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Review of Work Exchange Networks (WENs) and Work and Heat Exchange Networks (WHENs)

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Heat Exchange Networks (HENs) and Mass Exchange Networks (MENs) have been widely adopted and extensively studied for heat and material recovery to save energy and other resources. However, work recovery can also result in significant energy savings in for example oil refineries, petrochemical plants and cryogenic processes, such as the production of liquefied natural gas (LNG). The concept of Work Exchange Networks (WENs) was first proposed and identified as a new research topic in Process Synthesis in 1996. This research area has broadened considerably during the last 5-10 years, and it covers both flow work (material streams) and shaft work (energy streams or non-flow processes). More recently, there has also been considerable development in the combined problem of Work and Heat Exchange Networks (WHENs). Two research directions have developed for WHENs; one with a focus on work integration accounting for heat effects, and one focusing on heat integration accounting for heating and cooling produced by compression and expansion. The field of WENs and WHENs can be classified as follows: (1) Pressure Integration (flow work), (2) Power (or Work) Integration (shaft work), and (3) Work and Heat Integration (mechanical and thermal energies). The present review will cover WENs (both flow work and shaft work) and WHENs (with a focus on both mechanical energy and thermal energy) from both a pinch technology based and a mathematical programming (optimization) based perspectives.

1. Introduction

Heating/cooling (thermal energy), power/work (mechanical energy), and water/air (materials) are the most fundamental utilities in the process industries. The corresponding quality indicators of heat, work and material are temperature, pressure and concentration respectively. These properties (temperature, pressure and concentration) are also three very important specifications for industrial manufacturing processes. Due to the differences in the requirement of temperature, pressure and concentration, opportunities to integrate streams with opposite demands (such as heating and cooling) arise. To fully utilize the heat in processes with multiple streams, Heat Exchange Networks (HENs) emerged – see e.g. (Linnhoff et al., 1982) for an early introduction to the basic concepts, (Klemeš, 2013) for a Handbook of Process Integration with focus on energy, water and emissions, and (Smith, 2016) for a recent textbook on Process integration. HENs have been widely researched and adopted since the 1970s. The concept of Mass Exchange Networks (MENs) was introduced by El-Halwagi and Manousiouthakis (1989), and applied by Wang and Smith (1994) to minimize fresh water consumption and thus wastewater production. Heat exchange networks and mass exchange networks aim at recovering heat and material. In many industrial plants, such as refineries, petrochemical plants and cryogenic processes, pressure is equally important as temperature. Similar to HENs, the concept of Work Exchange Networks (WENs) was first proposed by Huang and Fan (1996) to recover pressure-based energy (work). A review paper (Chen and Wang, 2012) lists 108 references covering Heat Exchange Networks (HENs), Mass Exchange Networks (MENs), Water Allocation Heat Exchange Networks (WAHENs) and Work Exchange Networks (WENs). The review paper does not discuss WHENs, and it is sparse on WENs, however, it contains a good overview of energy recovery devices.

Pressure-based energy is a valuable form of energy. In industrial processes, streams are often pressurized or depressurized to meet process specifications. As heat and work are interchangeable, simultaneous integration

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between heat and work can result in considerable energy savings or total annual cost reductions. It is obvious that the simultaneous integration of heat and work is highly relevant.

Process integration, which regards industrial processes from a system's perspective, offers a set of powerful tools to synthesize WENs and WHENs. It mainly includes a conceptual approach based on Pinch Analysis and an optimization approach based on Mathematical Programming. The latter achieves the optimization by establishing a mathematical model, which can deal with large-scale problems and considers operating cost, equipment cost, environmental effects, etc. simultaneously. However, the Mathematical Programming approach has the limitation that the design process is hidden from the engineer, and a physical explanation about why a particular solution is selected is not given (Liu et al., 2014). In contrast, Pinch Analysis has the advantages of intuitiveness, simplicity, and clarity and hence is widely adopted in the process industries. On the other hand, Pinch Analysis cannot consider economic factors and environmental effects of the whole system. Pinch Analysis can provide fundamental insights, which can be used in combination with Mathematical Programming. It is obvious that each method has its advantages and disadvantages.

