The second law of thermodynamics is referred to as the “limiting law.” Historically, the study of the second law was developed by individuals such as Carnot, Clausius, and Kelvin in the middle of the nineteenth century. This development was made purely on a macroscopic scale and is referred to as the “classical approach” to the second law. More recently, this law has been integrated into heat transfer analysis and heat exchanger design.

Qualitative Review of the Second Law

The first law of thermodynamics is a conservation law concerned with energy transformations. Regardless of the types of energy involved in process – thermal, mechanical, electrical, elastic, magnetic, etc. – the change in the energy of a system is equal to the difference between energy input and energy output. The first law also allows free convertibility from one form of energy to another, as long as the overall quantity is conserved. Thus, this law places no restriction on the conversion of work into heat, or on its counterpart – the conversion of heat into work.

The unrestricted conversion of work into heat is well known to most technical individuals. Frictional effects are frequently associated with mechanical forms of work which result in a temperature rise of the bodies of contact. However, the transformation of heat into work is of greater concern. In nations with a partially developed or developing technological society, the ability to produce energy in the form of work takes on prime importance. Work transformations are necessary to transport people and goods, drive machinery, pump liquids, compress gases, and provide energy input to so many other processes that are taken for granted in highly developed societies. Much of the work input in such societies is available in the form of electrical energy which can then be converted to rotational mechanical work. Although some of this electrical energy is produced by hydroelectric power plants, by far the greatest part of it is obtained from the combustion of fossil fuels or nuclear fuels. These fuels allow the engineer to produce a relatively high-temperature gas or liquid stream that acts as a thermal (heat) source for the production of

work. Hence, the study of conversion of heat to work is extremely important – especially in light of developing shortages and increasing cost of fossil and nuclear fuels, along with the accompanying environmental problems, particularly with global warming. The brief discussion of energy conversion 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 its temperature (at which it may be discharged from a system). The higher the temperature, the greater the possible energy transformation into work. Thus, thermal energy stored at high temperatures generally is more useful to society than that available at lower temperatures. 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 transformations due to frictional effects and electrical resistance. Such effects are highly undesirable if the use of energy for practical purposes is to be maximized ⁽¹⁻³⁾.

The second law provides some 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 ^(2, 3).

There are a number of other phenomena which cannot be explained by the 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 produce the means of measuring the aforementioned “quality” of energy, including its effect on the design and performance of heat exchangers.

Exergy is another term that is closely related to both entropy and the second law. Exergy is defined as the maximum amount of work that may be produced by a system as it comes into equilibrium with a reference environment. It may also be viewed as “quality” energy and available energy. It is destroyed during any real process as a result of the second law. Exergy destruction is directly proportional to entropy generation. When properly applied, exergy analysis provides useful insights to how efficient a process may potentially become under ideal conditions ⁽⁴⁾.

Quantitative Review of the Second Law

Key equations pertinent to entropy calculations and heat exchanger design receive treatment in this Section. Each is treated separately below.

If ΔS_{syst} and ΔS_{surr} represented the entropy change of a system and surroundings, respectively, it can be shown that for a particular process (and as a consequence of the second law), the total entropy change ΔS_{tot} is given by:

$$\Delta S_{tot} = \Delta S_{syst} + \Delta S_{surr} \geq 0 \tag{1}$$

In effect the second law requires that for a real processes, the total entropy change is positive; the only exception is if the process is reversible (the driving force for heat transfer is at all times zero) and then:

