Cryogenics 59 (2014) 23–37

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Identification of critical equipment and determination of operational limits in helium refrigerators under pulsed heat load

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ARTICLE INFO

Article history:
Received 6 August 2013
Received in revised form 11 December 2013
Accepted 16 December 2013
Available online 22 December 2013

Keywords:
Helium liquefiers/refrigerators
Pulsed heat load
Plate-fin heat exchanger
Cryogenic turboexpanders
Aspen Hysys®

ABSTRACT

Large-scale helium refrigerators are subjected to pulsed heat load from tokamaks. As these plants are designed for constant heat loads, operation under such varying load may lead to instability in plants thereby tripping the operation of different equipment. To understand the behavior of the plant subjected to pulsed heat load, an existing plant of 120 W at 4.2 K and another large-scale plant of 18 kW at 4.2 K have been analyzed using a commercial process simulator Aspen Hysys®. A similar heat load characteristic has been applied in both quasi steady state and dynamic analysis to determine critical stages and equipment of these plants from operational point of view. It has been found that the coldest part of both the cycles consisting JT-stage and its preceding reverse Brayton stage are the most affected stages of the cycles. Further analysis of the above stages and constituting equipment revealed limits of operation with respect to variation of return stream flow rate resulted from such heat load variations. The observations on the outcome of the analysis can be used for devising techniques for steady operation of the plants subjected to pulsed heat load.

1. Introduction

Large-scale helium refrigerators at 4.2 K are used for cooling superconducting magnet systems, support structures, cryo-pumps etc. for fusion devices [1]. As discussed in [2,3], these superconducting magnetic systems generate heat load that are pulsed in nature and helium refrigerators have to handle such heat loads. Heat load characteristics from fusion experiments have been discussed in [3–7]. The amplitude of these pulsed heat loads vary from 1 kW to 3 kW depending upon the requirement of fusion devices [4,8]. The state-of-the-art technology of these large-scale helium refrigerators, designed for constant heat loads has enabled the use of turbines, screw compressors, plate-fin heat exchangers with high heat transfer surface area to weight ratio. However, all these equipment have narrow operating margins. High variations in heat load to the refrigerators may affect the performance of the plants bringing instability in operation of such equipment and may even trip the plant [2]. Therefore, it is necessary to understand the behavior of these refrigerators when they are subjected to pulsed heat load for finding out configurations of the plants and distribution systems that provide stable operation of fusion devices.

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http://dx.doi.org/10.1016/j.cryogenics.2013.12.005

2. Problem description

In this paper, the effects of pulsed heat load on operation of the helium refrigerators have been analyzed. To start with, an existing two-turbine based helium refrigerator, being the basic helium refrigerator, has been simulated in dynamic and quasi steady state scenario. The analysis has been repeated for a four-turbine based large-scale helium refrigerator adopted from literature for understanding the behavior of large-scale plants in comparison with that of the existing plant. The results of these studies have been analyzed and critical equipment have been identified. Dynamic simulations have been performed for these critical equipment to determine their operational limits for a wide range of variation of heat load.

3. Methodology

3.1. Cycle configurations and pulsed heat load characteristics

Large-scale helium refrigerators, typically of the order of a few tens of kilowatts at 4.5 K, are based on modified Claude cycle, where JT stage comprises the last stage. The thermodynamic cycles considered in this work are: (i) a modified Claude cycle based helium refrigerator of 120 W at 4.2 K consisting two turbines and seven plate fin heat exchangers with liquid nitrogen precooling (Fig. 1a) [9] and (ii) a 18 kW at 4.2 K consisting four turbines and nine plate fin heat exchangers (Fig. 1b) [5].

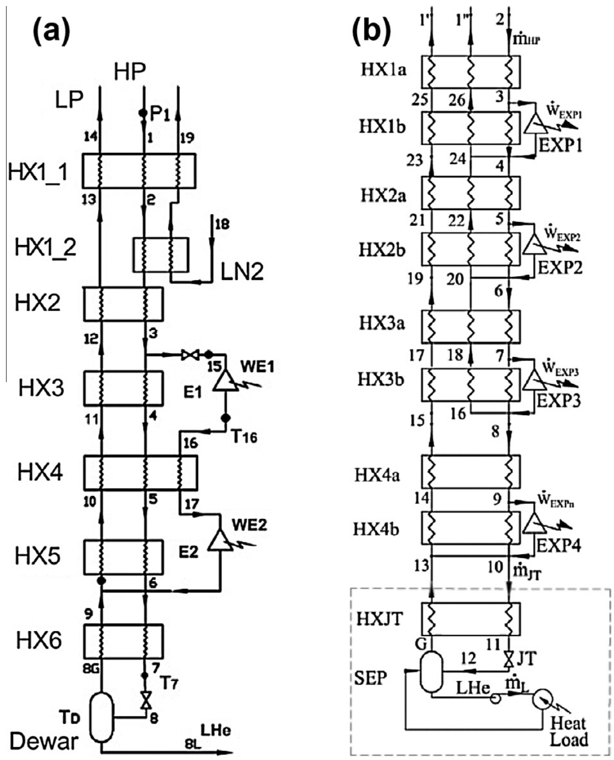

Fig. 1. (a) Existing plant of capacity of 100 W at 4.2 K; and (b) four-turbine based large-scale plant with a capacity of 18 kW at 4.2 K.

