Energy xxx (2016) 1–12

Contents lists available at ScienceDirect

Energy

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

Correct integration of compressors and expanders in above ambient heat exchanger networks

Chao Fu*, Truls Gundersen

Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form
19 May 2016
Accepted 21 May 2016
Available online xxx

Keywords:
Correct integration
Heat exchanger network
Compressor
Expander
Exergy

ABSTRACT

The Appropriate Placement concept (also referred to as Correct Integration) is fundamental in Pinch Analysis. The placement of reactors, distillation columns, evaporators, heat pumps and heat engines in heat exchanger networks is well established. The placement of pressure changing equipment such as compressors and expanders is complex and less discussed in literature. A major difficulty is that both heat and work (not only heat) are involved. The integration of compressors and expanders separately into heat exchanger networks was recently investigated. A set of theorems were proposed for assisting the design. The problem is even more complex when both compressors and expanders are to be integrated. An important concern is about the sequence of integration with compressors and expanders, i.e. should compressors or expanders be implemented first. This problem is studied and a new theorem is formulated related to the Correct Integration of both compressors and expanders in above ambient heat exchanger networks. The objective is to minimize exergy consumption for the integrated processes. A graphical design methodology is developed for the integration of compressors and expanders into heat exchanger networks above ambient temperature.

1. Introduction

Energy efficiency is expected to make the largest contribution to global emission reductions in the 2 °C scenario [1]. It will account for 38% of cumulative emission reductions until 2050. For comparison, renewables and CCS (carbon capture and storage) are responsible for 30% and 14%, respectively. Pinch Analysis (PA) [2] has proven to be an efficient methodology for improving energy efficiency in the past decades. The pinch temperature is fixed for a given minimum temperature difference for heat transfer (ΔT_{min}). Heat is exchanged separately above/below the pinch temperature. The minimum heating/cooling demands can then be identified. Any heat transfer across the pinch temperature increases both heating and cooling demands. Mathematical programming is another efficient methodology for dealing with heat recovery problems. The transshipment model [3] has been used as the basis of many optimization studies related to heat exchanger networks (HENs). It has also been used for the stepwise optimization and heat integration of chemical processes [4]. While early optimization approaches for HENs used a sequential approach, new superstructures enabled fully simultaneous optimization [5]. More recent studies have focused on the improvement of mathematical optimization models where retrofitting [6] and practical issues such as heat transfer intensification, pressure drop constraints and fouling mitigation [7] were considered. Graphical methods for retrofitting cases have also been proposed [8].

The concept of Appropriate Placement, also referred to as Correct Integration, is fundamental in Pinch Analysis, and represents a special case of the plus/minus principle [9]. A quantitative approach is based on the Grand Composite Curve (GCC) that gives the amount of heat that can be correctly integrated. While this type of analysis is simple for reactors [10], distillation columns [11], evaporators [12], heat pumps and heat engines [13], it is considerably more complicated for compressors and expanders since both heat and work are involved. The problem is thus extended to the integration of both heat and work. In addition, the shape of the GCC will change since the streams to be compressed or expanded are included when drawing the GCC. The placement of compressors was briefly discussed in the work by Glavič et al. [10] with focus on reactor systems. Aspelund et al. [14] formulated two heuristic rules for the placement of compressors and expanders in heat exchanger networks (HENs): (i) compression adds heat to the system and should

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* Corresponding author.
E-mail address: fuchao83@hotmail.com (C. Fu).

http://dx.doi.org/10.1016/j.energy.2016.05.092
0360-5442/

preferably be done above pinch, and (ii) expansion provides cooling to the system and should preferably be done below pinch. The rules were stated more specifically by Gundersen et al. [15] in the sense that both compression and expansion should start at the pinch temperature. An application example is the recuperative vapor recompression cryogenic air distillation process developed by Fu and Gundersen [16]. On the basis of the heuristic rules proposed by Gundersen et al. [15], Wechsung et al. [17] presented an MINLP optimization formulation for the synthesis of sub-ambient HENs including compression and expansion. The work is further extended by Onishi et al. [18] using a superstructure with the objective of minimizing total annualized cost. The recovery of low temperature (“waste”) heat using CO_2 power cycles has attracted increasing interest. Mondal and De [19] investigated CO_2 power cycles with multi-stage compression and intercooling. The trade-off between heat and work consumptions was an important concern in the study. Kansha et al. [20] developed a self-heat recuperation scheme and applied it to dimethyl ether production where compression heat had been utilized at the expense of more work being consumed. Ashrafi et al. [21] studied energy saving opportunities using heat pumps in a slaughterhouse. Again the trade-off between heat and work consumptions is important in the latter two studies.