$$(\Delta S_{tot})_{rev} = 0 \tag{2}$$

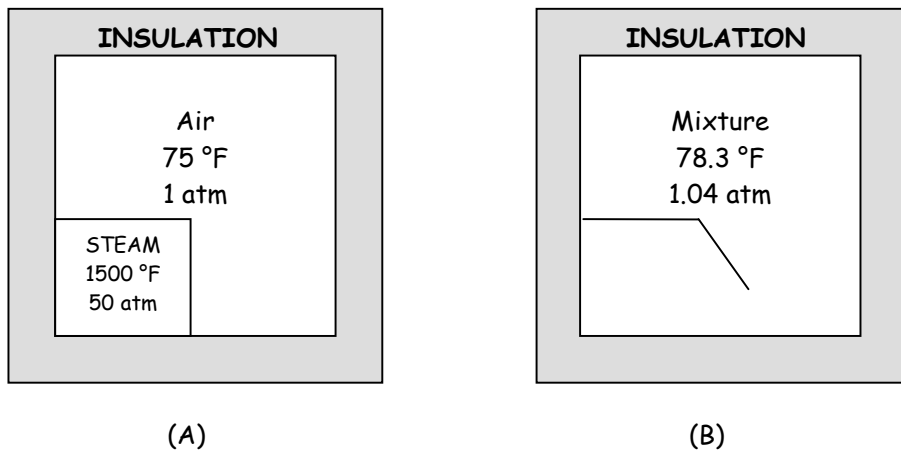


Figure 1: Entropy Analysis

To reexamine the aforementioned concept of “quality” energy, consider the insulated space pictured in Figure 1 (A)-(B) above. Space (A) contains air and steam that are separated; space (B) contains the resulting mixture when both components are mixed. Both spaces are insulated ($Q=0$) in this closed system with no work term ($W=0$), so that one can conclude from the first law ($Q+W=\Delta U$) that:

$$\begin{aligned} \Delta U &= 0 \\ U_A &= U_B; U \equiv \text{internal energy} \end{aligned} \tag{3}$$

Although the energy levels are the same, one notes that system (A) has the capability of doing useful work (because of the high-temperature high-pressure steam) while system (B) does not. If an entropy analysis is performed (see Illustrative Example) on both systems (A) and (B), one would deduce that (as noted earlier):

$$S_A < S_B \quad (4)$$

In effect, the entropy level has increased for the system that has lost its ability to do useful work due to the irreversible nature of the mixing process. It is in this manner that the concept of entropy can be used to determine a system's ability to either do useful work or lose its ability to do useful work. Thus, the second law leads to the conclusion that the greater the irreversibility of a process, the greater the (rate of) entropy increase and the greater the amount of energy that becomes unavailable for doing useful work.

Consider now the entropy change for gases. The entropy change of an ideal gas undergoing a change of state from pressure P_1 to P_2 at a constant temperature T is given by:

$$\Delta S_T = R \ln \left(\frac{P_1}{P_2} \right) \quad (5)$$

where R is the ideal gas law constant in consistent units. The entropy change of a liquid or an ideal gas undergoing a change of state from T_1 to T_2 at a constant pressure is given by:

$$\Delta S_P = C_P \ln \left(\frac{T_2}{T_1} \right) \quad (6)$$

where C_P is the heat capacity at constant pressure in consistent units. The entropy change for an ideal gas undergoing a change from (P_1, T_1) to (P_2, T_2) with constant C_P can be obtained by the Compatibility Equation:

$$T dS = dh - V dP \quad (7)$$

Integration leads to the following equation for a change in entropy $S_2 - S_1$:

$$\Delta S = R \ln \left(\frac{P_1}{P_2} \right) + C_P \ln \left(\frac{T_2}{T_1} \right) \quad (8)$$

If Q represents the rate of heat transfer between a hot and cold fluid flowing in a heat exchanger, application of the conservation law for energy gives

$$\dot{Q}_H = \dot{m}_H c_{P,H} (T_{HI} - T_{HO}) \quad (9)$$

And

$$\dot{Q}_C = \dot{m}_C c_{P,C} (T_{CO} - T_{CI}) \quad (10)$$

Where the subscripts H and C refer to the hot and cold fluids, respectively, I and O refer to the fluid inlet and outlet temperature, respectively, \dot{m} represents the mass flow rate and C_p is once again the heat capacity at constant pressure (assumed constant). In addition, if there is no heat lost from the exchanger to the surroundings,

$$\dot{Q}_H = \dot{Q}_C \quad (11)$$

The following important equation relates \dot{Q} to the average temperature difference between the hot and cold fluids,

$$\dot{Q} = UA\Delta T_{LM} \quad (12)$$

This is often referred to as the heat exchanger design equation. The terms U, A, and T_{LM} represent the overall heat transfer coefficient (a function of the resistance to heat transfer), the area for heat transfer, and the log mean temperature difference driving force (TDDF), respectively. For some exchangers, the latter term is given by

$$\Delta T_{LM} = TDDF = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)} \quad (13)$$

Where ΔT_2 and ΔT_1 represents the temperature difference between the hot and cold fluid at each end of the exchanger, respectively. If $\Delta T_1 = \Delta T_2 = \Delta T$, then $\Delta T_{LM} = \Delta T$. For purposes of the analysis to follow, Equation 11 is rearranged in the form

$$\frac{\dot{Q}}{U\Delta T_{LM}} = A \quad (14)$$

Heat Exchanger - Entropy Applications ⁽⁴⁻⁵⁾

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 temperature difference driving force (TDDF) in the exchanger approaches zero, the “quality” heat recovered increases.

