Applied Thermal Engineering 63 (2014) 468–479

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Energy transfer diagram for improving integration of industrial systems

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HIGHLIGHTS

- A new diagram for energy analysis is proposed.
- This diagram shows the conservation and degradation of energy in industrial process.
- All possible heat savings modifications in heat exchanger network can be identified with the diagram.
- It can be used to modify process operations in order to achieve heat savings.
- The diagram can also be used for site-wide analysis.

ARTICLE INFO

Article history:
Received 19 August 2013
Accepted 23 October 2013
Available online 12 November 2013

Keywords:
Energy integration
Retrofit
Heat-exchanger network
Exergy analysis
Site-wide analysis

ABSTRACT

In industrial processes, heat is transferred from the heating utilities to the environment or converted to another form of energy. Process operations and heat exchanges decrease the energy quality, i.e. the heat is cascaded to lower temperatures. This paper focuses on the energy retrofit analysis by screening the transfer of energy across process operations and heat exchangers. A new conceptual diagram is proposed to capture the flow rate of heat transferred from the heating utilities to the environment through each heat exchanger and process operation as a function of temperature. The diagram considers heat savings by retrofit of the process units and the heat exchanger network (HEN), which was not fully addressed by previous methods. As an example of application, the diagram is used to identify heat saving modifications in a furfural process, alone or hosted in a kraft pulp mill. The heat consumption in the furfural process alone can be reduced by 40% by two modifications in the HEN; the net heat consumption in the furfural process hosted in a kraft pulp mill can be reduced by 60%–84% with a few simple modifications in the HEN and process operations.

1. Introduction

1.1. Context and importance of the topic

The integration of industrial processes has positive economic and environmental impacts. Graphical methods have been widely used in the area of process integration [1–6]. Aided by these methods, many successful studies have been carried out. Most of these methods have been developed for grass-root design of heat exchanger networks (HEN) or mass exchange networks, where there is a large degree of freedom in the design. In retrofitting, the existing equipment constrains the opportunities for cost-efficient integration. Consequently information about the initial network has to be included; some analysis methods have thereafter been modified for retrofit situations [7–10]. However difficulties in application of existing approaches for HEN retrofit, especially when the heat and water networks are strongly interrelated, are still encountered; these are due to the lack of understanding of how the energy passes from the hot utilities to the environment. This shortcoming will be rectified in this paper, whose objective is to show that approaches for HEN retrofit can greatly benefit from considering the flow rate of heat cascaded through the existing heat exchangers and process operations.

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1359-4311/$ – see front matter
http://dx.doi.org/10.1016/j.applthermaleng.2013.10.046

Heat used in industrial processes is converted into electricity or chemical energy, or degraded through the HEN and unit operations. The process heat demands and sources are related by unit operations. For a plant-wide energy analysis, it is important to include the information about the degradation of energy due to the utility system, HEN, and process operations.

In this paper we present a graphical method for the analysis of an industrial plant heat system. The proposed diagram can be used to identify the heat savings modifications in the process operations and HEN. Energy transfer curves are proposed to represent the flow rate of heat transferred as a function of temperature through each process operation and heat exchanger from the heating utility to the environment. These curves are used to identify sets of modifications for improving the overall energy efficiency.

1.2. Earlier works

The representation of heat demands and sources with composite curves has contributed to the success of pinch analysis for heat exchanger network design [6]. The traditional hot, cold, and grand composite curves of Pinch analysis are based on process heat sources and demands. They do not include data about the existing HEN, although such information is important for the retrofit. The advanced composite curves [9–11] have been developed for HEN retrofit. These show in a single illustration the potential heat savings that would result from a reduced global temperature difference, the actual locations of heaters and coolers in the network before retrofit, the theoretical upper and lower temperatures of these, and the excess heat, both directly available and potential. These curves are used to estimate the heat-saving potential of economically feasible projects before detailed design calculations. The authors note that releasing heaters placed low in temperature and coolers placed high in temperature is usually easier and less expensive than releasing other heaters or coolers because fewer heat exchanger modifications and less exchange area are required. The curves can also be used to evaluate the amount of excess heat that can be extracted in practice at each temperature level for further heat integration.