The above literature review clearly shows that the integration between heat and work is an emerging research topic that can result in attractive energy saving opportunities in process industry. However, systematic design methodologies are not available in previous studies for this complex integration. The integration of compressors and expanders into HENs is not a straightforward task following the heuristic rules proposed by Gundersen et al. [15]. More recently, Fu and Gundersen [22] developed a set of fundamental theorems for the integration of expanders into above ambient HENs. Mathematical analyses and thermodynamic insights were used in the proofs of the theorems. Theorems for the integration of compressors [23] were developed in a similar way. Symmetry was found between the integration of expanders into below ambient HENs [24] and the integration of compressors into above ambient HENs [23]. Similar symmetry was also found between the integration of compressors into below ambient HENs [25] and the integration of expanders into above ambient HENs [22]. A notable advantage of these studies is that the integration of heat and work can be investigated using a straightforward graphical design procedure. However, the integration of both compressors and expanders was not investigated. The heat resulting from compression may be used for preheating a stream that is subject to expansion. As a result, more expansion work is recovered. Alternatively, the cooling resulting from expansion may be used for precooling a stream to be compressed. Less compression work is then consumed. The sequence of integrating compressors and expanders is thus an important concern, i.e. should compression or expansion be implemented first.

On the basis of the previous theorems proposed for separate integration of expanders and compressors, this paper develops a systematic methodology for the integration of both compressors and expanders into above ambient HENs. The objective is to minimize exergy consumption. The paper is an extension of the work by Fu and Gundersen [26]. A notable advantage of the current methodology is that it uses fundamental insight that is derived from thermodynamic and mathematical analyses. Graphical design procedures are proposed and the physical background is explicitly shown. The design procedures can be easily applied in combination with mathematical optimization approaches in future developments. As a result, the size of the optimization problem can be reduced and it is easier to find optimal solutions.

2. Problem statement

Design of Work and Heat Exchange Networks (WHEN) can be stated as follows: “Given a set of process streams with supply and target states (temperature and pressure), as well as utilities for power, heating and cooling; design a network of heat exchangers, compressors and expanders in such a way that the exergy consumption is minimized or the exergy production is maximized”.

The following assumptions are made: (1) supply and target states (temperature and pressure) for process streams and utilities for heating and cooling are given; (2) only one hot utility with constant temperature is used; (3) the compressor and expander polytropic efficiencies $\eta_{\infty,comp}$ and $\eta_{\infty,exp}$ are constant, (4) the fluid to be compressed/expanded behaves like ideal gas with constant specific heat ratio $\kappa \equiv c_p/c_v$, and (5) the reference temperature for exergy is equal to the ambient temperature (T_0) and also equal to the constant cold utility temperature, thus the exergy of cold utility is zero.

These assumptions are primarily introduced to simplify the calculations and proofs. For industrial use, simple hand calculations must be replaced by rigorous simulations. Assumption (1) is valid unless the basic process and/or utility system should also be optimized. Assumption (2) is a limitation in many industrial cases, and it represents an area of future research for the methodology. Assumptions (3) and (4) do not affect the methodology, only the way temperatures and energies are calculated. Of course, the exergies and savings will change. Assumption (5) makes it possible to neglect the exergy of cold utility. If cold utility temperature is different from the reference temperature for exergy and also non-constant (as the case is with cooling water or air), small values for exergy consumption related to the use of cold utility would result. However, since use of the proposed procedure reduces hot and cold utility consumption, the savings in exergy would be larger if the exergy of cold utility had been taken into account.

The stream data for an illustrative example is shown in Table 1, where T_s and T_t are the supply and target temperatures, p_s and p_t are the supply and target pressures, mc_p is the heat capacity flowrate, and ΔH is the enthalpy change due to temperature change. The following parameters are used: (i) $\eta_{\infty,comp} = \eta_{\infty,exp} = 1$, (ii) $\Delta T_{min} = 20$ °C, (iii) ambient temperature (T_0) and cold utility temperature (T_{CU}) are both 15 °C, (iv) hot utility temperature $T_{HU} = 400$ °C, and (v) $\kappa = 1.4$.

The question to be addressed is at what temperatures streams C1 and H1 should be compressed/expanded so that the total exergy consumption is minimized.

3. Theorems

This section presents a set of theorems that are used as basis for a design procedure for WHENs. Theorems developed in earlier work are first briefly introduced. A new theorem is then proposed and proven for the integration of both compressors and expanders. An example is used to illustrate this new theorem.

3.1. Earlier work

The following theorems have been developed for the integration of compressors in above ambient HENs with the objective of minimizing exergy consumption [23].

(1) A HEN design with Pinch Compression (compression starts at pinch temperature T_{PI}) consumes the smallest amount of exergy if the following conditions are satisfied: (i) the outlet temperature of Ambient Compression (compression starts at T_0), $T_{comp,0}$, is lower than T_{HU}, and (ii) Pinch Compression does not produce more heating than required.

Please cite this article in press as: Fu C, Gundersen T, Correct integration of compressors and expanders in above ambient heat exchanger networks, Energy (2016), http://dx.doi.org/10.1016/j.energy.2016.05.092