Applied Energy 219 (2018) 68–92

Contents lists available at ScienceDirect

Applied Energy

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

Optimal heat pump integration in industrial processes

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HIGHLIGHTS

- A comprehensive MINLP superstructure synthesis method for industrial heat pumps.
- Optimization of heat pump design and operating conditions.
- The superstructure includes sub-cooling, multi-stage phase-changes, presaturators, and others.
- Multi-objective bi-level solution strategy allowing augmentation by expert judgement.
- Benchmarking with three literature case studies shows improvements by 5–30%.

ARTICLE INFO

Keywords:
Industrial refrigeration
Fluid selection
MINLP superstructure
Multi-objective optimization
Genetic algorithm
Waste heat recovery and valorization

ABSTRACT

Among the options for industrial waste heat recovery and reuse which are currently discussed, heat pumping receives far less attention than other technologies (e.g. organic rankine cycles). This, in particular, can be linked to a lack of comprehensive methods for optimal design of industrial heat pump and refrigeration systems, which must take into account technical insights, mathematical principles and state-of-the-art features. Such methods could serve in a twofold manner: (1) in providing a foundation for analysis of heat pump economic and energetic saving potentials in different industries, and further (2) in giving directions for experimentalists and equipment manufacturers to adapt and develop heat pump equipment to better fit the process needs.

This work presents a novel heat pump synthesis method embedded in a computational framework to provide a basis for such analysis. The superstructure-based approach is solved in a decomposition solution strategy based on mathematical programming. Heat pump features are incorporated in a comprehensive way while considering technical limitations and providing a set of solutions to allow expert-based decision making at the final stage.

Benchmarking is completed by applying the method on a set of literature cases which yields improved-cost solutions between 5% and 30% compared to those reported previously. An extended version of one case is presented considering fluid selection, heat exchanger network (HEN) cost estimations, and technical constraints. The extended case highlights a trade-off between energy efficiency and system complexity expressed in number of compression stages, gas- and sub-cooling. This is especially evident when comparing the solutions with 3 and 5 compression stages causing an increase of the COP from 2.9 to 3.1 at 3% increase in total annualized costs (TAC).

1. Introduction

Heat pumping has gained increasing attention during the past decades not only for household applications but also for improving energy efficiency of industrial processes through waste heat recovery and valorization at elevated temperatures [1,2]. As demonstrated in Appendix A.1 (Fig. 11), research in the field of industrial *waste heat recovery* is largely dominated by organic rankine cycle (ORC) applications and thermoelectric devices. This may stem from a fully explored state-of-the-art of industrial heat pumps and integration methods; however, the marginal penetration of industrial heat pump systems (apart from basic refrigeration and air-conditioning) [2,3] contradicts this notion. The main barriers for broad usage in industry were identified as lack of knowledge and of comprehensive heat pump integration methods to provide improvement potentials [3,2]. This work mainly covers single fluid, mechanically driven systems due to their advanced technological development and operative flexibility (see Appendix A.1 for more explanation). After a state-of-the-art analysis of current synthesis methods, this work presents a novel heat pump superstructure with a bi-level solution strategy in the methodology

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https://doi.org/10.1016/j.apenergy.2018.02.114
Received 8 December 2017; Received in revised form 8 February 2018; Accepted 16 February 2018
0306-2619/

Acronyms

Capex	annualized capital expenses
COP	coefficient of performance
GWP	global warming potential
HEN	heat exchanger network
HFC	hydrofluorocarbons
HPS	heat pump superstructure
LNG	liquid natural gas
LP	linear programming
MILP	mixed integer linear programming
MINLP	mixed integer nonlinear programming
MIP	mixed integer programming
MOGA	multi-objective genetic algorithm
NLP	nonlinear programming
Opex	yearly operating expenses
ORC	organic rankine cycle
PA	pinch analysis
PI	process integration
TAC	total annualized costs
TSA	total site analysis

section, followed by application of the method to various literature cases in the results and discussion section.