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, and as it will be demonstrated in an Illustrated Example to follow, the corresponding entropy change is related to the driving force, with large temperature difference driving forces resulting in large irreversibilities and the associated large entropy changes.

The individual designing a heat exchanger is faced with two choices. He/she may decide to design with a large TDDF which results in both a more compact (smaller area) design (see Equation (13)) and a large entropy increase that is accompanied by the loss of “quality” energy. Alternately, a design with a small driving force results in a larger heat exchanger and a smaller entropy change/larger recovery of “quality” energy.

Regarding the cooling medium for a given heat transfer duty, the design engineer has the option of circulating a large quantity with a small temperature change or a small quantity with a large temperature change. The temperature change (or range) of the coolant affects the TDDF. If a large coolant quantity is used, the TDDF is larger and less heat transfer area A is required as a result of the large TDDF. Although this will reduce the original investment and fixed charges (capital and operating costs), the amount of “quality” energy recovered will also be smaller, owing to the greater quantity of coolant employed. It is therefore apparent that an optimum must exist between the two choices: too much coolant, smaller surface, and the recovery of less “quality” energy or too little coolant, larger surface, and the recovery of more quality energy. In the limit, as the $TDDF \rightarrow 0$ the area requirement $A \rightarrow \infty$, the entropy change $\Delta S \rightarrow 0$ and the aforementioned recovered “quality” energy increases. Clearly, cost must be minimized, but just as clearly, the “quality” energy recovered must be included in the analysis. This dilemma is addressed in the illustrative example to follow.

Illustrative Examples

Illustrative Example 1.

Stacey Shaefer, a recent graduate from Manhattan College's prestigious chemical engineering program was given the assignment to design the most cost-effective heat exchanger to recover energy from a hot flue gas at 500 °F. The design was to be based on pre-heating 100 °F incoming air (to be employed in the boiler) to a temperature that would result in the maximum annual profit to the utility. A line diagram of the proposed countercurrent exchanger is provided in Figure 2.

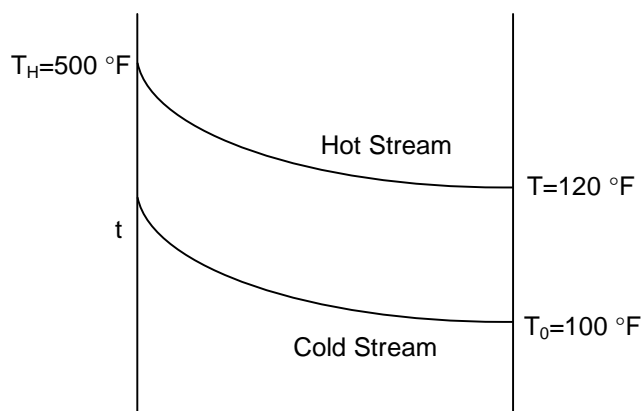


Figure 2: Proposed Countercurrent Heat Exchanger

Having completed a heat transfer and thermodynamic course, Stacey realized that there are two costs that need to be considered:

1. The heat exchanger employed for energy recovery, and
2. The “quality” (from entropy perspective) of the recovered energy.

She notes that the higher the outlet temperature of the heated air, t , the smaller will be the temperature difference driving force, and the higher the area requirement of the exchanger (and the higher the equipment cost). In addition, with a higher t , the “quality” of the recovered energy is higher, thus leading to an increase in “recovered” profits (by reducing fuel costs).

Based on a similar system design, JinFang Ni, Anna Nikolova and Mary Minnucci of JAM associates have provided the following annual economic models

Recovered energy profit: $A(t-t_c)$; $A=\$/\text{yr}\cdot^\circ\text{F}$

Exchanger cost: $B/(T_H-t)$; $B=\$/\text{yr}\cdot^\circ\text{F}$

For the above system, JAM suggests values for the coefficients in the model to be set at:

$A=10$

$B=100,000$

Employing the above information, Stacey has been asked to calculate a “t” that will

1. provide breakeven (BE) operation, and
2. maximize profits (MP).

