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Improving the energy efficiency of industrial refrigeration systems

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ABSTRACT

Various retrofit design options are available for improving the energy efficiency and economics of industrial refrigeration systems. This study considers a novel retrofit option using a mixed refrigerant (MR) in refrigeration cycles designed for use with a pure refrigerant (PR). In this way energy savings can be realized by switching refrigerants without requiring extensive and expensive reconfiguration of equipment. Hence, the aim here is to test the common thinking that equipment should always be extensively reconfigured when switching from pure to mixed refrigerants. To determine the most energy-efficient operating conditions for each refrigeration design an optimization framework is utilized linking a process simulator with an external optimization method. A case study is presented to demonstrate how the proposed process modeling and optimization framework can be applied and to illustrate the economic benefits of using the retrofit design options considered here. For the case considered in this paper, savings of shaft power required for the refrigeration cycle can be achieved from 16.3% to 27.2% when the pure refrigerant is replaced with mixed refrigerants and operating conditions are re-optimized.

1. Introduction

The energy efficiency of processes operating at sub-ambient conditions strongly depend on the refrigeration methods which are implemented to facilitate these low temperatures conditions. As absorption-based refrigeration systems can only be implemented to provide very limited sub-ambient cooling, refrigeration cycles based on vapor recompression are the most practical methods which are commonly used to meet the demands of low temperature for industrial-scale processes. Although the design and operation of such industrial-scale refrigeration cycles are well established in engineering communities, it is still important to look for thermal efficiency improvements which can reduce the considerable consumption of required shaft power for compression.

For the design of refrigeration cycles engineering communities have gained knowledge from graph-based tools. For example the most appropriate evaporation temperature levels for pure refrigerant cycles (subject to a minimum temperature approach for heat transfer) can be identified (giving energy-efficient solutions) using a GCC (Grand Composite Curve) method [1]. The GCC is effective to provide conceptual guidelines for selecting utilities in an economic manner because overall characteristics of energy systems in terms of demands for external utilities can be easily understood [2]. Also graphical representations of the available heat sources and sinks can simplify the procedure for energy targeting of pure refrigerant systems (i.e. determining the theoretical minimum refrigeration duties and their operating temperatures) [3]. However, this energy targeting is of limited use for cases where a mixed refrigerant is used as a result of the partial evaporation and condensation which occur during phase changes over a wide range of temperatures. Automated design method including superstructure approach can be considered for energy systems in which graphical methods may not be readily applicable due to complexity of the design and system interactions [4].

There are a wide range of possible design modifications which can reduce the shaft power used in refrigeration cycles, and these modifications can be grouped into three categories:

- Structure modifications.
- Adjustment of operating conditions.
- Modification of refrigerant composition.

Structural modifications increase the structural complexity of

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refrigeration cycles, typically through the addition of: a flash drum to reduce vapor refrigerant flowrate entering the compressor (this is widely known as an economizer or a pre-saturator), multiple levels of evaporation for the cycles to effectively accommodate required cooling duties at different temperatures, or the combination two or more refrigerant cycles to provide cooling at very low temperatures (known as a cascade cycle). This category of design modification improves energy efficiency of the refrigeration cycle at the expense of additional capital investment.

The adjustment of operating conditions and refrigerant composition are often considered simultaneously. Operating conditions including the refrigerant flowrate in addition to operating temperatures and pressures can be adjusted. In cases where a pure refrigerant (PR) is used changing the composition can mean either replacement with a different pure refrigerant or switching to the use of a mixed refrigerant (MR).

Ideally, refrigeration cycles should be designed considering all three elements: the identification of the most suitable configuration, the selection of the most appropriate refrigerant (and refrigerant composition) and the determination of optimal operating conditions in an integrated and cost-effective manner. However, due to the complexity of this design problem it is not straightforward to screen the various different combinations of structural options and to evaluate their potential. Hence the solution of these difficult problems requires a complex optimization procedure to simultaneously identify the optimal cycle configuration and operating conditions.

The existing body of literature considering the design of refrigeration cycles can be divided into two categories:

A) Design/Enhancement of pure refrigerant systems.
B) Design/Enhancement of mixed refrigerant systems.

For the design of pure refrigerants systems (category A) some of the early attempts to solve this are the MILP (Mixed-Integer Linear Programming) formulation of Shelton and Grossmann [5] and NLP (Non-Linear Programming) formulation of Colmenares and Seider [6]. Where Shelton and Grossmann considered the synthesis of refrigeration cycles integrated with heat recovery networks and Colmenares and Seider looked at the synthesis of cascaded refrigeration cycles for ethylene separation processes. However, their approaches require a certain degree of user input to determine the temperature intervals for heat integration.

