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Synthesis of indirect work exchange networks considering both isothermal and adiabatic process together with exergy analysis☆

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A B S T R A C T

In this paper, an efficient methodology for synthesizing the indirect work exchange networks (WEN) considering isothermal process and adiabatic process respectively based on transshipment model is first proposed. In contrast with superstructure method, the transshipment model is easier to obtain the minimum utility consumption taken as the objective function and more convenient for us to attain the optimal network configuration for further minimizing the number of units. Different from division of temperature intervals in heat exchange networks, different pressure intervals are gained according to the maximum compression/expansion ratio in consideration of operating principles of indirect work exchangers and the characteristics of no pressure constraints for stream matches. The presented approach for WEN synthesis is a linear programming model applied to the isothermal process, but for indirect work exchange networks with adiabatic process, a nonlinear programming model needs establishing. Additionally, temperatures should be regarded as decision variables limited to the range between inlet and outlet temperatures in each sub-network. The constructed transshipment model can be solved first to get the minimum utility consumption and further to determine the minimum number of units by merging the adjacent pressure intervals on the basis of the proposed merging methods, which is proved to be effective through exergy analysis at the level of units structures. Finally, two cases are calculated to confirm it is dramatically feasible and effective that the optimal WEN configuration can be gained by the proposed method.

1. Instruction

Energy is a major concern in the 21st century, whose worldwide demand is predicted to rise by 57% during 2004–2030 [1]. The total primary energy consumption is predicted to arise gradually all over the world in the past few decades, where the industrial sector was the largest consumer of energy accounting for over 20% [2]. As a result, the increase of energy efficiency is of vital importance in transformation processes due to its dominating responsibility for a large portion of expenditures and decisive actions on environmental aspects. The main reasons to develop techniques for sustainable energy utilization with high efficiency are the global greenhouse effect and the increasingly costly energy because of the rapid reduction in the available fossil fuels [3]. In other words, it is particularly critical to conserve energy in industrial plants.

The two most common forms of energy in these plants are heat and work. In spite of the fact that work is much more costly and has higher energy quality than heat, far more extensive studies have been conducted to optimize the heat exchange networks (HEN) than work exchange networks (WEN), the former of which has been widely adopted to recover more thermal energy in actual production [4]. Additionally, it has been demonstrated that HEN is critical to promote the decrease of gas emissions and fossil fuels consumption, as reducing energy consumption has great relations with the improvement of heat transfer. Thereby, optimal HEN can be attained consisting in promotion for thermal integration of the whole system through an effective network design, in thermodynamic and even economic terms including minimal number of heat exchangers and minimum utilities consumption [5].

Despite considerable efforts to synthesize HEN achieving the outstanding results, the other form of energy widely used in chemical plants, such as work, is rarely paid attention to, particular in the aspect of how to integrate work efficiently. In oil refineries, cryogenic processes such as the production of liquefied natural gas (LNG) [6] and synthetic processed like methanol and ammonia synthesis [7], it is vitally significant to take the responsibility for considerable energy consumption by handling pressure, where some streams need work for compression while others can undergo expansion to produce work [8]. However, very few papers have been published to describe the work integration and work has been poorly explored in process synthesis during the actual operation. Since work exchanger networks, as an important part of energy recovery systems, will have significant

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influence on energy consumption in process systems, it is significantly meaningful to integrate work between high-pressure (HP) streams and low-pressure (LP) streams. Furthermore, it would also be possible to realize the integration of both heat and work simultaneously to further conserve energy in the same network.

Work sources and work sinks can exchange work *via* direct or indirect work exchangers. Liu *et al.* [9] reported that the direct work exchanger was mainly composed of a pair of combined operating piston pumps. The mechanical energy can be transferred from work sources to work sinks directly with 100% recovery efficiency of a piston pump in theory. Nevertheless, it increases overreliance on the inlet and outlet pressures of streams that possess highly nonlinear relationship with work quantity. In addition, direct work exchangers may stay unstable during operation and conduce to bad performance of the system. In contrast, the indirect work exchangers can remain with higher stability and stronger operating performance. Hence, this paper mainly focuses on the use of indirect work exchangers.

In indirect work exchangers, namely, single-shaft-turbine-compressor (SSTC) units, energy is exchanged in two steps: the pressure energy of work sources is converted to mechanical energy through turbines at first and further converted to the pressure energy of work sinks through compressors [10], as illustrated in Fig. 1. The notion of SSTC is a straightforward extension of a gas turbine manipulating a compressor occupying a common shaft. To achieve the continuous operation of indirect work exchangers, a high-pressure stream in the turbine rotates the shaft further to drive the compressor pressurizing the low-pressure stream, which can also be generalized to involve multiple turbines with HP streams running multiple compressors with LP streams sharing a common shaft [11,12]. Constructing a network configuration for exchanging work in this manner would be called "indirect work exchange network synthesis". This is direct and useful extension of the well-known heat exchange network synthesis. Although it is very similar to HENS, surprisingly, only seldom papers have developed a systematic procedure to exchange work between HP and LP streams.

