Energy 86 (2015) 696–708

Contents lists available at ScienceDirect

Energy

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

Entransy dissipation-based constraint for optimization of heat exchanger networks in thermal systems

Yun-Chao Xu, Qun Chen*, Zeng-Yuan Guo

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

A R T I C L E I N F O

Article history:
Received 10 February 2015
Received in revised form
5 April 2015
Accepted 21 April 2015
Available online 18 May 2015

Keywords:
Heat exchanger network
Global optimization
Energy conservation
Entransy dissipation
Entropy generation

A B S T R A C T

The Lagrange multiplier method is introduced for the global optimization of HENs (heat exchanger networks) with fixed layouts to give the optimal configuration of thermal systems that cannot be determined by other methods, such as HEN synthesis or linear programming method. A four-loop HEN with five heat exchangers and heat exchangers in thermodynamic systems are optimized as two examples from different perspectives. The first perspective is based on energy conservation where the energy and heat transfer equations act as the constraints in the Lagrange function. The second perspective is the heat transfer irreversibility where the entransy dissipation-based equation acts as the constraint. The entransy dissipation-based constraint eliminates the number of unknown intermediate fluid temperatures in the HENs and the corresponding number of constraints for HENs in thermal systems, which greatly simplifies the solution of optimization equations. Although the entropy generation-based equation can also act as a constraint, the intermediate fluid temperatures in the HENs cannot be eliminated because the entropy generation is a function of the absolute fluid temperature. As a result, the number of constraints is the same as when using energy conservation, so the optimization procedure for multi-component thermal systems cannot be simplified.

1. Introduction

Heat exchanger networks are significant parts of many thermal systems such as power plants, chemical engineering plants and heating, ventilation, air conditioning, and thermal management systems. Improving the performance of heat exchanger networks will significantly improve energy conservation and reduce pollution reduction. Therefore, recent decades have seen many optimization-related studies of heat exchanger networks [1].

Among these heat exchanger network optimization literature, many have been for heat exchanger network synthesis in chemical engineering systems. In such systems, the heat capacity rates and the inlet and target temperatures of all the hot and cold streams are known in advance, with heat exchanger network synthesis then used to find the optimal network design, i.e. the pairing the hot and cold streams for the heat transfer, and the number, locations and areas of heat exchangers, to maximize the energy recovery and minimize the network cost. Optimal heat exchanger network synthesis methods have used the sequential synthesis and simultaneous synthesis [1]. In the sequential synthesis method, the pinch design method decomposes the problem into several sub-problems with different optimization objectives such as the maximum energy recovery, the least number of heat exchanger units or the minimum total cost [2–4]. However, because energy recovery, number of unit and cost actually influence each other, the sequential synthesis may not lead to the most optimal networks [5,6]. Therefore, studies have used mathematical programming algorithms to consider different variables and targets together to simultaneously synthesize the heat exchanger networks [5,7–10].

Heat exchanger network synthesis deals with the layout of the heat exchanger networks for prescribed stream heat capacity rates. However, designers often confront another situation where the network layout has been fixed and the stream heat capacity rates are not given, so the stream heat capacity rates and the heat exchanger areas need to be optimized to realize certain targets, such as minimizing the total cost, the total heat exchanger area or the pumping power. Quesada and Grossman [11] studied the global optimization of a heat exchanger network with a fixed topology and focused on the effects of different approximations on the objective function. Bojic and Trifunovic separately applied the linear

* Corresponding author. Tel.: +86 10 62796332.
E-mail address: chenqun@tsinghua.edu.cn (Q. Chen).

http://dx.doi.org/10.1016/j.energy.2015.04.024
0360-5442/

Nomenclatures

A	area, m^2
c_p	constant pressure specific heat, J kg^{-1} K^{-1}
F	Lagrange function
G	entransy flow rate, W K
k	heat transfer coefficient, W m^{-2} K^{-1}
m	mass flow rate, kg s^{-1}
n	number of loops in the heat exchanger network
p	pressure, Pa
q	heat flux, W m^{-2}
Q	heat transfer rate, W
R	entransy dissipation-based thermal resistance, K W^{-1}
S_g	entropy generation rate, W K^{-1}
T	temperature, K
x	thermal conductance allocation ratio
λ, α, β	Lagrange multipliers
π	pressure ratio
Φ	entransy dissipation rate, W K

Subscripts

am	arithmetic mean
c	cold fluid
h	hot fluid
HX	heat exchanger
i	inlet
l	cold end
o	outlet
w	isothermal fluid

programming method [12] and the mixed 1-0 sequential linear programming method [13] to optimize a district heating network with the aim of maximizing the thermal comfort.

