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Challenges in Work and Heat Integration

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Heat Integration has achieved a great success in both academic research and industrial applications since the 1970s. Traditional heat integration deals with process streams with temperature changes only. Pressure is an equally important parameter in the process industry. When the changes in both temperatures and pressures of streams are taken in consideration, the problem is extended from Heat Integration to Work and Heat Integration. The latter is much more complex due to the following reasons: (1) change in the pressure of a stream normally results in a change in temperature that influences the definition of the Heat Integration problem; (2) the amount of work consumed/produced will vary as a result of any change in the operating temperature of a stream before being compressed or expanded; and (3) work and heat have different energy quality (exergy). Work and Heat Integration is an emerging new research topic that has attracted increasing interest recently. This paper introduces the development and challenges for the topic with a focus on the following objectives: (1) a clear definition of Work and Heat Integration is presented; (2) a review of available literature related to this topic is performed; (3) the challenges in this topic using the Pinch Design Method and/or Mathematical Programming are addressed; and (4) potential industrial applications and the corresponding limitations are introduced.

1. Introduction

Heat Integration (HI) has achieved a great success in both academic research and industrial applications since the 1970s. Heat Exchanger Networks (HENs) design is the key research topic in HI. There are two well-defined methodologies for HEN design. The first is based on the concept of a heat recovery pinch with early pioneering work by Hohmann (1971) who presented the feasibility table for energy targeting, Huang and Elshout (1976) who were the first to publish Composite Curves, Linnhoff et al. (1979) who emphasized the decomposition effect of the Pinch, and Umeda et al. (1978) who presented an available energy diagram where composite lines were drawn showing the Pinch. The second one is based on Mathematical Programming and is motivated by the need for solving large-size HEN design problems, and to properly account for the economic trade-offs. The pioneering work is the models developed by Papoulias and Grossmann (1983).
Traditional heat integration deals with process streams with temperature changes only. Pressure is an equally important parameter in the process industry. Pressure manipulations such as compression/expansion of a stream normally result in a temperature change of the stream. For example, the temperature of a stream increases/decreases in an adiabatic compression/expansion process. Similarly, temperature manipulations of a stream by heating/cooling prior to the pressure manipulations can also change the work consumption/production. For example, the compression/expansion work increases when a stream is compressed/expanded at higher temperatures. When the changes in both temperature and pressure of streams are taken in consideration, the problem is extended from HI to Work and Heat Integration (WHI). The latter is much more complex due to the following reasons: (1) change in the pressure of a stream normally results in a change in temperature that influences the definition of the HI problem; (2) the amount of work consumed/produced will vary as a result of any change in the operating temperature of a stream before being compressed or expanded; and (3) work and heat have different energy quality (exergy).
Work and Heat Integration is an emerging research area that has attracted increasing research interest in recent years, although a common agreement on its definition has not yet been achieved. A special session entitled

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"Work and Heat Exchange Networks" (WHEN) has been organized in the 20th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction – PRES'17. One objective of the session is to share common interest and experiences in the research area of WHEN design. As one of the contributions to the special session, this work addresses the challenges in WHI with a focus on the following objectives: (1) a clear definition of WHI is presented; (2) a short review of available literature related to the topic is performed; (3) the challenges in studying the topic using the Pinch Design Method and/or Mathematical Programming are addressed; and (4) potential industrial applications and corresponding limitations are introduced.

2. Problem definitions

Fu and Gundersen (2016a) presented fundamental insights and the definition of WHI. The problem is stated in the following way: "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 work and heat exchange network of heat transfer equipment such as heat exchangers, evaporators and condensers, as well as pressure changing equipment such as compressors, expanders, pumps and valves, in such a way that the exergy consumption is minimized or the exergy production is maximized". The topic can also be extended to use economic performance as the objective, e.g. minimizing total annualized cost.
The differences in problem definitions between HI and WHI are illustrated in Figure 1. In the case of HI, only the temperatures of process streams change. In the WHI case, pressure manipulation of process streams, power utility and pressure changing equipment such as compressors and expanders are involved in addition to the elements defined in the HI problem.

