FACTA UNIVERSITATIS
Series: **Mechanical Engineering** Vol. 2, N° 1, 2004, pp. 135 - 140

EXERGY ANALYZING METHOD IN THE PROCESS INTEGRATION

UDC 536.73

Predrag Živković[1], Mirjana Laković[1], Predrag Rašković[2]

[1]Faculty of Mechanical Engineering, A. Medvedeva 14, 18000 Niš, Serbia and Montenegro
[2]Faculty of Technology, Trg Oslobođenja 124, 16000 Leskovac, Serbia and Montenegro

Abstract. *As a result of constant increase of energy consumption, the need for its rational usage also increases. For the purpose of energy savings, the methods of analysis, synthesis and optimization are becoming more important. The method of the Second Law of Thermodynamics is one of these methods. Its use gives good results in power and chemical plants optimization. In this way, it is also possible to obtain a significant increase of process efficiency. In this paper, the theoretical background of the Second Law analysis is given. The method is presented on the example of front end of the nitric acid production plant heat exchanger network system projecting. The use of this simple methodology is given in the form of 13 common sense guidelines, as well as a comparative analysis of the Second Law analysis and the Pinch design method.*

Key words: *Second Law Analysis, Destroyed Exergy, Common Sense Guidelines.*

INTRODUCTION

Traditionally, the basics of the energy systems studies were the Mass Conservation Law and the First Law of Thermodynamics. The Second Law was present only indirectly, in the TPE systems analyzing phase. Later, it was included by means of entropy, which is not feasible because of the non-conservability and absence of any direct and definite physical meaning. The usage of the Second Law was very simplified when the concepts of available work or exergy were introduced. It is closer to the terms of mass and energy, and has a concrete physical meaning but it is not conservative yet. It can be exceeded by taking into consideration exergy flows and losses. It means that conservation equations for exergy can be easily formulated and used, like the ones for mass and energy, which results in an additional set of equations. General acceptance of exergy led to a wide usage of the Second Law in all phases of the designing process, namely, in synthesis, analysis and optimization.

Received December 3, 2003

THERMODYNAMIC AVAILABILITY CHANGE ANALYSIS AT HEAT TRANSFER PROCESSES

The exergy of a stream is the maximum amount of work that can be obtained by bringing the stream into equilibrium with the ambient. For the processes involving only heat transfer, the exergy change is equal to the thermodynamic availability change, ΔB, where:

$$\Delta Ex = \Delta B = \Delta H - \Delta Exg = \Delta H - T_o \Delta S \quad (1)$$

and ΔH [W] – the heat transferred,
T_0 [K] – ambient temperature,
ΔS [W/K] – entropy change in the heat transfer processes.

Figure 1 depicts three characteristic cases of heat transfer considering stream temperature profiles related to ambient temperature. It should be noted that temperature profile slopes indicate a flow-heat-capacity difference of the shown flows and that an enthalpy change is related to the heat transfer between streams Q.

If both the streams are at the temperature above the ambient temperature (Fig. 1), the hot stream approaches $T_{0;}$ therefore, its availability decreases. The cold stream moves away from T_0, and, accordingly, its availability increases.

Conclusion – the hot stream transfers both heat and ability to the cold stream.

According to the Second Law, when driving forces (in form of a minimal temperature difference between flows $\Delta Tmin$ needed for heat transfer) are bigger than differential, all the processes are thermodynamically irreversible so the availability must be "consumed ". It is clear, by the space between the lines in Figure 1a, that the driving force is bigger than differential. Thus some of the availability in the hot stream is consumed.

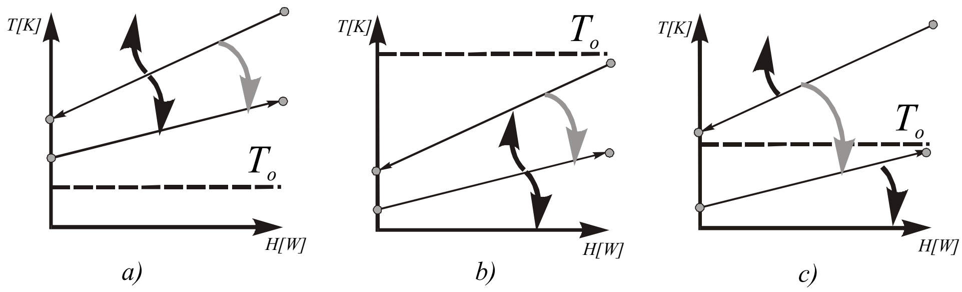


Fig. 1. Flow Availability Change Analysis in Heat Transfer Processes

The heat transfer process shown in Figure 1a can be made more thermodynamically reversible by reducing the approximate temperature between two streams. However, even with ΔT of zero at the close end, the heat exchange is still not reversible notwithstanding the fact that the infinite heat exchanger is required. Direct heat transfer between two streams can be reversible only if the ΔT approaches zero along the entire length of the exchanger, which is represented with identical slopes of *T-H* lines (identical heat-flow-capacities).