She is also required to perform the calculations if $A=10$, $B=400$ and $A=10$, $B=400,000$.

Finally, an analysis of the results is requested.

Solution:

Since there are two contributing factors to the cost model, one may write the following equation for the profit, P:

$$P = A(t - t_c) - B/(T_H - t); T_H = 500 \text{ and } t_c = 100$$

For breakeven operation, set $P = 0$, so that

$$(t - t_c) (T_H - t) = B/A$$

This may be rewritten as

$$t^2 - (T_H + t_c)t + (B/A + T_H t_c) = 0$$

The solution to this quadratic equation for $A = 10$ and $B = 100,000$ is

$$\begin{aligned} t &= \frac{600 \pm \sqrt{600^2 - (4)(1)(10,000 + 50,000)}}{2} \\ &= \frac{600 \pm 342}{2} \\ &= 473 \text{ }^\circ\text{F}, 127 \text{ }^\circ\text{F for BE operation} \end{aligned}$$

To maximize the profit, obtain the first derivative of P with respect to “t” and set it equal to zero, i.e.,

$$\frac{dP}{dt} = A - \frac{B}{(T_H - t)^2} = 0$$

Solving,

$$(T_H - t)^2 = \frac{B}{A} = 10,000$$

$$(T_H - t) = 100$$

$$t = 500 - 100$$

$$= 400^\circ\text{F for MP}$$

However, it is the second derivative that provides information on whether the above value for “t” represents a maximum or minimum. If the second derivative is evaluated at the above “t” and a positive value results, it represents a minimum; alternatively, a negative value indicates it is a maximum. For the second derivative,

$$\frac{d^2P}{dt^2} = -\frac{2B}{(T_H - t)^3}$$

For t = 400

$$\frac{d^2P}{dt^2} = -\text{number}$$

Therefore, operating at t = 400 °F does indeed represent the “maximum” profit.

Similarly, one can show that for A = 10, B = 400

t = 499, 101 for BE

And

t = 480 for MP

For A = 10, B = 400,000

t = 300 for BE

And

t = 300 for MP

In terms of analyses, the graphical results of the above three calculations are provide in Figure 3 below.

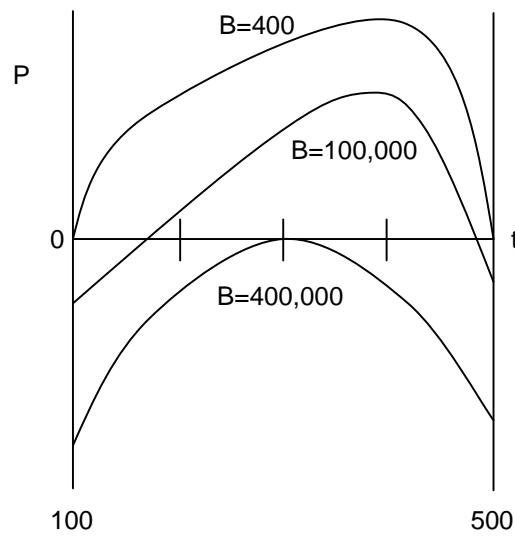


Figure 3: Profit-Discharge Temperature Plot

Illustrative Example 2.

A plant has three streams to be heated (see Table 1) and three streams to be cooled (see Table 2). Cooling water (90°F supply, 155°F return) and steam (saturated at 250 psia) are available. Note that saturated steam at 250 psia has a temperature of 401°F. Calculate the heating and cooling duties, and indicate what utility (or utilities) should be employed. Devise a network of heat exchangers that will make full use of heating and cooling streams against each other, using utilities only if necessary.

Solution: The sensible heating duties for all streams are first calculated. The results are shown in Table 3.

Table 1 Streams to be Heated in Illustrative Example 2

Stream	Flow rate (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 2 Streams to be Cooled in Illustrative Example 2

Stream	Flow rate (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

Table 3 Duty Requirements in Illustrative Example 2

Stream	Duty, Btu/h
1	7,745,000
2	6,612,000
3	9,984,000
4	12,600,000
5	4,160,000
6	3,150,000

The total heating and cooling duties can now be compared.

$$\text{Heating: } 7,745,000 + 6,612,000 + 9,984,000 = 24,341,000 \text{ Btu/h}$$

$$\text{Cooling: } 12,600,000 + 4,160,000 + 3,150,000 = 19,910,000 \text{ Btu/h}$$

$$\text{Heating} - \text{Cooling} = 24,341,000 - 19,910,000 = 4,431,000 \text{ Btu/h}$$

As a minimum, 4,431,000 Btu/h will have to be supplied by steam or another hot medium.

