Journal of the Taiwan Institute of Chemical Engineers 81 (2017) 295–304

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

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

Direct work exchanger network synthesis of isothermal process based on improved transshipment model

Yu Zhuang, Linlin Liu, Lei Zhang, Jian Du*

Institute of Chemical Process Systems Engineering, School of Chemical Engineering, Dalian University of Technology, Dalian 116012, China

ARTICLE INFO

Article history:
Received 17 July 2017
Revised 30 August 2017
Accepted 29 September 2017
Available online 31 October 2017

Keywords:
Work exchanger network
Direct work exchanger
Transshipment model
Isothermal process
Work cascade

ABSTRACT

Research on work exchange between high and low-pressure streams to reduce consumption of relatively expensive mechanical energy has great significance for improving energy efficiency in chemical plants. A novel methodology for the synthesis of direct work exchanger network of isothermal process is first proposed in this article. It is developed based on an improved transshipment model in a linear programming formulation. Two heuristic strategies and six matching rules that explicitly assist identifying feasible match between high and low-pressure streams are proposed. The former strategy is to construct intermediate pressures of low-pressure streams for solving pressure constraints of stream matches. The latter one is applied to find more feasible matches for further reducing both utility consumption and the number of work exchangers. Compared with solutions gained by graphical integration method, the presented method is proved to be more efficient by two examples where specific utility consumption is reduced by 23.4% and 17.6%, respectively.

1. Introduction

Energy consumption, a major global concern for world economy, is predicted to rise by 57% during 2004-2030 [1]. The efficient use of energy is recognized as a key element of sustainable development and an effective strategy for cost reduction and environmental acceptability for process industry [2]. The chemical industry accounts for a large portion of the total industrial energy consumption. Therefore, energy conservation in chemical plants is crucial as it contributes for reducing carbon oxide emissions as well as mitigating the global warming.

Heat and work are two fundamental forms of energy in chemical plants. Although work is much costlier and of higher energy quality than heat, heat integration has been studied far more extensively than work integration [3]. Various technologies for heat integration have been developed. The pinch technology was first introduced in 1978 [4] and then has been widely used in the synthesis of heat exchanger network (HEN) [5–7]. The pinch point and minimum utility consumption can be identified by shifting heat source and sink composite curves in the temperature *versus* enthalpy diagram (T-H) [8]. Based on this technology, numerous researches are conducted by considering more constraints with graphical methods or mathematical programming methods.

Despite outstanding results achieved in HEN, work, which is widely used in chemical plants, has attracted little attention. Actually, in many process industries, such as production of LNG and synthetic processes like ammonia and methanol synthesis [9], pressure manipulation is responsible for a significant amount of energy consumption. The high-pressure (HP) streams can be used to compress low-pressure (LP) streams which need pressurization, if the pressures of HP streams are high enough. In analogy to HEN, work exchanger network (WEN) which is composed of all streams demanding depressurization or pressurization, should be integrated to further reduce energy consumption [10,11].

Some researchers have started the work on how to optimize pressure manipulations to recover mechanical energy. Shin et al. [12] established a mixed integer linear programming (MILP) model to optimize boil-off gas (BOG) compressor operations targeting the minimization of the total average energy consumption in an LNG receiving and re-gasification terminal. Similarly, Hasan et al. [13,14] focused on the optimization of compressor operations for propane pre-cooled mixed refrigerant (C3MR) cycles to minimize the total energy cost of the refrigerant compressors. Moreover, Del Nogal et al. [15] made a design for optimal mixed refrigerant cycles of multistage refrigeration using multistage compressors. Later, they proposed a model to obtain an optimized power system for utility networks based on mathematical programming. The proposed model was applied to LNG systems, where turbines, helper motors and electric motors are supposed to be drivers to satisfy the given demand of compressors stages [16,17]. However, only the optimization of compression and expansion operations were

* Corresponding author.
E-mail address: dujian@dlut.edu.cn (J. Du).

https://doi.org/10.1016/j.jtice.2017.09.048

Nomenclature

DPU	Depressurized utility, kW
HP	High-pressure
K	Total number of pressure intervals
LP	Low-pressure
n	Molar flow rate, kmol/s
N_H	Total number of HP_i
NL	Total number of LPj
P	Pressure, kPa
PU	Pressurized utility, kW
R	Ideal gas constant, 8.314 J/mol/K
RW	Residual work consumption, kW
T	Temperature, K
W	Work quantity, kW

Subscripts or superscripts

s	Inlet pressure/temperature, kPa/K
m	Intermediate pressure, kPa
k	Order number of pressure intervals
t	Outlet pressure/temperature, kPa/K

considered in these works. Work integration between HP and LP streams needs to be further investigated.

