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Role of expanders in helium liquefaction cycles: Parametric studies using Collins cycle

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ABSTRACT

Large scale helium liquefaction/refrigeration plant is a key subsystem of fusion devices. Performance of these plants is dependent on a number of geometric and operating parameters of its constituting components such as compressors, heat exchangers, expanders, valves, etc. Expander has been chosen as the subject matter of analyses in the present study. As the sensible cold of helium vapor is lost in liquefiers, the expanders in liquefaction cycles have to provide more refrigeration than those in refrigeration cycles. The expander parameters such as rate of mass flow, operating pressure, inlet temperature, etc. are interdependent, and hence, it is difficult to predict the system behavior with variation of a particular parameter. This necessitates the use of process simulators. Parametric studies have been performed on Collins helium liquefaction cycle using Aspen HYSYS®. Collins cycle has all the basic characteristics of a large-scale helium liquefier and the results of this study may be extrapolated to understand the behavior of large scale helium liquefiers. The study shows that the maximum liquid production is obtained when 80% of the compressor flow is diverted through the expanders and it is equally distributed between the two expanders. The relationships between the liquid production and the isentropic efficiency of expanders are almost linear and both the higher and lower temperature expanders exhibit similar trends.

1. Introduction

Fusion devices generally have steady state as well as transient heat loads of varying magnitudes and durations arising from its magnets, support structures for magnets, current leads, cryopumps, thermal shields, etc. Gaseous, liquid, super-critical, and/or super-fluid helium are employed to absorb these heat loads. For some applications, the amount of heat that has to be removed at near 5 K is of the order of a few kilowatts or higher and the corresponding helium liquefaction/refrigeration plants may be called 'large-scale'. Detailed description about the large-scale helium liquefiers/refrigerators employed in fusion devices are given in open literature [1–3]. Configuration and operational control of these plants depend on the complexity of functions demanded and constraints imposed by the fusion devices. These plants generally have thermodynamically involved cycle configurations with a number of compressors, heat exchangers, expanders, expansion valves, etc. Their associated parameters viz. mass flow rates, operating pressure and temperature, the number of stages, the arrangement of heat exchangers and expanders have interdependent influence on the performance of the plants. The nature of final expansion stage for liquefaction (Joule-Thomson valve (J-T), wet expander and/or its combination), presence of specific devices such as cold compressors, ejectors, etc. also add to the complexity of the plant configuration. For all the above reasons, it is difficult to understand the behavior of helium liquefaction cycles without the help of process simulators such as Aspen HYSYS®.

Among all the gases, helium has the lowest liquefaction temperature of 4.2 K at atmospheric pressure. The compressed helium gas has to be cooled from ambient (300 K) to near its critical temperature of 5.2 K such that a portion of the gas gets liquefied upon isenthalpic or isentropic expansion (using Joule–Thomson valve or wet expander, respectively). In any helium liquefaction cycle, the expanders produce the refrigeration. In Collins cycle, there are 2 expanders and a final J–T valve. An expander and 2 heat exchangers constitute a reverse Brayton refrigerator. Hence Collins cycle may be assumed to be a Linde liquefier which is pre-cooled by 2 reverse Brayton refrigerators. The forward stream is cooled by the return stream which comprises of the discharge streams from the expanders apart from the cold vapor produced after the final isenthalpic or isentropic expansion.

The liquid produced in a liquefier generally is taken out and used to absorb the external heat load utilizing both latent heat (20.8 J/g) and sensible heat (1540 J/g in 300–4.2 K range). In a pure refrigerator, the latent heat is utilized for external cooling while the sensible cold is recovered in the heat exchangers. However, in the