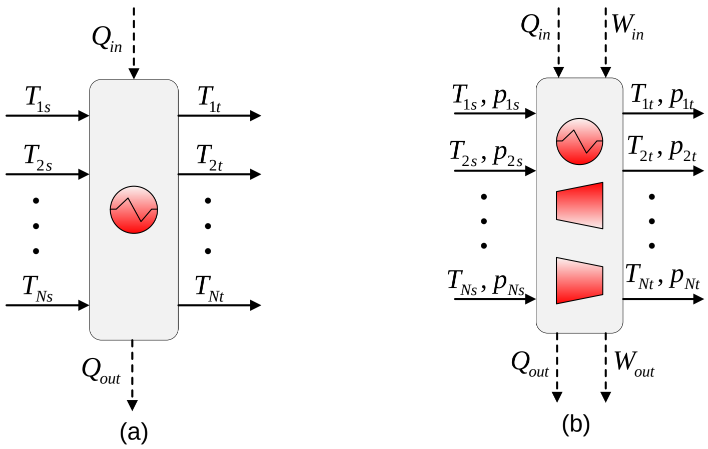

Figure 1: Illustration of problem definitions: (a) HI, and (b) WHI

3. A short literature review

Similar to HENs, El-Halwagi and Manousiouthakis (1989) proposed Mass Exchange Networks (MENs) that enable mass exchange between the rich and lean process streams. The MENs focus on the changes in concentration of process streams. Analogous to the HEN and MEN problem, the Work Exchange Networks (WENs) focus on the matching of compressors and expanders. Huang and Fan (1996) presented an analytical study of WENs for the recovery of mechanical energy. A mathematical optimization approach was developed for WEN design by Razib et al. (2012). Liu et al. (2014) developed a graphical approach for the design of WENs. Liu and Du (2013) presented a study on the simultaneous synthesis of combined mass and heat exchange networks (CMAHENs).
The design of WHENs is related to the concept of Appropriate Placement for pressure-changing equipment such as compressors and expanders in heat exchanger networks. Townsend and Linnhoff (1983) studied heat engines and heat pumps with focus on appropriate placement, and their work has some similarities to WHEN design, however, heat engines and heat pumps do not change the process streams since separate working fluids are used. The placement of compressors and expanders is defined by the inlet temperature of these units. The operation of compressors was briefly discussed by Glavič et al. (1989) with a focus on reactor systems. It was indicated that compressors act like hot utilities and can be placed above the Pinch temperature. Aspelund et al. (2007) proposed the following heuristic rules for the placement of compressors and expanders: (1) compression adds heat to the system and should preferably be done above Pinch; and (2) expansion provides

cooling to the system and should preferably be done below Pinch. Gundersen et al. (2009) stated the heuristic rules more specifically: both compression and expansion should start at the Pinch temperature. Kansha et al. (2009) developed a self-heat recuperation scheme where the compression heat has been utilized. Although it was not explicitly stated, both compression and expansion start at the Pinch temperature in the self-heat recuperation scheme. There are also several Mathematical Programming studies on the design of WHENs. Wechsung et al. (2011) presented an MINLP optimization study for the design of sub-ambient HENs including compressors and expanders. Onishi et al. (2014a) extended the work and used different Pinch operators to minimize total annualized cost. The authors also developed a superstructure for work exchange networks that interacts with heat exchanger networks (2014b). Dong et al. (2014) presented an optimization study on heat, mass, and pressure exchange networks.

A set of fundamental theorems has recently been proposed for the integration of compressors (Fu and Gundersen, 2015a) and expanders (Fu and Gundersen, 2015b) into above ambient heat exchanger networks (HENs). Considerable symmetry has been found for the integration of expanders (Fu and Gundersen, 2015c) and compressors (Fu and Gundersen, 2015d) into sub-ambient HENs. The objective has been to minimize exergy consumption. On the basis of these theorems, systematic graphical design procedures have been developed for WHI (Fu and Gundersen, 2015e). It was concluded that compression/expansion should start at Pinch, ambient, or cold/hot utility temperatures depending on the actual design problem. In many cases, compression/expansion at Pinch temperature (referred to as Pinch Compression/Expansion) can significantly reduce hot and cold utilities as well as exergy consumption. In the graphical design procedures, the Grand Composite Curve (GCC) has been used for identifying the maximum portions of streams that can use Pinch Compression/Expansion. Stream splitting is used in order to achieve the objective of minimum exergy consumption.