The reader should note that this is an open-ended problem. The below figure represents a system of heat exchangers that will transfer heat from the hot streams to the cold ones in the amounts desired. It is important to note that this is one of many possible schemes. The optimum system would require a trial-and-error procedure that would examine a host of different schemes. Obviously, the economics including the equipment and quality energy effects discussed in the previous example would come into play.

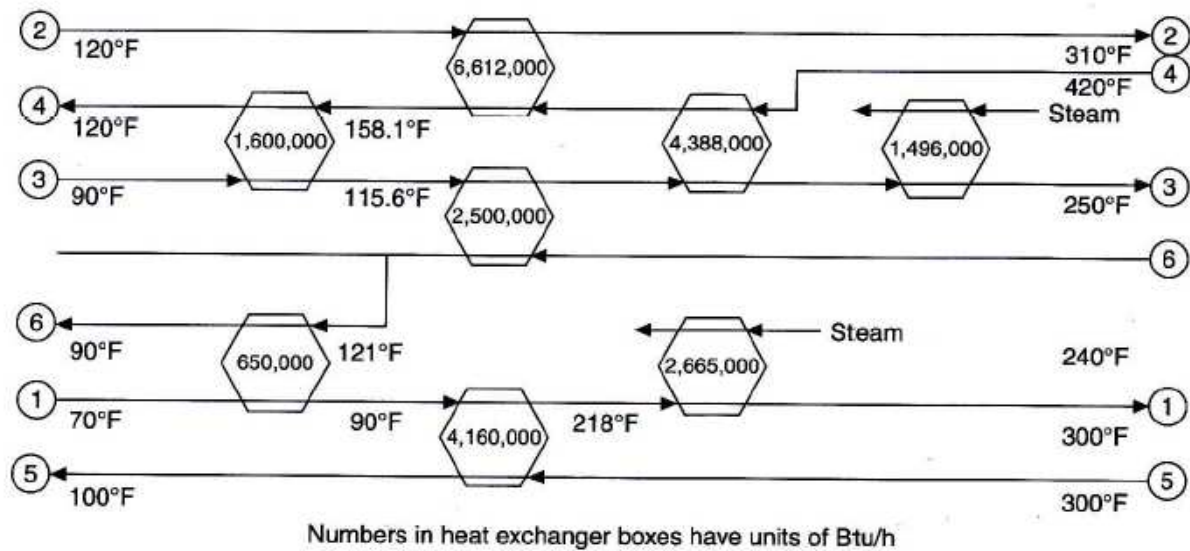


Figure 4: Flow Diagram for Illustrative Example 2

Conclusion

As noted in the two Illustrative Examples, from a “conservation of energy” perspective, second law considerations mandate its inclusion in heat exchanger applications with appropriate economic considerations. Both the cost of the exchanger and the economic factors associated with the “quality” of the recovered energy must be included for any meaningful optimization study and/or analysis. In addition, the students participating in the study were provided with a real-world environmental practical application of engineering. The students fulfilled their purpose of understanding the interrelationship of core chemical engineering disciplines, which was extremely valuable to their learning experience.

References:

1. M.K. Theodore and L. Theodore, "Introduction to Environmental Management", CRC Press/Taylor & Francis Group, Boca Raton, FC, 2009.
2. J. Smith, H. Van Ness and M. Abbott, "Chemical Engineering Thermodynamics", 6th Edition, McGraw Hill, New York City, NY, 2001.
3. L. Theodore and J. Reynolds," Thermodynamics", A Theodore Tutorial, Theodore Tutorials, East Williston, NY 1994.
4. F. Ricci, T. VanVliet and L. Theodore, "Thermodynamics for the Practicing Engineer", John Wiley & Sons, Hoboken, NJ 2009.
5. A.M. Flynn: unpublished notes, Manhattan College, Bronx, NY, 2005.
6. J. Ni, A. Nikolova, M. Minnucci (JAM Associates), Manhattan College, Bronx, NY, 2010.