Although heat exchange networks have been intensively studied since the 1970s, the literature on work integration is rather limited. This paper provides a review of the literature on Work Exchange Networks (WENs) and Work and Heat Exchange Networks (WHENs) from both Pinch Analysis based methods and the use of Mathematical Programming.

2. Work Exchange Networks (WENs)

The general Work Exchange Networks (WENs) problem can be stated as follows:

Given a set of process streams $S = I + J = \{1, 2, 3,\ldots,s\}$ with known supply pressure, target pressure and heat capacity flowrate. A subset $I = \{1, 2, 3,\ldots,i\}$ consists of streams whose supply pressure is greater than the target pressure, while a subset $J = \{i+1, i+2, i+3,\ldots,s\}$ consists of streams whose target pressure is greater than the supply pressure. These two subsets are referred to as high-pressure (HP) streams and low-pressure (LP) streams respectively. To recover pressure-based energy, HP and LP streams can exchange work via direct or indirect work exchangers. The objective is to synthesize a Work Exchange Network with maximum energy efficiency, minimum exergy destruction, minimum total annual cost, etc.

The above problem is derived from the process industry. Many chemical and petrochemical processes take place under different pressure levels with or without any temperature requirements. Under these circumstances, mechanical energy recovery becomes conceivable among process streams with different pressure levels. Similar to heat exchangers, work exchangers are proposed for work exchange between process streams. Work exchangers can be classified into direct and indirect devices. Cheng et al. (1967) originally conceived a device called flow work exchanger, which can simultaneously pressurize one stream and depressurize another stream. Thus, it is a kind of direct work exchange device. The flow work exchanger is a displacement vessel in essence to form a closed loop with process streams. However, the flow work exchanger is limited to condensed state fluids. The flow work exchanger can be applied to reverse osmosis desalination, hydrogenation and phenol production processes. The flow work exchanger operates essentially in a batch mode. For the potential application field of hydrogen management in the refining industry, Deng et al. (2010) analyzed gas-gas work exchangers from a thermodynamic perspective. A simplified equation for a quick estimate of work recovery efficiency of gas-gas work exchangers was derived. Due to the higher compressibility of gases compared to liquids, mechanical and thermal energy are transferred simultaneously in a gas-gas work exchanger. As proposed by Cheng et al. (1967), the gas-gas work exchanger has more work losses compared to the flow work exchanger.

Huang and Fan (1996) introduced the concept of Work Exchange Networks (WENs) in analogy to Heat Exchange Networks (HENs) and Mass Exchange Networks (MENs). They proposed the necessary and sufficient conditions for stream matching. However, their focus is on the analysis instead of the synthesis of work exchange networks. Liu et al. (2014) developed a graphical integration method for work exchange networks based on characteristics of the flow work exchanger. Five matching rules are proposed for optimally matching the work sources and work sinks. However, for direct work exchangers, the outlet pressure of the work source should be lower than the inlet pressure of the work sink, while the inlet pressure of the work source is higher than the outlet pressure of the work sink. As flow work exchangers are limited to condensed state fluids, these studies are not applicable to work exchange network design under general conditions. In addition, the studies mentioned above only contribute to matching rules for two or a few streams. Thus, until very recently the problem of Work Exchange Network (WEN) synthesis has remained unsolved.

