WORK AND HEAT EXCHANGE NETWORKS (WHENS) FOR PROCESS INTEGRATION IN SUB-AMBIENT PROCESSES

ABSTRACT

When combining Work and Heat Integration, the classical Heat Exchanger Network (HEN) problem is extended to Work and Heat Exchange Network (WHEN). This contribution describes how the recent developments in WHENs can increase the use of Process Integration in sub-ambient processes, and thereby enables the design of significantly more energy efficient low temperature processes.

The WHENs problem can be defined as: *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 consisting 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 exergy consumption or total annual cost is minimized.*

The fundamental issue is the fact that manipulating the pressure of streams (by compressors and expanders) will affect the Composite Curves, the Heat Recovery Pinch and temporarily also the identity (hot or cold) of the process streams. A set of Theorems has been developed [1] to guide the integration of compressors and expanders into HENs. These Theorems are equally valid above and below ambient temperature. The key questions are related to the inlet temperature of such pressure-changing equipment, the splitting of the streams involved to allow compression or expansion at different temperatures, and the use of stage-wise compression and expansion. The Theorems and use of the Grand Composite Curve form the basis for a manual design procedure for small scale WHENs.

In order to handle larger industrial size problems, and to properly account for the economic trade-offs, the manual design procedure needs to be replaced by optimization frameworks such as Mathematical Programming or Stochastic Search. The Mathematical Programming approach requires identification of a sufficiently rich superstructure and the subsequent modeling of the problem, ending up with an NLP or an MINLP model. The Stochastic Search approach overcomes the problems related to local optima in non-convex optimization formulations, but suffer from very long computing times and the inability to guarantee global optimum. Good solutions can be found with moderate computing times

Small industrial examples will be used to illustrate how the WHEN methodology can be used in sub-ambient processes to significantly reduce their energy demand. While waiting for a breakthrough in the use of optimization methods, these examples have been solved using the manual design procedure.

SCOPE

There are 4 fundamental concepts that form the basis of Process Integration [2] and its extension from Heat Integration to other Process Synthesis tasks: (1) Composite Curves that show accumulated values for an amount (e.g. heat) with a quality (e.g. temperature), Performance Targets ahead of Design, (3) the Pinch Point and its Decomposition effect, and (4) Appropriate Placement of special equipment.

The use of analogies has made it possible, based on heat transfer processes (HENs – Heat Exchanger Networks), to develop tools for analysis (targets), design and optimization in mass transfer processes (MENs – Mass Exchange Networks) [3]. From Heat Pinch and Mass Pinch (with special applications to wastewater minimization [4] and distributed effluent treatment processes [5]), the development has resulted in concepts such as Hydrogen Pinch [6], Oxygen Pinch [7] and Carbon Emission Pinch [8].

Another development with inspiration from Heat Integration is Work Integration (WENs – Work Exchange Networks) [9]. It should be emphasized, however, that despite the apparent analogy with Heat Integration, the Pinch Concept is not valid in Work Integration. Work Integration can be of a direct form (exchanging flow work) or an indirect form (exchanging shaft work). In both cases, the concepts of non-negative driving forces and a "Work Recovery Pinch" are not valid. A flow work exchanger [10] (direct exchange of pressure levels) will have crossing profiles in a Pressure vs. Work (P-W) diagram. As expected, the inlet pressure of the high-pressure (HP) stream must be higher than the outlet pressure of the low-pressure (LP) stream. More surprisingly is the fact that the outlet pressure of the HP stream must be lower than the inlet pressure of the LP stream. Indirect work exchange means that streams are exchanging pressure using shaft work as the intermediate energy form. The pressure levels (inlet and outlet) of the fluid being expanded can be lower than the pressure levels of the fluid being compressed, since there are no driving forces (in the form of pressure difference) that need to be satisfied between the two streams involved.

When combining Work Integration and Heat Integration, referred to as Work and Heat Integration, there are also 2 distinctly different scenarios, one with a focus on Work Integration accounting for heat effects [11, 12], and one focusing on Heat Integration accounting for heating and cooling produced by compression and expansion [13]. While the Pinch concept has little to offer in the first case (as explained above), the second case can fully benefit from basic Pinch Analysis. There is, however, one fundamental issue that makes WHENs with focus on Heat Integration much more complex than HENs. Changes in pressure of the process streams will affect the Composite Curves, the Pinch point and also temporarily the identity (hot or cold) of the process streams. This means that the use of the Appropriate Placement concept (that is closely related to the Plus/Minus principle in Pinch Analysis) is not straightforward when applied to compressors and expanders.