Table 1
Comparative heat load characteristics [3,10,11].

Parameters	ITER	KSTAR	Kuendig et al.
High heat load	30.0 kW	5.5 kW	24.0 kW
Duration	1500 s	4050 s	1750 s
Ramp-down time	1950 s	450 s	1 s
Low heat load	24.0 kW	3.3 kW	12.0 kW
Duration	1 s	6300 s	1749 s
Ramp-up time	149 s	450 s	100 s
Difference between high and low heat load	6 kW	2.2 kW	12 kW
Ratio of high and low heat load	1.25	1.67	2.0

Typical heat load characteristics of some fusion devices are compared in Table 1 [3,10,11]. In this paper, the heat load profile for large-scale plant has been adopted from [3] as a representative one and presented in Fig. 2. The operating schedule of the heat load is as following:

12 kW heat load:	1749 s
12 kW to 24 kW ramp-up:	100 s
24 kW heat load:	1750 s
24 kW to 12 kW ramp-down:	1 s

The functions used for the heat load ramp-up and ramp-down are,

$$\text{Ramp-up}: y = 0.12(t - t_{ru}) + 12$$
$$\text{Ramp-down}: y = -12(t - t_{rd}) + 24$$

where t_{ru} is the time of starting of the ramping-up and t_{rd} is the time of starting of the ramp down and t is the variable time. The time-averaged heat load has been chosen to design the large-scale plant at steady state [3,5].

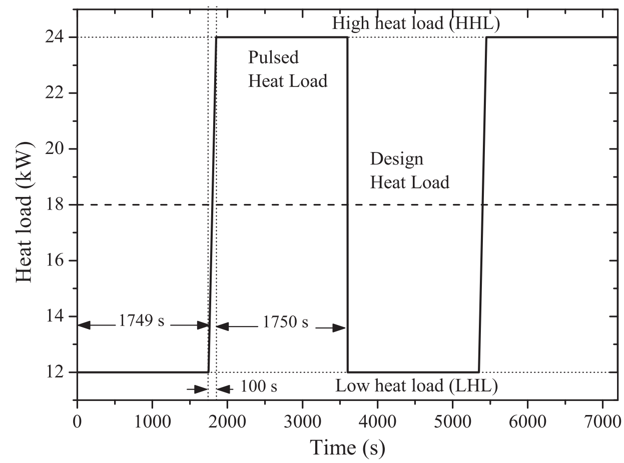

Fig. 2. Profile of the pulsed heat load for the large-scale helium refrigerator (adopted from [3]).

Similarly the pulsed heat load profile for the existing plant has been scaled down for a time average heat load of 120 W at 4.2 K with a heat load variation of ±33%.

3.2. Solution methodology

For simulations of the plants, Aspen Hysys® has been used. Suitability of Aspen Hysys® for simulating helium liquefier/refrigerator and required customizations are discussed in [9,12].

For helium, 32-term Modified Benedict–Webb–Rubin (MBWR) and for Nitrogen, Peng–Robinson–Twu (PR–Twu) equations of states (EOS) have been used for calculating the thermodynamic properties. Euler implicit method and an equation oriented approach have been used by Aspen Hysys® for calculation of the pressure and flow characteristics (Pressure-Flow (P-F) solver). For a flow-sheet, all boundary streams attached with each unit operations have to be specified. During simulation, we have used the pressure specification for all the boundary streams as shown in the Fig. 1a (stream 1, 14, 19) and Fig. 1b (stream 1′, 1″ and 2). The time-step of the integrator has been chosen as the minimum value that gives no numerical instability. The order of calculation has been set as follows:

(i) Solution for pressure using P-F solver at each time-step.
(ii) Mass and energy balance equations after every two time-steps.
(iii) Flash calculations after every ten time-steps.

Before starting simulation, all the streams and equipment have been completely specified in accordance to the process condition. After initialization, the heat load has been applied according to the profile mentioned in Section 3.1.

4. Effects of pulsed heat load on helium refrigerator

The two-turbine based existing plant and the large-scale four-turbine based plant have been analyzed both in dynamics and in quasi steady state applying the heat load profiles described in Section 3.1.

Initially dynamic simulations have been performed to analyze the performances of two plants under similar pulsed heat load characteristics. Reasons behind dynamic simulations of both the plants are: