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Role of heat exchangers in helium liquefaction cycles: Simulation studies using Collins cycle

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ABSTRACT

Energy efficiency of large-scale helium liquefiers generally employed in fusion reactors and accelerators is determined by the performance of their constituting components. Simulation with Aspen HYSYS® V7.0, a commercial process simulator, helps to understand the effects of heat exchanger parameters on the performance of a helium liquefier. Effective *UA* (product of overall heat transfer coefficient *U*, heat transfer surface area *A* and deterioration factor *F*) has been taken as an independent parameter, which takes into account all thermal irreversibilities and configuration effects. Nondimensionalization of parameters makes the results applicable to plants of any capacity. Rate of liquefaction is found to increase linearly with the effectiveness of heat exchangers. Performance of those heat exchangers that determine the inlet temperatures to expanders have more influence on the liquid production. Variation of sizes of heat exchangers does not affect the optimum rate of flow through expanders. Increasing *UA* improves the rate of liquid production; however, the improvement saturates at limiting *UA*. Maximum benefit in liquefaction is obtained when the available heat transfer surface area is distributed in such a way that the effectiveness remains equal for all heat exchangers. Conclusions from this study may be utilized in analyzing and designing large helium plants.

1. Introduction

Fusion devices which employ superconducting magnets require cooling at very low-temperatures utilizing gaseous, super-critical, liquid or even super-fluid helium. High heat loads arising out of these applications calls for the use of large-scale helium liquefiers/refrigerators [1–4]. In case of these cycles even the Carnot power requirement is about 70 W for transporting 1 W heat from the low-temperature source (4.2 K) to the atmospheric sink (300 K). A proper design and analysis of these energy-intensive cycles would reduce substantial capital and operating cost. Compared to the basic Collins helium liquefaction cycle, these large-scale helium liquefiers/refrigerators constitute of a larger number of components and have more involved cycle configuration; so, there are more parameters influencing their performances. The combined and intertwined effects of these cycle parameters call for the use of process simulators such as Aspen HYSYS® to aid analyze performance of these plants. This study is expected to serve as a ground work for future understanding of the behavior of large-scale helium liquefaction plants.

As the maximum inversion temperature of helium is 45 K, a helium liquefier/refrigerator needs pre-cooling either by LN_2–LH_2 or by reverse Brayton cycles. One expander and two heat exchangers constitute a reverse Brayton refrigerator stage. Whether the cycle is based on external pre-cooling or Brayton refrigerator stages or a combination of both, the production capacity of the liquefier is determined by performance of the heat exchangers. A Collins helium liquefier consists of a simple Linde cycle with two such reverse Brayton refrigerators in series. However, in a large-scale helium liquefaction cycle, more pre-cooling Brayton stages are used. For the best performance of a helium liquefaction cycle, it is imperative that the expanders produce the highest possible refrigeration and the heat exchangers allow the least amount of cold loss. In Collins cycle, there is an array of five heat exchangers, which are kept at different temperature levels between ambient to liquid helium temperature (300–4.2 K). If the working pressures and mass flow rates through each component of the cycle are fixed, the performances of expanders and of J–T valve are dependent on their inlet temperatures. Therefore, the overall performance of the cycle (rate of liquefaction) would be determined by the efficacy of heat exchangers which decide the inlet temperatures to the expanders and the J–T as well as the loss of refrigeration. Increase or decrease of heat transfer area of heat exchangers, thus, results in increase or decrease of rate of liquefaction. Performances of heat exchangers also depend on the imbalance of rates of heat capacities of the streams, which comprises of mass flow rates and specific heat capacities. Owing to the withdrawal of liquid from the liquefier and diversion of flow to the expanders, there is considerable difference

