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## Thermodynamic analysis of different cold end configurations for mixed mode cryogenic helium plant

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# Thermodynamic analysis of different cold end configurations for mixed mode cryogenic helium plant

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**Abstract.** With the development of scientific installations like particle accelerators, tokomaks and colliders involving in the large-scale and multiple-cryogenic-users way, more and more cryogenic helium plants operate in mixed mode, neither pure refrigeration nor pure liquefaction. As a main functional section of the mixed mode cryogenic helium plant, performance of cold end section influences the performance of the whole system. In this paper, thermodynamic performance of six cold end configurations for mixed mode cryogenic helium plant will be evaluated based on exergy analysis. The influence of the inlet pressure, temperature of high pressure helium stream and mode of operation on thermodynamic performance of the cold end section will be investigated. Results from the analysis may help to design and optimize cold end configuration for mixed mode cryogenic helium plant.

## 1. Introduction

With the development of scientific installations like particle accelerators, tokomaks and colliders involving in the large-scale and multiple-cryogenic-users way, more and more cryogenic helium plants have to be operated in liquefier-refrigerator mixed mode to absorb steady and transient heat loads from multiple cryogenic components. To cool superconducting magnets, thermal shields, HTS current leads, cryopumps, NBI and pellet injection system, the cryogenic system of Experimental Advanced Superconducting Tokamak (EAST) is designed with cooling capacity of 1050 W/3.5 K + 200 W/4.5 K + 13 g s<sup>-1</sup> LHe + 13 kW/80 K [1]. As a main functional section, the helium gas is converted to liquid in the cold end section of the mixed mode cryogenic helium plant. An efficient design of cold end reduces destruction of the exergy, which has a positive impact on the performance of the whole system [2]. Apart from single Joule-Thomson (JT) expansion, there are several different cold end configurations. The variation in thermo-physics properties of helium at low temperature as a function of both temperature and pressure has an influence on the performance of the heat exchangers employed at the cold end [3].

Early helium refrigerator and liquefier employed simple Joule-Thomson (JT) expansion at the cold end. Collins replaced JT by a Wet expander in liquefier, which noticeably improve the performance of the cycle [4]. Ergene and Trepp improve the efficiency the liquefier by double JT [5]. Quack got the patent of EXP+JT in cold end [6]. Ziegler and Quack studied the performance of the cold end using single JT, double JT, single EXP, and double EXP configurations for helium refrigeration cycle [7].



Thomas investigated five cold end configurations in helium liquefiers from exergy efficiency, reliability of operation and complexity of equipment design aspects [2].

However, thermodynamic performance of various cold ends for mixed mode cryogenic helium plant has not been evaluated. In this study, the operating efficiencies of different cold end configurations under various operating conditions are compared. The aim of this work is to provide a theoretical basis for choosing cold end configuration for mixed mode cryogenic helium system.

## 2. Thermodynamic model of different cold ends

Schematic diagrams for six cold end configurations are presented in figure 1. The 1J-T configuration (figure 1. a) adopts single JT and heat exchanger. The cold high pressure helium from the precooling section further is cooled in heat exchanger, then enter JT valve throttling to low pressure. Part of the helium liquefies and goes into the phase separator. The 1EXP one (figure 1. b) replaces the JT expansion in the first configuration with one wet expansion. The 2JT one (figure 1. c) employs two JT valves and two heat exchangers. The 2EXP (figure 1. d) has two expanders and two heat exchangers. The last two are 1JT+1EXP (figure 1. e), 1EXP+1JT (figure 1. f) respectively.