For indirect work exchange devices, the pressure energy of the work source is converted to mechanical energy through a turbine or expander, and then the mechanical energy is converted back to pressure energy by driving a compressor or pump. This kind of technology is easier to implement in practice compared to flow work exchangers, since there are no pressure relations between the streams. The disadvantage of the indirect

recovery device is the low recovery efficiency. To improve recovery efficiency, Razib et al. (2012) proposed a single-shaft-turbine-compressor (SSTC) unit, where multiple turbines and multiple compressors share a single shaft. They proposed a superstructure for Work Exchange Networks (WENs) and developed a mixed-integer nonlinear programming (MINLP) model to minimize the total annual cost. Only shaft power is transferred from depressurized streams to pressurized streams through the SSTC unit, and there are no limitations regarding inlet and outlet pressure as with flow work exchangers. This model can synthesize optimal Work Exchange Networks for multiple streams. However, their study did not consider heat integration. The temperature specifications of process streams are satisfied by heaters and coolers located at the end of the WEN stage.
Despite the fact that Work Exchange Networks originally were inspired by Heat Exchange Networks, it is important to notice that WENs do not have driving force requirements ($\Delta p \geq \Delta p_{min}$) similar to HENs ($\Delta T \geq \Delta T_{min}$) and there is no Work Recovery Pinch.

3. Work and Heat Exchange Networks (WHENs)

The most general Work and Heat Exchange Networks (WHENs) problem can be stated as follows: Given a set of process streams $S = PCS + NPCS = \{1, 2, 3,\ldots,s\}$ with known supply state (temperature, pressure, phase, mass flowrate and specific heat capacity) and target state. The streams can be classified into the following subsets:

i) The set of Pressure-Change streams

$PCS = \{s \mid \text{Pressure-Change Streams}\} = \{s \mid PIN_s \neq POUT_s\}$

Further, *PCS* can be classified into high-pressure and low-pressure streams with and without phase change. The following sets can be defined:

$HP = \{s \mid \text{High-Pressure-Change Streams}\} = \{s \mid PIN_s > POUT_s, \text{Without Phase Change}\}$

$LP = \{s \mid \text{Low-Pressure-Change Streams}\} = \{s \mid PIN_s < POUT_s, \text{Without Phase Change}\}$

$HPPC = \{s \mid \text{High-Pressure-Change Streams}\} = \{s \mid PIN_s > POUT_s, \text{With Phase Change}\}$

$LPPC = \{s \mid \text{Low-Pressure-Change Streams}\} = \{s \mid PIN_s < POUT_s, \text{With Phase Change}\}$

$PCS = HP \cup LP \cup HPPC \cup LPPC$

ii) The set of Non-Pressure-Change streams

$NPCS = \{s \mid \text{Non-Pressure-Change Streams}\} = \{s \mid PIN_s = POUT_s\}$

Further, *NPCS* can be classified into hot and cold non-pressure-change streams. The following sets can be defined:

$HNPCS = \{s \mid \text{Hot Non-Pressure-Change Streams}\} = \{s \mid TIN_s > TOUT_s\}$

$CNPCS = \{s \mid \text{Cold Non-Pressure-Change Streams}\} = \{s \mid TIN_s < TOUT_s\}$

$NPCS = HNPCS \cup CNPCS$

The objective is to synthesize Work and Heat Exchange Networks (WHENs) of compressors, pumps, expanders, valves, motors, generators, heat exchangers, heaters and coolers in order to reach the target states of all the process streams while minimizing an objective function. The objective function can be energy efficiency, exergy destruction, total annual cost, etc.
The above problem is derived from processes having requirements on both temperature and pressure. Under these circumstances, work and heat are equally important for the process. In sub-ambient processes, heat (cold energy) may actually be more valuable than work. As heat and work are interchangeable, especially for gas streams, the integration between heat and work becomes possible and may lead to considerable energy savings.
Two research methods have been developed for WHENs; Graphical methods based on Pinch Analysis and optimization approaches based on Mathematical Programming as discussed in the introduction. Two research directions have emerged for WHENs; one with a focus on work integration accounting for heat effects, and one focusing on heat integration accounting for heating and cooling produced by compression and expansion. In what follows, the published studies will be analyzed according to these research methods and research directions.
Townsend and Linnhoff (1983) presented the Appropriate Placement of heat engines and heat pumps in a heat exchanger network during the early stages of Pinch Analysis. Procedures for preliminary design involving heat engines and heat pumps were proposed. This problem is in essence Work and Heat Integration. Aspelund et al. (2007) proposed a graphical methodology referred to as Extended Pinch Analysis and Design (ExPAnD), where traditional Pinch Analysis is extended with pressure considerations and Exergy Analysis. ExPAnD is applicable to pressure based energy recovery systems. The procedure is illustrated by developing a novel process for

