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Operational optimisation of centrifugal compressors in multilevel refrigeration cycles

Maria Montanez-Morantes, Megan Jobson*, Nan Zhang

Centre for Process Integration, School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, UK

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A B S T R A C T

Low-temperature energy systems are processes that require cooling at temperatures below ambient, which are accomplished using refrigeration cycles. Little research has addressed the operational optimisation of refrigeration cycles considering the performance of existing equipment. This work develops a methodology for operational optimisation of refrigerated processes, taking into account existing centrifugal compressors. For the optimisation of multilevel cycles, the evaporation temperatures of each level are varied to find a set of operating conditions that minimise shaft work demand. The optimisation takes into account equipment constraints, including compressors on a common shaft, minimum and maximum allowable inlet flow rates, etc. Two examples are presented; the first represents a three-level refrigeration cycle and the second a cascade cycle. For the two examples, the conditions of the base case are optimised, identifying improvements of around 3% in shaft work demand. In addition, both cycles were also optimised for a range of process cooling demands.

1. Introduction

Low-temperature energy systems are processes that need to operate below ambient temperature and thus require the use of refrigeration cycles. Very-low-temperature energy systems, such as ethylene separation processes or liquefied natural gas (LNG) plants, operate at temperatures of around −150 °C or below, and are also known as cryogenic processes (Timmerhaus and Reed, 2007, Ch. 1). In a simple closed refrigeration cycle, the refrigerant is vaporised (by removing heat from the process streams), compressed, condensed at the discharge pressure by a cold utility or heat sink, and expanded to the vaporisation pressure. If the cooling temperature range of the process streams is wide, then cycles with several evaporation temperatures can be implemented (e.g. multilevel cycles, cascade cycles) (Dinçer and Kanoğlu, 2010, Ch. 5). One of the main issues with refrigeration cycles in cryogenic processes is that their associated costs tend to be very high because of the capital cost of the compression trains and the operating cost of the shaft work required to drive them (Mokhatab et al., 2014, Ch. 3.2). Once the refrigeration cycle has been designed and put in operation, the compression shaft work dominates the processeconomics; thus the shaft work is typically used (and is used in this work) as a key performance indicator for the design and operational optimisation of refrigeration cycles.

The synthesis (design) of refrigeration cycles is a subject of much interest because of its economic importance. It is a challenging problem that considers complex interactions between the process that requires cooling, the heat exchanger network (HEN) and the refrigeration cycle. While the synthesis of refrigeration cycles has been widely researched, the operational optimisation of refrigeration cycles is an important subject that has not been as extensively investigated. The target of operational optimisation of refrigeration cycles is to minimise operating costs of a cycle that has already been designed and is already in operation. Minimising the operational costs can lead to higher energy efficiency, improved process economics and reduced carbon emissions to the environment. The publications that have, so far, addressed the operational optimisation of refrigeration cycles (discussed further in Section 3) do not include the performance of the existing equipment nor its limitations. Thus, the optimised results from these publications could overestimate the real achievable savings, which are restricted by the operation of the existing equipment. Furthermore, few of the published models are able to predict the performance of centrifugal compressors for different operating conditions, and no published work was found that considered the physical and/or operational limitations of compressors (e.g. minimum or maximum allowable volumetric flow rates).

* Corresponding author. Tel.: +44 1613064381.
E-mail address: megan.jobson@manchester.ac.uk (M. Jobson).

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Nomenclature

$\%H_p$	polytropic head correction factor (1)
$\%Q$	inlet volumetric flow rate correction factor (1)
f_p	polytropic head factor (1)
g	acceleration due to gravity (m s^{-2})
I	total number of cooling levels
H_p	polytropic head (ft)
h	specific enthalpy (kJ kg^{-1})
lb	vector of lower bounds (K, °C)
M	number of compression stages
m	mass flow rate (kg s^{-1})
N	rotational speed of compressor (rpm)
n_p	polytropic coefficient (1)
n_s	isentropic coefficient (1)
P	pressure (Pa)
Q	heat duty (MW)
Q^V	actual volumetric flow rate (ACFM)
T	temperature (K, °C)
ub	vector of upper bounds (K, °C)
v	specific volume (m^3 kg^{-1})
W_p	polytropic work (kW)
γ	ratio of the inlet gas heat capacities
$\Delta T_{\min}$	minimum temperature difference (K, °C)
η_m	mechanical efficiency of the compressor (1)
η_p	polytropic efficiency (1)
Θ	vector of evaporation temperatures and ΔT_{min} (K, °C)