4. Challenges in WHI

Although quite a few studies have been performed on the topic of WHI, as described in previous literature review, there are some challenges and remaining problems in both fundamental research and applications. The challenges are described in the following sections.

4.1 Targeting

The GCC has been developed as part of Pinch Analysis for the targeting and selection of utilities at an early stage of process design. The targeting is a considerable challenge when both heat and work are involved. The reason is that heat and work have different energy qualities, i.e. exergy. Exergy is a thermodynamic parameter that can be used to calculate the theoretical work content of heat and may thus be used to combine heat and work. Several studies attempted to set the minimum exergy target where both heat and work are involved. Linnhoff and Dhole (1992) introduced the Exergy Grand Composite Curve. The heat target was converted into an exergy target using the Carnot factor. Feng and Zhu (1997) introduced the energy level (defined as the ratio between exergy and energy) to set the exergy target. Marmolejo-Correa and Gundersen (2013) proposed a new graphical approach for exergy targets based on the decomposition of exergy into temperature and pressure based parts. The interactions between temperature changes and pressure changes of streams have not been considered in these studies.

The targeting of WHENs, e.g. minimum exergy consumption, can be very helpful for both grassroots and retrofit designs of WHENs since the targets on utility consumptions can be known before the design process. Methodologies for such targeting have not yet been developed. Further research work on this topic is expected.

4.2 Fundamental thermodynamic insights

The fundamental theorems developed mentioned above have the following limitations:

(1) The theorems mainly apply to one stream being compressed/expanded. When multiple streams are involved, the integration sequence of streams being compressed/expanded represents a challenge. The sequence influences the thermodynamic losses related to heat transfer between the streams with pressure changes and other process streams.

(2) The pressure manipulations have been assumed to be operated with a single stage. Multiple stages can be used when the pressure ratios are large. The splitting of pressure ratios and the integration sequence are challenges.

(3) A single hot and cold utility with constant temperatures are assumed. Further validations and modifications of the theorems are necessary when utilities with non-constant temperatures and/or multiple-utilities are involved.

(4) Exergy has been used as a thermodynamic parameter in the objective function in order to include both heat and work. The exergy content of heat is calculated using the Carnot factor that is related to

reversible processes. Work is more valuable than the exergy content of heat from the viewpoint of thermodynamics.

Further fundamental theoretical research on these limitations will enable the realization of more general applications of WHI. The Mathematical Programming studies on this topic may also benefit from the fundamental research work.

4.3 Mathematical Programming

The Pinch Design Method can be time consuming when dealing with large size HEN problems. It is also a considerable challenge when the entire process is to be optimized. In this case, the stream temperatures can be variables, which is hard to handle in the Pinch Design Method. The Mathematical Programming method is more competitive when solving such problems. However, it may still be very time consuming or even impossible to solve the mathematical models when the problems are too complex, e.g. nonlinear, nonconvex and too many binary variables involved. The Pinch Design and Mathematical Programming methods are thus often combined so that the problems are simplified and/or easier to solve.

As indicated in the Introduction section, the WHI problem is much more complex than the HI problem. Actually, the design of WHENs could be time consuming even for a small size problem with only one stream being compressed/expanded (see examples in Fu and Gundersen, 2015a-d). Mathematical Programming approaches should be developed for the design of WHENs. Compared to the studies on HENs, a considerable challenge for WHENs is that the Pinch Points are not fixed due to pressure manipulations of streams. The problem can be nonlinear and nonconvex with binary variables being included or possibly non-smooth without binary variables included. More details can be found in the work by Vikse et al. (2017).