2. State-of-the-art

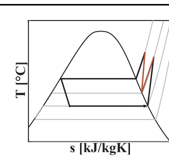
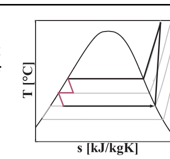
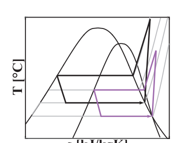
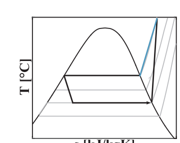
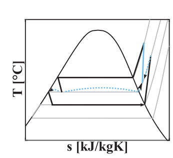
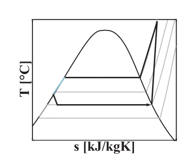
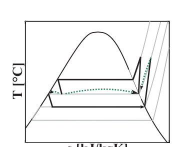
The focus of this work lies on mechanically driven heat pump synthesis methods for industrial processes. Since these techniques rely on modeling state-of-the-art heat pump technologies, a short review of available heat pump features was conducted. Chua et al. [2] and most recently Arpagaus et al. [4] presented comprehensive literature reviews on advances in mechanically driven (multi-temperature) heat pump systems. The most recurring features relevant for large-scale modeling of industrial heat pumps were identified and are presented in Table 1. These include multi-stage compression and expansion, ejectors, cascaded cycles, gas-cooling, subcooling, economizers, and presaturators. Other developments, which impose different system architectures (desiccant cooling [2]) or more refined equipment modeling (scroll and oil-free compressors [2,5,4,6]) are not discussed in this work.

Table 2 provides an overview of the studies introducing synthesis methods discussed in this section. In the presented approaches, it is differentiated between conceptual methods which are based on expert judgment, heuristic rules, or graphical analysis; and mathematical methods, which rely of mathematical programming to perform systematic optimization. This work presents a contribution to the latter which is thus discussed at greater length.

2.1. Conceptual methods

Conceptual, or insight-based, methods are not limited by the problem size and therefore always lead to a solution though global optimality will seldom be reached. As early as 1974, Barnés and King [7] and later Cheng and Mah [8] proposed methods based on a set of heuristic rules, dynamic programming, and expert judgment for synthesis of industrial heat pump systems. In 1978, a milestone was achieved, when Linnhoff and Flower [9] proposed a method now commonly known as pinch analysis (PA) [10] which, for the first time, allowed systematic analysis of a process net thermodynamic requirements and maximum heat recovery potential. This led Townsend and Linnhoff [11] to derive the theoretical foundation for ideal placement of heat engines and heat pumps based on the principles of PA. They concluded that system improvement from a thermodynamic standpoint can only be achieved if heat pumps are placed across the process pinch temperature (Appendix A.1). Industrial capital budgeting, however, is seldom based upon thermodynamic objectives. Other drivers play a

Table 1
Heat pump features considered in this work as identified by [2,4].

Feature	Description		Feature	Description	
(A) Multi-stage compression [13,14,4,15]	Provide higher COP through intermediate vapor cooling while imposing challenges for direct vapor injection (multi-stage compressor) or lubrification management (multiple single-stage compressors)		(B) Multi-stage expansion (inter-cooling) [16,17]	Offers lower technical complexity and higher performance through cooling at intermediate pressure level (with aid of several expansion valves for a single-stage compressor)	
(C) Cascaded cycles [18]	Enable coverage of wider temperatures ranges due to the possibility of working fluids switching with applications in natural gas liquefaction or other cryogenic processes, or waste heat recovery with a strong temperature lift		(D) Gas-cooling [19]	Allows to recover heat from the superheated vapor at the compressor outlet (e.g. in a separate heat exchanger), and therefore generates a multi-temperature profile at a single pressure level at higher capital expenses	
(E) Economizer [19]	Permits to preheat the saturated vapor before entering a compressor by mixing with superheated vapor at the same pressure level		(F) Subcooling [15,17,18]	Subcooling before expansion improves the performance of heat pumps, however, possibly at the cost of additional heat exchanger installation	
(G) Presaturators (flash-drums) [15,20,19]	Enable to saturate superheated vapor and to remove flash gas between expansion stages which improves the coefficient of performance in multiple ways		(H) Ejectors [4,20,21,17,22]	Allow compression of a low pressure fluid through the expansion of a high pressure fluid (principle of suction) at low maintenance and capital expenses. *Ejectors were not considered in this work, but are mentioned due to their promising characteristics*