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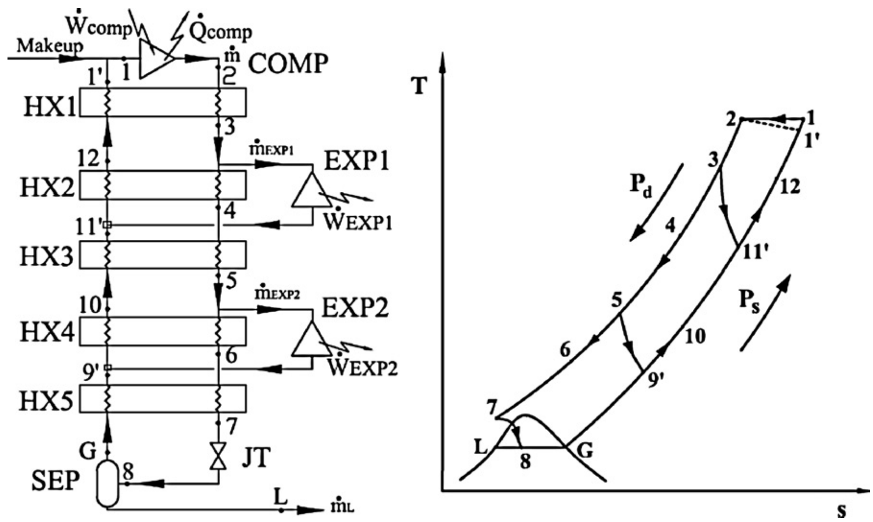

Fig. 1. Schematic and *T–s* diagrams of the Collins helium liquefaction cycle.

liquefier, this sensible cold is not available for pre-cooling the high pressure stream and hence, the expanders have to produce additional refrigeration to make it up. Therefore, the optimum operating parameters and the specifications of the components for a refrigerator cycle may not be the same in case of a liquefaction cycle of same capacity.

Research on helium liquefiers has gained momentum due to the demand for more efficient large-scale helium liquefiers for cooling the superconducting magnets used in applications like particle accelerators, tokomaks, etc. Aronson [4] has discussed the factors affecting the expansion efficiency and the considerations to be made while using multi-expanders in a cycle. Khalil and McIntosh [5] has determined the optimum inlet temperature to expander for Claude-based refrigeration cycles up to six expanders. Hilal [6] has optimized both refrigeration and liquefaction cycles in terms of number of expanders, their arrangements and inlet temperature to expanders. For a 1.8 K refrigerator with two expanders, Hilal and Eyssa [7] determined the optimum inlet temperature to expander and the flow fraction through expander. A study on the optimum flow fraction through the expanders for a two-expander liquefaction cycle has been performed by Atrey [8].

1.1. Problem statement

The expander performance is dependent on a number of parameters and the relation between them are quite complex. This fact may be the reason for scarcity of detailed analysis on this aspect of helium liquefaction system in the open literature. Many of the studies do not convert their findings to design suggestions that could help in modifying existing cycles or designing improved large-scale helium liquefaction cycles. Since all the large-scale configurations may be considered to have evolved out of the basic Collins cycle, it has been thought to be appropriate to undertake a detailed investigation on Collins cycle vis-à-vis the role of expanders on its performance. This may provide a better understanding about the role of expanders in a large scale helium liquefaction cycle and also help in the appropriate selection of expander parameters for larger systems. The study has been performed using a commercial simulator, Aspen HYSYS®, to understand the impact of variation of mass flow rates and efficiency of the expanders on the cycle performance.

2. Methodology

2.1. Thermodynamic cycle

The schematic and temperature–specific entropy (*T–s*) diagrams of Collins helium liquefaction cycle selected for the study have been shown in Fig. 1.

2.2. Assumptions

The study has been performed on the basis of the following assumptions:

(1) The system is at steady state condition.
(2) The efficiencies of components like compressor and expanders or the effectiveness of heat exchangers do not vary with pressure, temperature and mass flow rate.
(3) There is no heat in-leak into the system.
(4) Pressure drops in heat exchanges and pipelines are considered negligible.

2.3. Solution procedure

A simulation model for Collins helium liquefaction cycle has been developed using a commercial process simulator Aspen HYSYS®. This simulator has necessary tools for performing design and simulation, viz. steady state design specifications, sensitivity analysis, optimization etc. The 32-term modified BWR Equation of State (EOS) which is a widely accepted EOS for helium is utilized for generating the thermo-physical properties of helium. Efforts have been made to understand the effects of variations of different expander parameters on the liquefaction capacity of Collins helium liquefaction cycle.

While one parameter is varied, other parameters have been kept constant at some “base values”, which are selected according to the practical data available in open literature. They are as follows: isentropic efficiency of the compressor is 60%, while that of both the expanders are 70%. For all the five heat exchangers the effectiveness has been kept at 0.97. The compressor suction (P_s) and compressor discharge (P_d) pressures are 1.01 bara and 14 bara, respectively.