This contribution will discuss Work and Heat Exchange Networks focusing on Heat Integration while accounting for heating and cooling effects from compression and expansion. The operation of such pressure-changing units, in particular their inlet temperatures, will be a central part of the discussion. The applications will be related to sub-ambient processes, where utility cooling takes the form of refrigeration cycles, i.e. the combination of compression and expansion. Examples of important sub-ambient processes include Air Separation Units (ASUs), liquefaction of natural gas to LNG, hydrogen liquefaction, and the cold end of Ethylene plants.

Dealing with sub-ambient processes also means there is a strong relation between compressor work to produce refrigeration and exergy losses in the process. Since the exergy of heat increases very rapidly below ambient temperature when moving towards lower temperatures, and exergy losses for heat transfer depend on both temperature difference and the absolute temperature level, using a constant value for the economic parameter ΔT_{min} will result in non-optimal solutions. It has been shown that using a constant UA_{max} parameter results in much better utilization of invested heat transfer area [14].

Conclusions and Significance

Recent developments in analysis, design and optimization of Work and Heat Exchange Networks (WHENs) constitute important extensions to Pinch Analysis and the discipline of Process Integration. This is particularly true for sub-ambient processes, where the removal of heat is done by refrigeration cycles where the key input is compressor work.

Even though the methodology for WHENs is still under development, in particular the transition from manual procedures to optimization formulations, there have been a number of applications that illustrate the considerable savings that can be obtained by including compression heat and expander cooling effects in the classical heat recovery problem.

Savings can be obtained, even for processes that are considered very tightly integrated with limited scope for improvement. The classical Linde coupled column design [15] for Air Separation Units (ASUs) has been studied by exergy analysis to identify the largest losses and to suggest improvements [16]. Savings on the order of 10% have been obtained by a single column design with distributed reboiling and heat pumping referred to as a recuperative vapor recompression heat pump [17]. In the modified process, a fan replaces the main air compressor, and the distillation process is operated at significantly lower pressure. An offshore process for liquefaction of natural gas by using liquefied CO_2 and liquefied N_2 [18] was developed by the manual and heuristic ExPAnD procedure [13] and later by a Mathematical Programming (MINLP) model based on a novel superstructure for heat exchange, compression and expansion [19].

Considerable energy savings have also been obtained by using the new WHENs methodology in studies of CO_2 capture processes [20]. Three processes have been studied: (1) An oxy-combustion process, where 10.1 % is saved in the cryogenic ASU process, (2) a post-combustion process, where energy consumption for CO_2 capture is reduced by 12.9%, and (3) the future scenario of membrane processes for ASU, saving 90% of the net work required (excluding heat requirement).

In a recent publication focusing on explaining the key issues in WHENs [21], the Appropriate Placement of compressors and expanders in subambient processes, the corresponding insight that has been formulated as a set of Theorems, and the manual design procedure using the Grand Composite Curve, have been presented. A small sub-ambient example with 2 hot streams and 2 cold streams, one stream being subject to compression and one stream being subject to expansion, is used for illustration purposes. Since WHENs are dealing with two types of energy (heat and work) with different quality, exergy (i.e. the maximum ability to produce work) has been used as the objective function. The example shows that using the new insight about inlet temperature to compression and expansion reduces exergy consumption by 75.1% compared to compression and expansion at the supply temperatures of the streams. In energy terms (since this is a sub-ambient example), the reduction in cold utility consumption is 189.6 kW, while the net amount of work produced (expansion work minus compression work) is reduced with 101.0 kW. This corresponds to a Coefficient of Performance (COP) of 1.88. Hot utility is almost eliminated as it is reduced from 300.2 to 9.6 kW.

Unfortunately, this solution is quite complex and requires considerable investment in equipment (2 compressors, 2 expanders, 10 heat exchangers, 3 Pinch points and 4 stream splits). If compression and expansion is performed at the original Pinch only (i.e. not following the manual procedure), the exergy improvement is reduced from 75.1 to 67.2%, cold utility reduction is 166.6 kW rather than 189.6 kW, and the net amount of work produced is 86.0 kW rather than 101.0 kW. As a result, the COP is actually slightly improved from 1.88 to 1.94. The network complexity (and thus investment cost) is significantly reduced (1 compressor, 1 expander, 7 heat exchangers, 2 Pinch points and 1 stream split).

The results from this example form the basis of 2 important conclusions: (1) The manual design procedure for WHENs based on insight about the Appropriate Placement of compressors and expanders in heat recovery systems should only be considered as a targeting tool (i.e. the best performance from an exergy point of view), and (2) the need for an efficient optimization formulation minimizing Total Annual Cost rather than exergy is obvious. While this contribution focuses on sub-ambient applications of the recently developed WHENs procedure, the new insight is equally valid in above ambient applications.

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