Conclusion – thermodynamic inefficiency increases as the disparity between the heat-flow-capacities increases.

Figure 1b depicts heat transfer between the two streams below the ambient temperature. Heat is transferred from the hot stream to the cold stream, as dictated by the Second Law. However, it is now the cold stream which approaches the ambient temperature, and therefore decreases in availability, while the hot stream diverges from the ambient temperature and increases in availability.

Conclusion – in heat transfer below the ambient, the availability is transferred in the opposite direction, *i.e.*, from the cold stream to the hot stream.

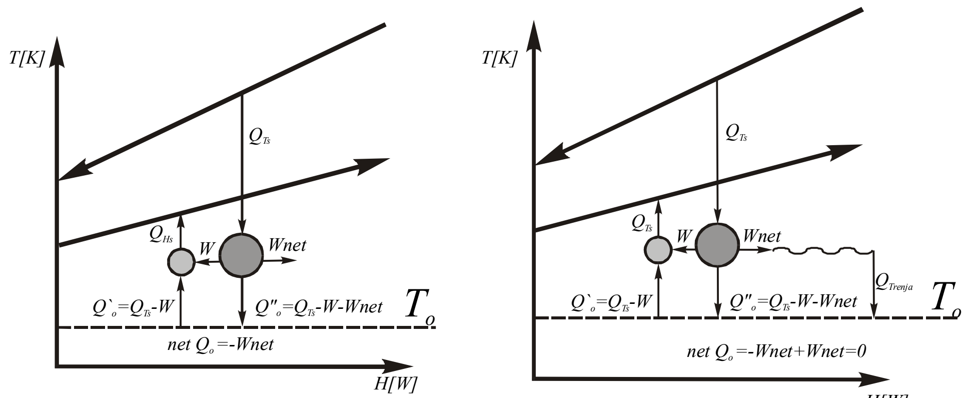
Figure 1c depicts heat transfer between two streams across the ambient temperature. Heat is transferred from the hot stream to the cold stream. However, both the streams approach the ambient temperature and, accordingly, both streams decrease in availability. Thus, in heat transfer across the ambient, no availability is transferred, but the availability of both streams is consumed. Heat from the ambient could have been used to heat the cold stream. Using the hot stream to heat the cold stream is an unnecessary waste of the temperature's driving force, i.e., of availability. The ambient represents a "pinch" temperature. This is, from a Second Law viewpoint, the cornerstone of pinch technology.

The availability analysis leads to another logical question, namely, where does the availability that is not transferred between streams go, that is, how it can be best used.

The traditional thermodynamic approach is based on the fact that heat transfer between streams of different heat-flow-capacities cannot be done reversibly, even with an infinite heat exchanger. The reversible work obtainable from the hot stream, or required to heat the cold stream, is:

$$W_{rev} = \int \frac{T - T_0}{T} dQ_H \qquad (2)$$

The amount of heat transferred, Q_H, from the hot stream is the same as transferred to the cold stream.



a) *b)*

Fig. 2. Flow Availability Loss Analysis at Heat Transfer Processes

The traditional thermodynamic approach does not take into account the equipment size and cost. The heat exchangers required in reversible heat engines and heat pumps must be infinite in size and are, therefore, infinite in cost. Additionally, it would take an infinite time for heat exchange to occur reversibly. The conclusion of this analysis is that it is possible to exchange heat only when there are finite temperature differences between streams, which causes availability consumption.

Except for the unavoidable availability loss in TPE plants, other losses resulting from the errors observed in the use of the Second Law can occur. An example is a high pressure steam throttling before being used for heat transfer. No work is produced, and there is no reduction in plant requirements, which increases the cost of the plant. As a conclusion to the above discussion, we have come to the following:

The availability in a stream can be:

1) Transferred to another stream
2) Used to produce work
3) Expended
   - To reduce equipment size and cost
   - To allow processes, such as heat transfer, to occur in a finite time
4) Destroyed without any benefit, i.e., a Second Law error

The identification of, and distinction between, items 3 and 4 is particularly important in any process design, including the design of *HENS*. Unfortunately, the current terminology does not make such a distinction. Hence, the sum of items 3 and 4 is often referred to as destroyed availability, or destroyed exergy.

METHODOLOGY FOR SECOND LAW DESIGN OF HENS

Existence of errors in existing heat exchanger network, like unnecessarily high pressure steam throttling, causes the lack of optimality of that network in the energy as in the financial way. It can be stated that a HEN with no Second Law errors in it, and which contains a minimal number of exchangers, is economically optimal.

In the case of grassroots design methodology for Second Law HENS designing is divided into 5 steps

1) Phase of obtaining initial solution - usually by a simple method, often Ponton and Donaldson's Fast matching algorithm,
2) Phase of error elimination – based on the following 13 common-sense Second Law guidelines,
3) Phase of calculating the minimal number of heat exchangers needed,
4) Phase of solution evaluation considering the number of exchangers and availability consumption, and,
5) Selection of an optimal solution.

