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Steady-state optimisation of a multiple cryogenic air separation unit and compressor plant

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HIGHLIGHTS

- Material and power consumption modelling of a multi-unit gas separation network.
- Piece-wise linear data-based modelling of compressor and ASU power consumption.
- Development and implementation of a MILP approach to network optimisation.
- Demonstrates achievable optimal demand side load management scheduling benefits.

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ABSTRACT

The development and on-line application of a steady-state optimisation strategy for a multiple cryogenic air separation unit and compressor plant is discussed. Implemented using mixed integer linear programming (MILP), it is demonstrated that the optimiser improves site efficiency at steady state by reduction of power consumption by up to 5% (a significant saving for such an energy intensive process) while meeting customer demand specifications. This is achieved through determination of the production distribution of the air separation units and optimal load distribution of the compression network, while simultaneously ensuring network material balance and network component operating constraints are met. In addition, the work demonstrates achievable benefits of demand side load management during peak power pricing periods, using liquid oxygen as an effective energy storage device. A key constituent of the optimisation strategy is linear modelling to predict individual unit power consumption. Piece-wise linear data-based models of compressor and air separation unit power are shown to provide accurate models which improve existing on-site power prediction by up to 80% for compressors and 60% for the air separation units.

1. Introduction

Cryogenic air separation plants are energy intensive processes consuming significant amounts of power (electricity) as a result of air separation into oxygen, nitrogen etc. and the subsequent compression or liquefaction of the gas products. Key peculiarities of industrial air separation are well documented; air is the only raw material (it is free and supply is unlimited), the cost of power (electricity) is the primary operational cost, >90% [1], which varies throughout the day and the networks simultaneously produce gas and liquid that may be used to satisfy customer demand (the stored liquid being used to satisfy demand at times when electricity is at its most expensive) e.g. see Manenti and Rovaglio [2]. The purpose of this paper is to report the development and on-line application of a steady-state optimisation strategy that aims to minimise power consumption of a network of air separation and gas compression units. This is achieved by optimal production distribution of the air separation units and load distribution of the compression network.

Related to this work therefore, is the optimisation of industrial gas supply chains that comprise of networks of pipework, compressors and gas production units which are operated to meet customer demand and optimised for economic and environmental cost reductions, e.g. see Üster and Dilaveroğlu [3], Azadeh et al. [4] and Gao and You [5], who use a mixed integer nonlinear programming (MINLP) algorithm to optimise economic and environmental objectives. In Cortinovis et al. [6], a MINLP approach to the optimisation of a natural gas transmission system comprising

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Nomenclature

Abbreviations

ASU	air separation unit
HP	high pressure
LN	liquid nitrogen
LP	low pressure
MP	medium pressure
GO	gaseous oxygen
IC	internally compressed
LO	liquid oxygen
ME	model mean error (kW)
TLO	total liquid oxygen

Parameters

$\hat{b}$	model coefficient
C_{LO}	liquid make cost (£/HCM)
δ	Boolean coefficient
F	flow rate (HCMS/h)
P_D	discharge pressure (bar)
y	flow/Boolean auxiliary variable
C_{kW}	spot power cost (£/MWh)
C_s	liquid use cost (£/HCM)
ε	machine efficiency (kW/HCM)
J	cost function (£/hr)
W	power consumption (kW)

Subscripts

c	compressor
k	pseudo-machine number
s	liquid back-up supply
v	valve
j	compressor or ASU number
m	model number
u	unit (ASU)

of parallel compressors power consumption is also reported. This allows the monitoring of power regression curves against real time data to track compressor performance and identifying when maintenance is required. The optimal load sharing of a network of compressors has also been considered by Han et al. [7] and Abbaspour et al. [8] who developed off-line optimisation approaches while Paparella et al. [9] and Xenos et al. [10] considered the on-line optimisation of a network of air compression units. In Paparella et al. [9] the optimal load distribution of a number of parallel compressors in a natural gas pipe-line were considered. While Xenos et al. [10] optimised an industrial compressor station that served compressed air to air separation and chemical plants. Where compressor load sharing performance can be robustly modelled, Øvervåg [11] uses a MINLP model predictive controller to optimally load share using efficiency curve data.