Although better heat exchanger network performance can be obtained using both heat exchanger network synthesis and optimization parameter design with a fixed structure, such designs still need two types of improvements. One is that the objective function and constraints obtain the preferable configuration by selecting a better solution among all the possible configurations, rather than establishing the optimization equation set and solving the equations to directly reach the optimal solution. The other is that the procedure for deducing the models relies on the energy conservation and heat transfer equations, rather than on the heat transfer irreversibility.

Energy is conserved during heat transfer processes in heat exchangers, but heat transfer irreversibilities always exist due to the finite temperature difference between the hot and cold fluids. The structural and operating parameters of heat exchanger networks have been optimized by analyzing the whole system in terms of the irreversibilities. The entropy generation is widely used as a typical irreversibility measure to optimize both heat transfer processes and thermal systems, where the entropy generation (or exergy destruction) is minimized to obtain the best performance in both heat transfer processes and thermal systems [14–19]. However, the practical optimization objectives for thermal systems differ for different applications and the boundary conditions are usually quite complex, so the best thermal system performance does not always correspond to a single optimization objective [20,21], especially when a thermal system has multiple power, heating and cooling outputs. Sekulic et al. declared [22] that “it is unlikely that any of them will operate ideally on any basis, including an entropy basis and an exergy basis.” Therefore, optimization of practical thermal systems is still a problem.

Due to the limits on the use of entropy generation (or exergy destruction) minimization to optimize heat transfer processes, Guo et al. [23,24] introduced a physical quantity called entransy to describe the heat transfer ability of an object during a pure heat transfer process, which is not related to the heat-work conversion. In addition, they deduced the expression for the entransy dissipation as an alternative measure for the heat transfer irreversibility. The entransy dissipation extremum corresponds to the maximum heat transfer coefficient, which Bergles declared [25] is a practical optimization objective for heat transfer processes with prescribed heat loads, thermal conductance, and inlet velocities and temperatures. The entransy dissipation extremum can then be used as an alternative optimization objective for heat transfer processes [20,26–28]. Also, others [29,30] have tried to extend the entransy dissipation extremum principle to thermal system optimization, but the complex structures and multiple purposes made applications of the entransy dissipation extremum to be a case dependent, rather than a general objective for thermal system optimization. Therefore, a different entransy-based method for thermal system optimization was introduced where the entransy balance equation acts as a constraint [31–36].

Sekulic et al. [22] challenged the value of entransy for optimizing thermal systems but did not distinguish the difference between entransy-based optimization methods in heat transfer processes and thermal systems. They claimed that the entropy-based method is universally applicable which entransy-optimized outcomes seldom have real world value and heat transfer processes or heat exchangers should not be optimized in isolation but only in concert with other system components. As has been requested by the editors, this paper shows if entransy dissipation-based method has advantages for the optimization of heat exchanger networks in thermal systems in comparison with entropy or exergy methods.

2. Analyses of heat exchanger networks from the perspective of energy conservation

2.1. Analysis of an individual heat exchanger

Consider the counter-flow heat exchanger shown in Fig. 1 as an example. The heat transfer rate can be expressed as the heat released from the hot fluid, received by the cold fluid or transferred between the two fluids.

The energy conservation equations for the hot and the cold fluids are

$$Q = (mc_p)_h(T_{h,i} - T_{h,o}), \tag{1a}$$

$$Q = (mc_p)_c(T_{c,o} - T_{c,i}). \tag{1b}$$

The heat transfer rate between the fluids is given by

$$Q = (kA)\frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln\frac{T_{h,o}-T_{c,i}}{T_{h,i}-T_{c,o}}}. \tag{1c}$$

where T is the temperature, m is the mass flow rate, c_p is the constant pressure specific heat, mc_p is the fluid heat capacity rate, Q is the heat transfer rate and (kA) the thermal conductance of the heat exchanger. Subscripts i and o represent the heat exchanger inlet and the outlet and h and c represent the hot and the cold fluids.