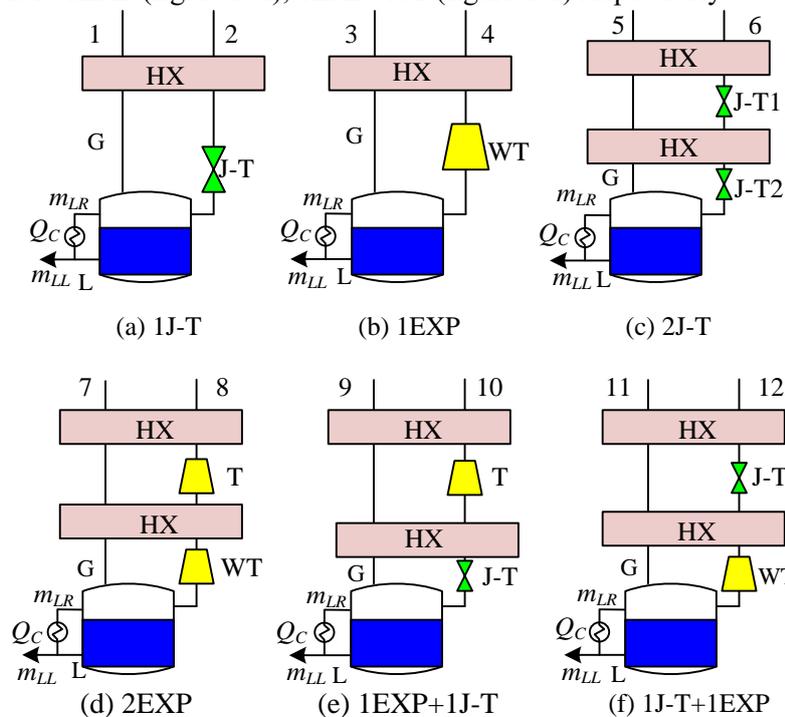


Figure 1. Six different arrangements of the cold end section

For a stream, specific exergy is defined as:

$$ex = (h - h_0) - T(s - s_0) \quad (1)$$

where  $ex$  is the maximum work per unit mass that can be extracted out of the system while taking it to the reference state ( $T_0, P_0$ ). Usually, atmospheric condition is taken as the reference state ( $T_0 = 310$  K,  $P_0 = 1.01$  bar).  $h$  is specific enthalpy,  $s$  is specific entropy of the fluid. Subscript '0' refers to the reference state.  $h_0$  is specific enthalpy,  $s_0$  is specific entropy of the reference state [8].

Exergy transfer associated with mass flow rate ( $\dot{m}$ ) is given as:

$$Ex_{flow} = \dot{m} ex \quad (2)$$

For a cryogenic helium plant operated on liquefier-refrigerator mixed mode, if X% of the liquid is drawn out from the system, and the remaining (100-X)% liquid is vaporized while absorbing the heat

load and returns to the system, then the plant is said to operate at  $X/(100-X)$  mixed mode. By this definition, a liquefier is in 100/0 mode, while a refrigerator is in 0/100 mode [3].

For steady state, exergy balance across the control volume as presented in figure 1.a gives

$$\dot{m}_2 ex_2 + \dot{m}_{LR} ex_G = \dot{m}_{LL} ex_L + \dot{m}_{LR} ex_L + \dot{m}_1 ex_1 + Ex_{loss\_1JT} \quad (3)$$

where  $\dot{m}_{LL}$  is the liquid helium extracted,  $\dot{m}_{LR}$  is the liquid helium used for refrigeration. Some part of exergy supplied to the control volume is lost due to irreversibility associated with the processes.  $Ex_{loss\_1JT}$  denotes total exergy loss in the cold end section with single JT valve.

Rearranging Eq. (3):

$$\dot{m}_2 ex_2 - \dot{m}_1 ex_1 = \dot{m}_{LL} ex_L + \dot{m}_{LR} ex_L - \dot{m}_{LR} ex_G + Ex_{loss\_1JT} \quad (4)$$

Terms on left hand side of Eq.(4) represent the exergy input to the cold end section with liquid nitrogen. The outlet exergy is denoted by the first three terms on right hand side of Eq.(4).

Exergy efficiency for the cold end with single JT valve is:

$$\eta_{ex\_1JT} = \frac{\dot{m}_{LL} ex_L + \dot{m}_{LR} ex_L - \dot{m}_{LR} ex_G}{\dot{m}_2 ex_2 - \dot{m}_1 ex_1} \quad (5)$$

Similarly, exergy efficiency for other cold end configurations are as followed.

$$\eta_{ex\_i} = \frac{\dot{m}_{LL} ex_L + \dot{m}_{LR} ex_L - \dot{m}_{LR} ex_G}{\dot{m}_{2i} ex_{2i} - \dot{m}_{2i-1} ex_{2i-1}}, \quad i=2,3\dots6 \quad (6)$$

$\eta_{ex\_2}$ ,  $\eta_{ex\_3}$ ,  $\dots$ ,  $\eta_{ex\_6}$ , respectively denotes exergy efficiency in the cold end section with 1EXP, 2JT, 2EXP, 1JT+1EXP, 1EXP+1JT.