Additionally, Vaidyaraman and Maranas [7] and later Zhang and Xu [8] have considered the selection and use of multiple different pure refrigerants as part of their synthesis approaches. These approaches have used more complex MINLP (Mixed-integer Non-Linear Programming) formulations allowing for more detailed consideration of different structural modifications, refrigerant options and temperature levels used in the refrigerant cycles. However, Vaidyaraman and Maranas [7] point out that under certain conditions their formulation reduces to an MILP formulation and the more recent methods such as that of Dinh et al. [9] have also been formulated as MILP problems. In addition to these synthesis methods Montanez-Morantes et al. [10] have looked at the operational optimization of existing pure refrigeration cycles by considering the performance data for existing centrifugal compressors. Montanez-Morantes et al. [10] point out that this is important because it allows for energy savings to be achieved for existing refrigeration cycles (i.e. not changing the structure but modifying operating conditions, for example if the plant capacity changes).

For the design of mixed refrigerant systems (category B) there have been a large number of studies looking at possible energy-saving modifications. For example Vaidyaraman and Maranas [11] proposed an optimization approach for the determination of optimal compositions of mixed refrigerants and operating pressure levels in refrigeration cycles having multiple vertical and horizontal stages. Later, Del Nogal et al. [12] proposed a design methodology based on the optimization of operating conditions for multi-stage cascaded mixed refrigerant cycles which rigorously tests the feasibility of the heat transfer. Recent studies have looked at the optimization of mixed refrigerant compositions in addition to operating conditions for some common configurations such as the single mixed refrigerant (SMR), propane pre-cooled mixed refrigerant cycle (C3MR) and duel mixed refrigerant (DMR) processes. In particular Wang et al. [13] have performed economic optimization of C3MR and DMR refrigeration processes, Khan et al. [14] have minimized the compression energy required for SMR and C3MR processes and Cao et al. [15] have optimized the SMR process together with exergy analysis. Also, to account for the possibility of changing work-loads in SMR processes Xu et al. [16] suggest a control strategy for varying refrigerant compositions while Sun and Ding [17] suggests the optimization of SMRs under part-load conditions. Additionally, novel driver cycle configurations [18] and different multi-stage compression structural options [19] have been investigated and tested with the aim to enhance efficiency (in particular for LNG plants).

While these studies looking at structural and operational optimization of mixed refrigerant-based refrigeration cycles (category B) reveal some useful energy saving options in all cases the equipment configuration has been specifically designed to take advantage of the properties of the mixed refrigerant.

This is a significant point because it is well known that there are significant differences between cycles designed for pure and mixed refrigerants. Chang [20] states that pure refrigeration cycles require multi-stage cycles in order to achieve a high efficiency while mixed refrigerant cycles can achieve thermal efficiency with a smaller number of components. In particular it can be seen from the 16 different refrigeration configurations considered by Chang [20] that the mixed refrigerant systems use fewer cycles than those using pure refrigerants. One exception to this is the mixed fluid cascade (MFC) process using mixed refrigerants in three cycles which is similar to a three cycle pure refrigerant cascade [21]. However, in general these differences between pure and mixed refrigerant systems imply that the retrofit (from pure to mixed refrigerants) also requires significant modification of the equipment configuration (requiring significant capital investment).

Hence, the aim of this paper is to assess the feasibility of retrofit using mixed refrigerants in refrigeration cycles originally designed for use with pure refrigerant. To the best of our knowledge this retrofit idea has not been considered in the existing literature. This is new strategy labelled S3 below is different from the conventional strategies for design (strategy S1) and retrofit (strategy S2) of refrigeration systems.

Existing strategy for design

S1) select refrigerant → Design cycle structure & Optimize operating conditions.

Existing strategy for retrofit

S2) Select new refrigerant → Re-design/modify structure & Optimize operating conditions.

Novel new strategy

S3) Select new refrigerant (switching from pure to mixed) → Optimize operating conditions.

The advantage of this approach is that significant capital investment can be avoided by considering only minimal structural modifications while still achieving energy savings through switching to a mixed refrigerant. As mentioned above the current body of mixed refrigerant research suggests that this equipment should be designed and modified explicitly for the mixed