Development of predictive models of both compressor and air separation unit power consumption is a particular focus of this work. The operating principles of compressors (e.g. their characteristic performance and operation limits) are normally described in terms of compressor efficiency and detailed hybrid models of power consumption in industrial multistage compressors have been developed, e.g. see Han and Han [12]. Similarly, mechanistic models of air separation units exist within the literature which may be used as the basis for prediction of power consumption e.g. see Huang et al. [13]. However, the development of a set of robust and reliable models from fundamental principles would be an onerous task for a complex mix of industrial air separation units and compressors. Therefore, an empirical data-based modelling approach is used in this work. Related work includes Puranik et al. [14] who used nonlinear regression models as the basis of a MINLP approach to the optimisation of an oxygen and nitrogen customer network. Similarly, in Cao et al. [15], an MINLP approach was used to determine the optimal production rates required to meet customer nitrogen demands and assess dynamic compressor performance. In addition, Kopanos et al. [16] and Xenos et al. [10] also describe power consumption modelling using nonlinear empirical models to capture the relationship between power consumption, flows, temperatures and pressures for use within an optimiser to improve the operational costs of a parallel network of air compressors and to optimally schedule maintenance.

In all previous work on air separation unit and compressor plant optimisation, site optimisation for gas network demand is developed using a MINLP approach with dynamic optimisation using demands predicted for the days and weeks ahead. A key operational aspect of the process considered in this work is that customer demands are unknown and unpredictable, with time horizons of hours, not days. The implementation of an MINLP approach using nonlinear empirical models, reported in Adamson et al. [17] generally yielded excessive solution times rendering the on-line application impractical. In this work the steady-state optimisation problem is formulated as an MILP in order to ensure robust and efficient on-line optimisation.

To develop a MILP optimisation model, the power consumption of network components (ASU and compressors) are determined using a piece-wise linear modelling approach. Lin et al. [18] present a review of the use of piecewise linearisation techniques, finding methods can be used to efficiently discover approximated globally optimal results. There are many recent examples in literature regarding the use of piece-wise linearisation techniques to partially or fully formulate a MILP approach to gas network optimisation. For example, Martin et al. [19] formulates a large MILP problem to solve the optimisation of natural gas networks using piece-wise linear approximations of nonlinear constraints at steady state. While Kolb et al. [20] describe how gas network optimisation can be better achieved by developing piece-wise linear approximations of network components. In Camponogara et al. [21] and Aguiar et al. [22] gas-lifted oil field production costs are optimised by combining convex nonlinear regression curves with piece-wise linear approximations of these curves at given pressure and routing constraints. While Domschke et al. [23] solve a complex natural gas network optimisation problem by integrating piece-wise linear approximations to partially linearise a nonlinear cost function. Furthermore, in Correa-Posadaa and Sánchez-Martın [24] the piecewise linearisation of general gas flow equations and the development of linear models of other gas network components, such as machine power are discussed. Adopting a similar approach, in this work, it is demonstrated that piecewise linear models can accurately predict the power consumption of both air separation units and compressors with prediction accuracies comparable to the best nonlinear alternative.

Where power consumption can be accurately predicted at a given time of use, the operational network cost can be determined ahead of use, subject to the predicted price of power. Flexible power loads can be selectively purchased on spot power markets at variable prices to reduce overall commodity costs in conjunction with demand side load management, Merkert et al. [25]. We refer to the examples in Karagiannopoulos et al. [26] in which flexible loads are manipulated into an overall less energy efficient operation strategy whilst still delivering operational cost savings by reducing load at peak power price. Similarly, Zhang et al. [27] use a MILP scheduling approach to liquefy air off-peak and generate power directly via turbine at peak on underutilised air