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Optimum number of stages and intermediate pressure level for highest exergy efficiency in large helium liquefiers

Rijo Jacob Thomas [a,*], Parthasarathi Ghosh [b], Kanchan Chowdhury [b]

[a] Department of Mechanical Engineering, T.K.M. College of Engineering, Kollam, Kerala 691005, India
[b] Cryogenic Engineering Centre, Indian Institute of Technology, Kharagpur 721302, India

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ABSTRACT

In this paper, an attempt has been made to study the influence of different design and operating parameters on the performance of large scale helium liquefiers through the concept of pre-cooling stages. Through exergy analysis and simulation with Aspen HYSYS® 7.0, it has been demonstrated that four refrigeration stages is the best option for large helium liquefiers when all expanders operate between the entire available pressure differences. However, when some of the expanders are operated at intermediate pressure, a more number of stages gives a higher thermodynamic efficiency. Relationship between the number of stages, effective heat exchanger area and operating pressure levels of expanders, which could optimally be employed for least specific power consumption has been established through exergy analysis. Optimum number of stages, intermediate pressure and corresponding plant efficiency are, however to a large extent, dictated by the prevailing compressor efficiency. The intermediate pressure that gives the maximum exergy efficiency for the plant increases from 0.2 MPa with constant compressor efficiency to 0.35 MPa when considering two-staged compressor where pressure ratio influences compressor efficiency. Results presented may be useful in designing energy-efficient helium liquefiers of large capacity.

Nombre d'étages et niveau de pression intermédiaire optimaux, en vue du meilleur rendement exergétique dans de grands liquéfacteurs d'hélium

Mots clés : Liquéfacteur d'hélium ; Analyse exergétique ; Étapes de réfrigération ; Pression du détendeur ; Cycle de Brayton inversé ; Aspen HYSYS

* *Corresponding author*. Tel.: +91 474 271 2022, +91 9400 4900 11 (Mob); fax: +91 474 271 2023.
E-mail address: rijojthomas@gmail.com (R.J. Thomas).
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Nomenclature

A	heat transfer surface area (m^2)
c_P	specific heat (kJ kg^{-1} K^{-1})
ex	exergy $Ex = (h - h_0) - T_0(s - s_0)$ (kJ kg^{-1})
$\dot{E}x$	rate of exergy flow (kW)
$\dot{E}x_{DEST}$	rate of exergy destruction (kW)
$\dot{m}$	rate of mass flow (kg s^{-1})
$\dot{Q}$	rate of heat transfer (kW)
U	overall heat transfer coefficient (W (m^2-K)$^{-1}$)
$\dot{W}$	work (kW)
η_{COMP}	isothermal efficiency of compressor
ε	heat exchanger effectiveness

Abbreviations

Config.	configuration
COMP	compressor
DEST	destruction
EXP	expander
HX	heat exchanger
JT	Joule Thomson valve
L	liquid helium
St.	stage

Subscripts

0	reference state
COMP	compressor
d	discharge
DEST	destruction
EXP	expander
HP	high pressure
HX	heat exchanger
i	any point
IP	intermediate pressure
JT	Joule Thomson valve
L	liquid helium
LP	low pressure
RS	refrigeration stage
s	suction

1. Introduction

Practical helium liquefier comprises of three basic functional sections: i) the compressor section whose function is to perform near-isothermal compression process using multiple stages and inter-coolers and after-coolers, ii) the pre-cooling section usually consisting of refrigeration stages (*RS*) which has the duty of bringing down the temperature of a part of the high pressure (*HP*) helium gas to below its maximum inversion point and iii) the final liquefaction section, where a fraction of the gas is liquefied by isenthalpic and/or isentropic expansion (Thomas et al., 2012a,b). Pre-cooling and liquefaction sections together constitute the "cold box". Although the pre-cooling section consist of several expanders and heat exchanger, these may be resolved into sequence of cooling stages composed of basic thermodynamic reverse Brayton refrigeration cycle (Arkharov et al., 1981). The schematic diagram of a generalized helium liquefaction cycle composes of '*n*' such reverse Brayton stages is given in Fig. 1. A Brayton refrigeration stage consists of two heat exchangers (*HX*1a and *HX*1b, for example) and one expander (*EXP*1) and they are connected as shown in Fig. 1 (Thomas et al., 2012a). Two Brayton refrigeration stages and the final liquefaction section (based on Simple Linde–Hampson liquefaction cycle) form a basic cycle for a large scale helium liquefier or a refrigerator, known as Collins cycle.

Liquid nitrogen (LN_2) is often used for the pre-cooling of *HP* helium gas. However, the decision of employing an external pre-cooling stage using LN_2 depends on the availability of LN_2.

A helium plant may be a liquefier or refrigerator depending upon the way of utilization of liquid produced and therefore, functionally a liquefier is different from a refrigerator. In helium liquefier, output liquid exits the system along with the latent and sensible heat associated with it. Refrigerators are closed systems, where heat is absorbed using only the latent cold. The boil-off gas returns to the compressor through the array of counterflow heat exchangers allowing the system to retrieve most of the sensible cold contained in it. At atmospheric pressure, latent heat of 1 kg of liquid helium is about 20 kJ, while the sensible heat is about 1540 kJ per kg. Therefore, there ought to be differences in configuration as well as design and operating parameters between liquefiers and refrigerators. Studies reported in the literature showed that addition of more refrigeration stages has positive influence on the performance of both liquefiers and refrigerators, though to a different extent. In this paper, the focus is given on liquefiers as considerable attention has been given to refrigerators by previous researchers (Khalil and McIntosh, 1977; Hilal, 1979; Kundig, 1986; Quack et al., 1992; Lohlein and Fukano, 1993; Ziegler and Quack, 1992; Quack, 1994; Jeong and Smith, 1994; Kuendig, 2008) and a few studies have been performed on helium liquefiers. Toscano and Kudirka (1978) found that addition of refrigeration stages improves thermodynamic performance of helium liquefaction cycles. They used four stages in their analysis of helium plant: LN_2 stage and 3 refrigeration stages. However, expanders are not arranged exactly as in a Brayton stage. Arkharov et al. (1981) mentioned that minimum number of stages required for a helium liquefier is 3 and this number should increase for an improved plant performance. As *JT* expansion is also counted as one of the stages, his suggestion essentially means that a Collins Cycle is the minimum configuration required for a helium liquefier. The optimization study of Hilal (1979) on two-, three- and four-engine liquefiers showed that the maximum coefficient of performance increased and the optimum pressure decreased with the addition of number of Brayton stages. Narinsky and Chernokov (1992) showed that for helium liquefiers, there is much higher rate of liquefaction when the number of stages is increased from 2 to 3, though the quantum of additional improvement is only marginal when the number of stage is further increased to four. A recent study found that there is an excessive loss of