Shin *et al.* [13] proposed a mixed integer linear programming (MILP) to optimize boil-off gas compressor operations targeting the minimization of total average energy consumption in an LNG receiving and regasification terminal. Likewise, an optimization and framework with a combination of MILP model and stochastic formulation was presented by Del Nogal *et al.* [14–16] to integrate the power system and refrigeration process based on the previous paper published by them where an MILP model was introduced driver and power plant selection using the opinion of superstructure for multistage compressors. However, their purpose is to arrange compressor stages rather than to design the whole networks.

In addition, Aspelund *et al.* [17,18] presented a heuristic graphical method by utilizing the pressure-exergy to minimize energy consumption under sub-ambient condition on the basis of the Extended Pinch Analysis and Design (ExPAnD). By means of the optimization of compression and expansion work for process streams and the work needed to produce essential cooling utilities, this method shows great potential for energy requirement conservation. However, since compressors and turbines are used separately, no mention is referred to the use of combinations with these pressure manipulation devices running on a common axis, where only the aspects on the exergy analysis of the system were evaluated as well. Beside this, a heuristic-based method could not offer the most reasonable network as the number of devices is ignored. Therefore, there is a need for a comprehensive structural optimization approach for indirect work exchange network synthesis as presented in this paper.

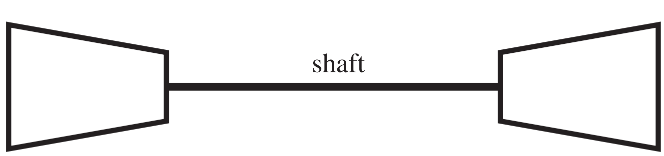

Fig. 1. Structure of indirect work exchanger.

M.S. Razib *et al.* [19,20] proposed a superstructure for the WEN configuration and developed a mixed integer non-linear programming (MINLP) to minimize the total annualized cost (TAC) for a constant speed of the single shaft on 2-stream SSTC units. Furthermore, In the paper published by Onishi *et al.* [21,22], a superstructure for synthesizing HEN simultaneously is proposed with the adjustment of pressure levels of streams taken into account to improve heat integration, where several configuration possibilities including compressors, turbines and valves are discussed at a goal of minimal the TAC of the network. However, the pressure operating equipment was considered independently, such as stand-alone turbines and compressors. Later, they introduced a novel multi-stage superstructure to optimize WEN configuration with heat integration simultaneously at a constant speed of the single shaft for SSTC, also with the goal of TAC.

In respect to the exergy analysis, the exergy composite curves were adopted to explore the potential for ORC (organic Rankine cycle) process improvements [23]. Then O. Ozgener *et al.* [24] evaluated the exergy performance of pressure reduction stations with turbo-expanders to improve the potential of the system. Nevertheless, in these works the exergy analysis is aiming at the single heat exchanger or the single ORC to recover more energy and decrease the exergy loss which is mainly focusing on the temperature exergy, not relating to the pressure exergy that is involved in the turbines, compressors and work exchangers.

In what follows, based on the literature researches as mentioned before, study on the integration of WEN with multiple streams using transshipment model in the indirect work exchanger has not been reported. Hence, we employ the transshipment model with work cascades taken into account and formulate the synthesis of work exchanger network as MINLP in adiabatic process together with exergy analysis. Then an example is used to demonstrate the benefits of this method.

2. Problem Statements

The problem in this study to be solved is as follows:

Given a set of gaseous streams at high pressure and low pressure with known mass flows, inlet pressure and outlet pressure, inlet temperature and outlet temperature, as well as utilities for work (mechanical energy) *etc.*, a network of work exchangers, compressors and expanders is designed in such a way that the utility consumption is minimized combined with the minimal number of units by determining the equipment configuration and its corresponding operating conditions.

In addition, the maximum compression/expansion ratio is also provided. The main objective is separately to synthesize an initial WEN with the minimum utility consumption and to obtain the optimal WEN configuration with the minimal number of units through work recovery between HP and LP streams, utilizing turbines and compressors running on a common shaft on the basis of the transshipment model. Compression ratio, expansion ratio, inter-stage pressure, inter-stage temperature, energy requirement and number of units are variables in the synthesis of this work exchange networks.

For simplicity of solving the built systematic mathematical model, the following assumptions are made:

(1) All streams are in ideal gas phase without phase transition.
(2) Only isothermal and adiabatic reversible compression/expansion is considered.
(3) The work transfer efficiency is constant in different pressure intervals.
(4) All the compressors and turbines for operating alone or in the SSTC are single-stage and centrifugal.

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