Graphical tools also include the heat exchange area versus energy consumption plot, driving-force plot, and heat loads plot for the analysis of indirect-contact heat exchanger networks [12]. Pinch-based approaches have thereafter been developed to improve direct-contact heat exchange networks in grassroots or retrofit situation, e.g. water tank curves for the hot and warm water management in industrial processes [13,14]. Developments in data extraction for non-isothermal mixing and retrofit situation especially have been accomplished [15].

Energy is conserved and degraded though the process operations and heat exchanges. Reducing the overall heat demand implies reducing the flow rate of heat transferred from the heating utility to the environment through the operations or the heat exchanges. Although the concept of a heat cascade has been in use for many years, the progressive transfer of heat, through the process operations and existing heat exchanges from the heating utility to the environment, is not explicitly analyzed in the present methods for heat integration retrofit. The advanced composite curves which have been developed for HEN retrofit do represent the flow rate of cascaded heat through the existing heaters and coolers, but do not represent the transfers in the existing process–process heat exchangers, nor in the individual process operations. To reduce the heat consumption in an existing HEN implies bridging heat outlets to hot utility users via a set of HEN modifications. Bridge analysis enumerates the fundamental sets of modifications, which are termed “bridges”. A bridge links heat outlets to hot utility users through a set of modifications. All the bridges can be identified on an energy transfer diagram. Although all the bridges can be systematically identified with an algorithm, the energy transfer diagram presented in this paper is useful to understand the principles of bridge analysis.

1.3. Objectives of the paper

This paper presents the fundamental thermodynamic insights to better understand and to visualize the degradation of energy while passing through the HEN and process operations. The proposed diagram provides a global picture about the plant energy system and the possible modifications for energy efficiency improvement.

More specifically, the objectives are the following:

- To present the concept of energy transfer curve
- To present how to use the proposed diagram
- To present an application for the energy analysis of an industrial process.

1.4. Organization of the paper

Principles of bridge analysis to reduce the heat consumption by HEN retrofit are first presented. The second part includes a general presentation of the diagram and describes the concept of energy transfer curve, which represents the flow rate of heat transferred through a heat exchanger or process operation as a function of temperature. To illustrate the concept, the energy transfer curves corresponding to a heat exchanger and a distillation column system are then evaluated. The next part explains how to identify heat savings modifications in the HEN or process operations. Finally, the diagram is used for the heat integration of a furfural production process.

1.5. Terminology and conventions

Heat is transferred in a heat exchanger from a supplier to a receptor. Supplier of cooling system C_x, internal (process–process) heat exchanger E_y, and heater H_z are notedc_x^s, e_y^s andh_z^s, respectively. Receptor of cooling system C_x, internal (process–process) heat exchanger E_y and heater H_z are noted c_x^r, e_y^r and h_z^r respectively. These conventions are summarized in Table 1. The supplier in a heater comes from a heating utility *HU*. Heat is sent to the environment through a cooling system. A match is a couple composed of a supplier and receptor. For example, the match corresponding to heater c_x^s is noted $h_z^s h_z^r$.

The conventions are the following:

c_x^r: Receptor of cooling system C_x (environment)
c_x^s: Supplier of cooling system C_x
C_x: Cooling system
E_y: Internal heat exchanger
e_y^r: Receptor of internal heat exchanger E_y

Table 1
Conventions for heat exchanges.

Equipment	Cooling system, C_x	Internal heat exchanger, E_y	Heater, H_z
Match	$c_x^s c_x^r$	$e_y^s e_y^r$	$h_z^s h_z^r$
Source stream	Process sources		Heating utility, HU
Supplier	c_x^s	e_y^s	h_z^s
Heat transfer	↓	↓	↓
Receptor	c_x^r	e_y^r	h_z^r
Sink stream	Environment, Env	Process demand	