Use of Second Law in Process Integration

It has been noted before that heat integration exergetical method represents an interactive method based on the following guidelines for elimination Second Law errors. The common-sense Second Law analysis was used by *Sama, Quian and Gaggioli* (1989). The following thirteen, simple and common-sense Second Law guidelines were proposed as an aid to detecting, or avoiding, Second Law errors.

1) Don't use excessive thermodynamic driving forces in process operations,
2) Minimize the mixing of streams with differences temperature, pressure or chemical composition,

3) Don't discard heat at high temperatures to the ambient, or to cooling water,
4) Don't heat refrigerated streams with hot streams or with cooling water,
5) When choosing streams for heat exchange, try to match streams where the final temperature of one is close to the initial temperature of the other,
6) When exchanging heat between two streams, the exchange is more efficient if the heat capacities of the streams are similar. If there is a big difference between the two, consider the splitting the stream with the larger heat capacity,
7) Minimize the use of intermediate heat transfer fluids when exchanging heat between two streams,
8) The more valuable heat (or refrigeration) is, the further its temperature from the ambient is,
9) The economic optimum ΔT at a heat exchanger decreases as the temperature decreases, and vice versa,
10) Minimize the throttling of steam, or other gases,
11) The larger the mass flow, the larger the opportunity to save (or to waste) energy,
12) Use simplified exergy consumption calculations as a guide to process modifications, and,
13) Some Second Law inefficiencies cannot be avoided unlike others. Concentrate on those which can.

Using the preceding guidelines, two unnecessary Second Law errors in the nitric acid plant design, shown in the second part of the paper, were easily detected and eliminated. The result was an increase in power output of over 34%, with only slightly higher capital costs.

CRITICAL REVIEW OF USING SECOND LAW ANALYSIS IN RELATION TO THE PINCH METHOD

The Introduction referring to Heat Integration thermodynamical methods also includes a discussion from the nineties about advantages of the exergetical method related to the Pinch method. The arguments of Second Law analysis defenders can be expressed as:

– Some practitioners of the pinch technology have suggested that efforts in Second Law analysis are irrelevant. The power of Second Law extends far beyond the singular concept that heat flows only from a higher temperature to a lower one. As a result, the pinch technology concept was seriously flawed.

– Heat transfer across the pinch is due to Second Law errors in the original design. This cross-pinch heat transfer is a result, not the cause, of the poor design. The Second Law approach is one of learning and understanding. It uses common sense and Second Law to easily avoid the poor design choices. It targets without efforts the true causes of the poor design, Second Law errors, so that the engineer can make appropriate adjustments.

– Finally, whereas the pinch technology (in that period) was limited to a relatively simple problem of heat exchanger network design, the suggested common-sense Second Law approach is also applicable to the efficient design of complex chemical and industrial processes. This can be seen by comparing the differences in the proposed designs for the integration of a nitric acid plant into an existing industrial complex arrived at using the Second Law analysis (Gaggioli, 1991.), and that arrived at via the pinch technology

(Linnhoff and Alanis, 1991.). The energy saved using the Second Law approach was far greater than that saved by the pinch technology.

Our opinion is that the use of the common-sense Second Law guidelines could present an even more successful method for relatively simpler problems (Domenic Sama has pointed to his critics the way of solving relatively simpler problems, for which his Second Law analysis gives the same solutions as the Pinch method, but in a much easier way). On the other hand, in the case of more complex problems, relaying on common sense principles clearly shows all its disadvantages related to the "compact" Pinch method mathematical model. Also, certain indistinctness in the guidelines can be noted in using the attributes excessive, high, and close; that puts the systematic character of this method into question.

REFERENCES

1. Sama, D. A. Difference between Second Law Analysis and Pinch Technology. Transactions of the ASME 1995, 117, 186 191.
2. Sama D. A. The Use of the Second Law of Thermodynamics in Process Design. Journal of Energy Resources Technology 1995, 117, 179 185.

METOD EKSERGETSKE ANALIZE PROCESNOJ INTEGRACIJI

Predrag Živković, Mirjana Laković, Predrag Rašković

Kao rezultat stalnog porasta utrošene energije, raste i potreba za njenim racionalnim korišćenjem. Radi uštede energije, metodi analize, sinteze i optimizacije postaju sve važniji. Metod Drugog Zakona termodinamike je jedan od ovih metoda. Dobijeni su dobri rezultati korišćenjem ovog metoda u optimizaciji energetskih i procesnih postrojenja. Na ovaj način je takođe moguće postići znatno povećanje efikasnosti procesa. U ovom radu su date teoretske osnove analiza Drugog Zakona. Metod je predstavljen na primeru projektovanja mreže razmenjivača toplote za prednji kraj postrojenja za proizvodnju azotne kiseline. Dato je korišćenje ove jednostavne metodologije u obliku 13 zdravorazumskih preporuka, kao i komparativna analiza Analiza Drugog Zakona i Pinč metode dizajniranja.

Ključne reči: *Analize Drugog Zakona, uništena eksergija, zdravorazumske preporuke.*