offshore liquefaction of natural gas. The methodology considers pressure, temperature, phase transition, heat exchangers, compressors, and expanders simultaneously. However, compressors and expanders are used separately and the combination of pressure manipulating equipment operating on the same shaft is not considered in their work. Later, Gundersen et al. (2009) addressed the rules to manipulate stream pressure and phase as well as the sequence of heating, cooling, compression and expansion. Based on ExPAnD, Aspelund and Gundersen (2009a) applied this systematic method to design an efficient energy chain for liquefaction, transportation, and utilization of natural gas for power production with CO_2 capture and storage. Details about the offshore and the onshore processes are provided in Aspelund and Gundersen (2009b).

Inspired by the work mentioned above, Fu and Gundersen (2015a) presented a systematic graphical design procedure for integration of compressors in HENs above ambient temperature. They concluded that compression should be performed at pinch or ambient temperature to achieve minimum exergy consumption. Similarly, Fu and Gundersen (2015c) integrated compressors into heat exchanger networks below ambient temperature. Four theorems were proposed and used as the basis for the design methodology. It is concluded that compression should start at pinch temperatures, ambient temperature or cold utility temperature in order to minimize exergy consumption. The same authors also integrated expanders into heat exchanger networks above (Fu and Gundersen, 2015b) and below (Fu and Gundersen 2015d) ambient temperature. To integrate both compressors and expanders into heat exchanger networks above ambient temperature, a new theorem was proposed to minimize exergy consumption for the integrated process (Fu and Gundersen, 2016a). Based on the above work, Fu and Gundersen (2016b) summarized the fundamental thermodynamic insights and applied these insights to three carbon dioxide capture processes. Significant energy savings can be achieved by proper heat and work integration. The applicability and practicality of the ExPAnD method are successfully demonstrated by LNG and carbon capture processes.

The above studies mainly rely on Pinch Analysis, and the methods have proven to be effective and successful for the design of real life industrial processes. However, methods based on Pinch Analysis cannot properly take into account the capital cost of the whole system. Methods related to Pinch Analysis could generate a scheme that is highly energy efficient but may be economically infeasible. In some processes, such as LNG, ammonia, and methanol synthesis, compressors and turbines are more expensive equipment than heat exchangers. The economic aspects of the system should be examined while designing a process, and Mathematical Programming can properly deal with the economic trade-offs in design. In what follows, studies of WHENs using Mathematical Programming will be presented.

Wechsung et al. (2011) combined Pinch Analysis, Exergy Analysis, and Mathematical Programming to synthesize heat exchanger networks below ambient temperature with compression and expansion of process streams. A state space approach was presented dividing the model into a pinch operator (heat integration) and a pressure operator (work integration). The pinch operator is based on the simultaneous heat integration and process optimization idea proposed by Duran and Grossmann (1986). The objective function is to minimize total irreversibility. An industrial application related to LNG undergoing pressure change, temperature change, and phase change demonstrated that the optimization formulation was capable of generating a reasonable design. However, the thermodynamic behavior of the fluids is assumed to be ideal gas.

Onishi et al. (2014c) proposed a mathematical model for the simultaneous synthesis of heat exchange and work exchange networks. A superstructure based on Yee and Grossmann (1990) was proposed for Heat Exchange Networks (HENs) considering work recovery. This model is formulated using generalized disjunctive programming (GDP) and reformulated as a mixed-integer nonlinear programming (MINLP) problem. The superstructure is based on a pre-fixed specific pressure manipulation route of expansion and compression (Onishi et al., 2014a). The route is taken from the previous mentioned pinch based method (Aspelund et al., 2007). However, the pressure manipulating equipment was considered as stand-alone, except allowing a match between one compressor and one turbine on a single common shaft. To overcome this shortcoming, a new model allowing the use of several single-shaft-turbine-compressor (SSTC) units, as well as helper motors and generators was proposed (Onishi et al., 2014b). Of course, the space requirements in the plant should be considered when introducing several SSTC units.

Similarly, Onishi et al. (2014d) proposed another superstructure for Work Exchange Networks (WENs) considering heat integration. The proposed WEN superstructure is composed of several stages of compression or expansion for each pressure-changing stream. Heat integration is performed between the compression and expansion stages of the Work Exchange Network. However, they assume that all the streams are gaseous. Phase change is not considered in their work. Later, they proposed a new mathematical model for the retrofit of Heat Exchange Networks considering pressure recovery of the process streams (Onishi et al., 2015). The proposed multi-stage superstructure allows the increment of the existing heat transfer area, as well as the use of new heat exchangers and pressure manipulators.

Based on the study by Onishi et al. (2014d), Huang and Karimi (2016) proposed a similar Work and Heat Exchange Network (WHEN) superstructure consisting of two distinct, but interconnected networks. One network

is exclusively for heat integration, and the other is for work integration. The superstructure explicitly considers constant pressure streams for heat integration and enables optimal selection of end-heaters and end-coolers. Their approach yields a network with 3.1 % lower total annualized cost, 10.6 % more work exchange, and 81.0 % more heat exchange than the best solution obtained from the previous study by Onishi et al. (2014d).
The mathematical formulation of WHENs results in a complex MINLP problem, whose effective solution is a challenge. Further work is needed to develop more efficient formulations and tools. To avoid high non-linearity and non-convexity of the models, all the research mentioned above assumes the streams to behave as ideal gases and the costs are estimated by linear or simplified functions. Phase change and rigorous thermodynamic correlations are not considered, which are crucial for a sub-ambient process such as natural gas liquefaction. Linear or simplified equipment cost correlations are not able to realistically represent the true cost of the process. Thus, the Mathematical Programming method also has its inherent limitations. To consider the effect of pressure on phase change, thermodynamic models for the process fluid should be incorporated. However, most of the proposed methods do either not incorporate a thermodynamic model, or the simple ideal gas model is used.
The ultimate challenge for future research on WHENs is to develop a superstructure that is rich enough to handle real industrial problems while at the same resulting in a mathematical model that can be handled by the optimization algorithm to provide global solutions in reasonable computing times. Equipment models, thermodynamic models and cost equations must properly encapsulate reality. In addition, the superstructure should be able to handle issues such as for example (i) multiple thermal utilities of both constant and non-constant types, and (ii) multi-stage compression and expansion. For sub-ambient applications, the model should be able to handle process streams temporarily as utilities, i.e. even streams with the same supply and target pressure could be subject to pressure change.

4. Conclusions

The synthesis of WENs and WHENs are challenging tasks in the fields of Process Integration and Process Systems Engineering. Many methods have been proposed to solve these problems. This paper provides a state-of-the-art overview of WENs and WHENs aiming at benefiting the research and applications in the future. Both graphical methods based on Pinch Analysis and optimization approaches using Mathematical Programming are being used to synthesize WENs and WHENs, and each method has its merits and limitations. Despite the significant progress in WEN and WHEN synthesis over the past few years, there is an urgent need to develop more widely applicable, systematic methods to optimally integrate work and heat simultaneously. Further development is expected to focus on the unexplored aspects of WEN and WHEN design problems.

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