Subscripts

cond	condensation
est	estimated
evap	evaporation
i	cooling level
in	inlet
m	compression stage
out	outlet
p	polytropic
r	reference
req	required
s	isentropic

Abbreviations

ACFM	actual cubic feet per minute
C3-MR	propane precooled mixed refrigerant cycle
GA	genetic algorithm
GCC	grand composite curve
HEN	heat exchanger network
LNG	liquefied natural gas
MINLP	mixed-integer non-linear programming
NLP	non-linear programming

This paper proposes a model for the optimisation of the operating conditions of an existing refrigeration cycle for a given cooling requirement, arising from process needs, taking into consideration the operational limits of the existing centrifugal compressors (e.g. lower and upper volumetric flow rate limits). In particular, the physical properties and the cooling requirements of the process streams are taken as given, i.e. the cooling duties are known, as are their physical properties. The proposed model extends previous work on synthesis and operational optimisation of refrigeration cycles (presented in Section 3) to model the part-load performance of multistage compressors in multilevel refrigeration cycles. The model finds a set of operating conditions (evaporation temperatures, cooling duties, refrigerant flow rates and rotational speed of compressors) that minimise the shaft work demand of the refrigeration cycle. A multistart optimisation algorithm, which uses a gradient-based non-linear programming (NLP) solver together with a scatter search algorithm, is applied to search for such set. This optimisation algorithm is implemented to avoid getting trapped in locally optimal solutions, which are due to the highly non-linear nature of the model, and to find an approximation to a globally optimum solution.

First, an overview related to the basic thermodynamic theory of refrigeration cycles and centrifugal compressors is presented, followed by a literature review on the design and operational optimisation of refrigeration cycles, focusing on works that address the modelling of centrifugal compressors in these cycles. Section 4 introduces the models for estimating the performance of centrifugal compressors and for the optimisation of their operating conditions in refrigeration cycles. Finally, the benefits of the use of the proposed models are illustrated by means of two different examples in Section 5, a multilevel cycle and a cascade cycle.

2. Centrifugal compressors in refrigeration cycles

2.1. Introduction to refrigeration cycles

A simple vapour-compression cycle with a pure refrigerant, illustrated in Fig. 1, comprises a compressor (where the pressure of the vapour is raised), a condenser (where the superheated vapour is cooled and condensed to its bubble point), an expansion valve (where the liquid is expanded through an isenthalpic valve) and an evaporator (where the process stream rejects heat to the refrigerant and the refrigerant is vaporised to saturation conditions) (Dinçer and Kanoğlu, 2010, Ch. 4.2). Note that pressure drops in the heat exchangers and piping are assumed to be negligible in this work.

A more complex refrigeration cycle may provide cooling at multiple temperature levels (known as a multilevel cycle). For example, in the two-level cycle illustrated in Fig. 2, the cooling duty is satisfied at two different evaporation temperatures using a single refrigerant expanded to two different pressure levels. The use of two cooling levels reduces the refrigerant flow through the low-pressure compressor, which in turn reduces the overall shaft work demand of the cycle, compared to a simple refrigeration cycle (Smith, 2005, Ch. 24.6). In this simple cycle, the cooling duty is provided at the lowest cooling level of the two-level cycle and the condensing pressure and cooling duty are the same for both cycles. However, with increasing number of cooling levels, the capital costs of the cycle may also rise, as a higher number of exchangers and compression stages are needed; thus, the final design of the refrigeration cycles is a trade-off between shaft work demand and capital costs.

Cascade cycles consist of two or more cycles, where each cycle uses a different refrigerant, and are normally implemented when cooling is required at low temperatures and a single refrigerant

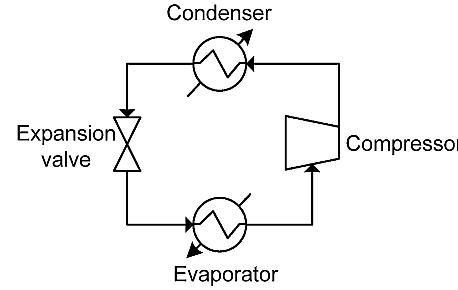

Fig. 1. Simple refrigeration cycle.