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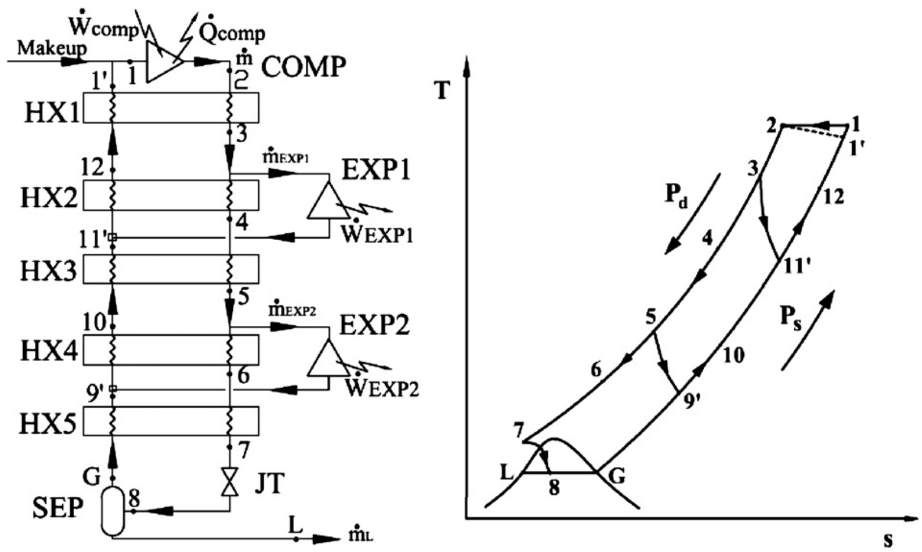

Fig. 1. Schematic and T-s diagrams of Collins helium liquefaction cycle [COMP: compressor, HX: heat exchanger, EXP: expander, SEP: separator, JT: Joule Thomson valve, G: gas, L: liquid, P_s: compressor suction pressure, P_d: compressor discharge pressure].

between mass flow rates of the streams in heat exchangers. Further, a wide fluctuation of specific heat of helium gas with pressure at near critical temperature also results in variation of heat capacity rate between the streams [5,6].

Some studies have investigated the importance of heat exchangers on a helium liquefaction/refrigeration cycles. Daus et al. [7] have shown the power consumption, heat transfer surface and the relative plant costs as functions of the temperature difference of heat exchanger. Toscano et al. [8] have evaluated the thermodynamic performance of the central helium liquefier of Fermi National Accelerator Laboratory (FNAL) for different sets of temperature approach of heat exchangers. Khalil et al. [9] have given the practical temperature approaches of heat exchangers for different multi-expander Claude based helium refrigeration cycles having up to five expanders. For a helium liquefier based on the Collins cycle consisting of six heat exchangers and two reciprocating expanders, Atrey [10] has evaluated the relative importance of the effectiveness of each heat exchanger on the performance of the liquefier.

1.1. Problem description

Though, it is generally known that higher heat exchanger effectiveness leads to improved cycle performance, detailed studies in this aspect is scarce. This paper performs a study to analyze the effects of variation of heat exchanger parameters on the rate of liquid production. Effectiveness of heat exchangers and the effective thermal sizes of heat exchangers have been varied to determine their effects on the cycle performance. As Collins cycle is the basic cycle for any large-scale helium liquefaction cycle, it is appropriate that a detailed investigation on Collins cycle is undertaken in relation to the role of heat exchangers on its performance. This may provide a clear understanding on the role of the heat exchangers and help in deciding the effective size of heat exchangers for larger systems.

2. Methodology

The schematic and temperature-specific entropy (T-s) diagrams of Collins helium liquefaction cycle are shown in Fig. 1.

2.1. Assumptions

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

1. System is at steady state condition.
2. Efficiencies of components do not depend on pressure, temperature and mass flow.
3. Pressure drops in the heat exchangers and pipelines are considered negligible.
4. Thermal effects such as heat in-leak, axial heat conduction, specific heat variation in fluids, flow maldistribution etc. and configuration effects of non-counterflow heat exchanger are accounted in the definition of effective *UA*.

2.2. Definitions and nondimensionalization

Defining the parameters in nondimensional forms makes the results applicable to plants of any size. The rate of mass flow through the compressor $\dot{m}_{\mathrm{COMP}}$ has been chosen as the characteristic unit for the purpose of nondimensionalization of various independent and dependent parameters. This approach is expected to reduce the efforts of designing large-scale helium liquefier which has complex cycle configuration with a large number components and whose performance is dependent on the geometric and operating parameters of these components.

1) The rate of liquid production $\dot{m}_L$ is nondimensionalized as the fraction of the total compressor flow as follows:

$$\text{Fraction of gas liquefied} = \frac{\dot{m}_L}{\dot{m}_{\mathrm{COMP}}} \tag{1}$$

2) The heat exchanger loss is nondimensionalized as:

$$\dot{\bar{Q}}_{\mathrm{Loss,HX}} = \frac{\dot{Q}_{\mathrm{Loss,HX}}}{\dot{m}_{\mathrm{COMP}}(h_1 - h_G)} \tag{2}$$

where h_1 is the specific enthalpy at the suction of the compressor and h_G is the specific enthalpy of saturated vapor at 1.01 bara.

3) Nondimensionalization of *UA* of heat exchanger