The complexity of the mathematical models is expected to be considerably reduced with the utilization of fundamental thermodynamic insights. Maurstad Uv (2016) has performed a preliminary mathematical optimization study on the design of WHENs. It has been shown that the problem can be simplified from Mixed Integer Nonlinear Programming (MINLP) models to Linear Programming (LP) models with the help of fundamental insights developed by Fu and Gundersen as mentioned above. The study also helped improving the fundamental insights. The following new insight has been formulated for the choice of the best true Pinch temperature: The Pinch identity (hot or cold) should be the same as the identity of the stream segment at the inlet of compression/expansion.

Due to the limitations of the fundamental thermodynamic insights that have been developed as introduced in Section 4.2, the combination of the Mathematical Programming method and fundamental insights is currently limited to some small size problems. Further developments of both the insights and the mathematical models are essential to be able to deal with large size problems.

4.4 Industrial applications

WHI has promising industrial applications in both above and sub ambient temperature processes. Some studies related to the potential applications of WHI have already been investigated, e.g. the application of the Self-Heat Recuperation scheme in azeotropic distillation processes (Kansha et al., 2009) , the utilization of compression heat for boiler feedwater preheating processes (Fu et al., 2015f), the design of LNG processes using liquid CO_2 and N_2 as cold carriers (Wechsung et al., 2011), simple applications in CO_2 capture processes (Fu and Gundersen, 2016a), and the industrial sensible heat pump (Fu and Gundersen, 2016b). However, there are some challenges as introduced in the following section to realize the applications in industry.

The operating temperature of compressors and expanders is a considerable challenge. WHI requires compressors/expanders to be operated at temperatures out of normal operating ranges. For example, a stream may be preheated before being compressed in order to upgrade the compression heat and utilize it. As a result, the compressor is operated above ambient temperature. The operating temperature could be limited by the materials of construction. In addition, the efficiencies of compressors/expanders vary with operating temperatures. Constant efficiencies are assumed for simplification in the studies by Fu and Gundersen (2015a-e). The variation of efficiencies with temperature should be investigated in order to quantify the energy saving potentials more precisely.

Economics is an important concern when it comes to industrial applications. The pressure change equipment such as compressors and expanders are normally much more complex and expensive than heat exchangers. It is thus important to reduce the number of compressors/expanders used, e.g. the splitting of streams to be compressed/expanded should be fully justified by the additional energy savings. At an early stage of a process design, it is normally difficult to perform detailed economic analyses. Similar to the Pinch Design Method, heuristic rules related to the removal of small units would be very helpful for WHEN designs if the rules could be developed.

The objective in the problem definition as presented in Section 2 has been focused on thermodynamic performance that is related to the 1st and 2nd Law of Thermodynamics. The Carnot factor has been used to calculate the exergy content of heat so that it is thermodynamically comparable with work. Using the Carnot factor results in optimistic values for the exergy (quality) of heat, since it assumes reversible (ideal) processes. In addition, the relative prices of hot/cold utilities and work do not always follow the 2nd Law of Thermodynamics. As explained in Section 4.2, work is more valuable than the exergy content of heat from a thermodynamic point of view. In many cases, it is true that work is much more expensive than heat that has an exergy content equal to the work. This means that it is normally not valuable to save hot/cold utilities at the expense of more work consumed. There are, however, some cases where heat is even more expensive than work, and it is essential to save heat. The relative value between work and heat is a challenge for the design of WHENs.

The process complexity will of course increase in many cases when both work and heat are integrated. The flexibility and reliability may thus be reduced. Practical limitations such as the plant size and controllability should also be taken into consideration for industrial applications.

5. Conclusions

Temperature and pressure are two equally important process parameters. When the changes in both temperatures and pressures of streams are taken in consideration, the problem of Heat Integration is extended to Work and Heat Integration. This emerging new topic has attracted considerable research interest. It also shows promising applications in the process industry. However, there are limitations in the available literature studies. Further research work on the following challenges related to the topic is necessary to realize the industrial applications: (1) targeting at an early stage of process design has not yet been achieved, (2) the fundamental thermodynamic insights available are limited to small size problems where constant-temperature utilities and pressure manipulations with single stages are assumed, (3) the Mathematical Programming models are complex to solve and are expected to be simplified with the help of fundamental insights, and (4) the economic issues, operating temperatures, process flexibility and reliability should be taken into consideration for practical industrial applications.

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