For work integration, Razib et al. [18] presented a mixed integer non-linear programming (MINLP) formulation to integrate pressure energy among multiple streams with stand-alone compressors. But in their work, work exchange was not taken into account. In a subsequent paper, a superstructure was introduced for work exchanger network synthesis and an MINLP model was established to minimize the total annualized cost [19]. Mathematical programming methods are applied in all these works introduced above, without considering the direct work exchangers.

The direct work exchanger is mainly composed of a pair of combined operated piston pumps. Mechanical energy can be transferred from work sources to work sinks directly [20]. Compared with relatively low energy efficiency (30%−50%) of indirect work exchangers [21–23], recovery efficiency of piston pumps is 100% in theory (90%−95% in practice). This is one of the reasons why direct work exchanger network synthesis is studied in this article. In addition, to guarantee continuous operations of direct work exchangers, the inlet pressure of work sink should be higher than the outlet pressure of the matched work source while the outlet pressure of work sink should be lower than the inlet pressure of the matched work source [24]. Based on this, novel work integration techniques should be developed.

For direct work exchange between HP and LP streams, Aspelund et al. [25] proposed a graphical heuristic method utilizing pressure exergy to minimize energy consumption in sub-ambient process such as LNG, which optimized compression and expansion work of process streams to create cooling utilities. Huang and Fan [26] presented operational principles to exchange work among two streams using pressure *versus* work diagram without consideration of work integration. To integrate work in multi-stream system, Liu et al. [27] developed a graphical method for work exchanger network synthesis by plotting composite curves of work sources and sinks in the logarithmic pressure *versus* work diagram, in which two assistant composite curves of work sinks were proposed to help identify feasible matches between work sinks and sources. However, all these methods employed graphical techniques which follow a complex and verbose computing process.

From the above literature review, no study on work integration with direct work exchangers using mathematical programming method has been reported. In this article, a novel methodology for direct work exchanger network synthesis of isothermal process based on the improved transshipment model is proposed. In Section 2, problem description and simplified assumptions are presented. In Sections 3 and 4, the improved transshipment model is formulated to illustrate how mechanical energy can be saved by optimal work integration. The two heuristic strategies and six matching rules are presented in Section 5 to describe how to solve pressure constraints and optimize the initial WEN configuration. Results and limitations of the method are presented in Section 6. The overall conclusions and future developments are presented in Section 7.

2. Problem statement

A set of HP and LP streams with known flow rates, inlet temperature, inlet pressure and outlet pressure are considered in a chemical process. In addition, the minimum approach pressure and units for handling pressure are also provided. Let P^s_{HP} and P^t_{HP} denote the inlet and outlet pressure of work sources undergoing expansion ($P^s_{HP} \geq P^t_{HP}$) while P^s_{LP} and P^t_{LP} denote the initial and target pressure of work sinks, which undergo compression ($P^s_{LP} \leq P^t_{LP}$). In this problem, an optimal WEN is designed to achieve the target pressure of all streams through work recovery between HP and LP streams *via* direct work exchangers. In addition to these work exchangers, the WEN may comprise some stand-alone turbines and compressors regarded as utility units, but valves are not taken into account. Moreover, compression and expansion work, intermediate pressure, split fraction and number of units are the decision variables in the synthesis of work exchanger network. For simplifying synthesis process, we make the following assumptions:

(1) All streams are in ideal gas phase.
(2) All compressors and turbines in the network are single-stage.
(3) All compressors and turbines are reciprocating.
(4) Starter energy required by any turbine or compressor is zero.
(5) Isothermal reversible compression/expansion is considered.

3. Improved transshipment model construction

3.1. Division of pressure intervals

The first step to construct the transshipment model is to divide stream pressures into different pressure intervals (sub-networks) according to the proposed rule.

The rule can be stated as follows:

The minimum approach pressure ΔP_{min} is the minimum driving force required by work exchange between high-pressure streams and low-pressure streams, which is set by experience based on the recommend value range (35 and 70 kPa) [20]. It is also a guarantee of the high momentum transfer rate and the avoidance of an excess temperature of the work exchanger during the actual operation. Then analogical to the method on division of temperature intervals in HEN, a vertical line with a specific direction from high to low is plotted in a data table according to the entire initial and target pressures of streams, which can be regarded as coordinates of various streams in a vertical axis. Meanwhile, the pressure of work sources is a minimum approach pressure higher than that of work sinks at the horizontal axis, expressed as follows.

$$P^{hor}_{HP,k} - P^{hor}_{LP,k} = \Delta P_{min} \quad (1)$$

Furthermore, horizontal lines are plotted to divide these pressures into several pressure intervals, which can be labeled as 1, 2,…K (where K is the total number of pressure intervals).

For example, three high-pressure streams and two low-pressure streams with their respective initial and target pressures are shown in Table 1. The pressure of HP stream and LP stream is respectively listed in each vertical line in the descending order. According to