The thermodynamic study has been performed on the basis of the following assumptions: (1) The system is in steady state; (2) The isentropic efficiency of turbine is kept constant at 70% and efficiency of heat exchanger is constant at 90%; (3) Pressure loss in heat exchanger and pipes is negligible; (4) Heat leak from the surroundings to heat exchangers is negligible; (5) The out pressure of the first JT and turbine is the same, 4bara; (6) The pressure of helium separator is 1.3bara. Thermo-physical properties of helium are obtained using HEPAK.

### 3. Results and discussions

When the inlet temperature and pressure of hot stream of the first heat exchanger in each cold end is 12 K and 20 bara, the relationship between exergy efficiency and mode of operation is presented in figure 2. In mixed liquefaction-refrigeration mode, cold ends with expander such as 2EXP, 1EXP+1JT, 1EXP and 1JT+1EXP have much higher exergy efficiency than single JT or 2JT. The 2EXP configuration has the highest exergy efficiency among 6 cold end configurations. However, the second expander has to use a wet expander to deal with two-phase flow at the discharge, which is similar with 1EXP and 1JT+1EXP. Since a large amount of exergy is destroyed in JT valve, the lowest exergy efficiency is the cold end with 1JT. Once adding one JT and one heat exchanger to the 1JT, the exergy efficiency is improved. Due to difficulty in design and operation, a wet expander is usually not adopted in helium cryoplants. Excluding wet turbines, the exergy efficiency of the cold end with 1EXP+1JT is higher than with 2JT and 1JT.

When helium cryoplant transfers from pure refrigerator to pure liquefier, the exergy efficiency has a large increase before operated at 25/75 mixed mode, then a slow growth. Thus, employing 1EXP+1JT is a good choice because of simple design, relatively high exergy efficiency, low cost and high reliability. When the inlet pressure of hot stream helium in the first heat exchanger is 13bara, the relationship depicted in figure 3 is similar.

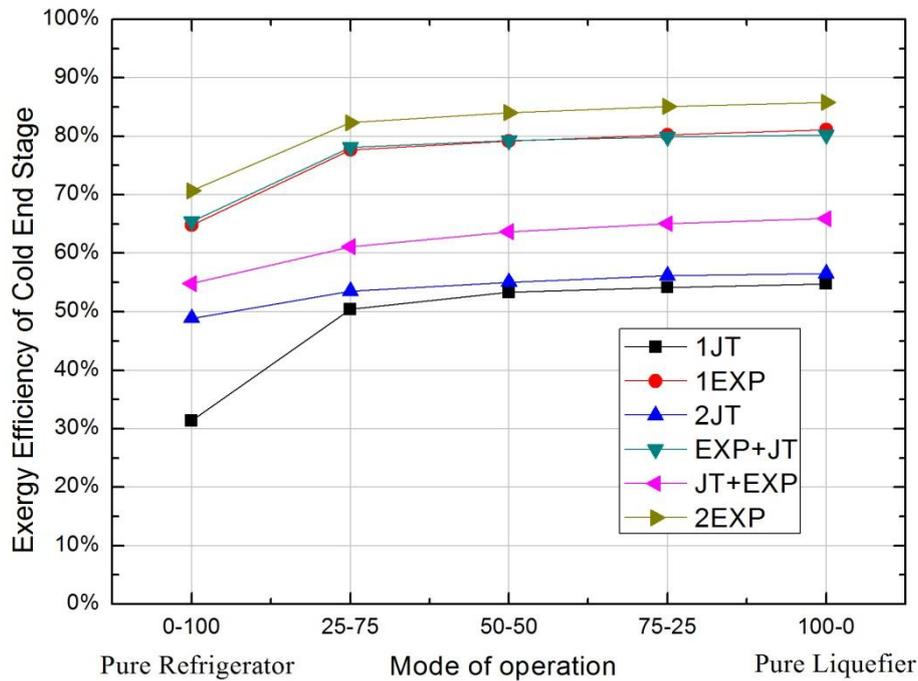


Figure 2. Exergy efficiency of cold end with helium with hot helium at 20 bara

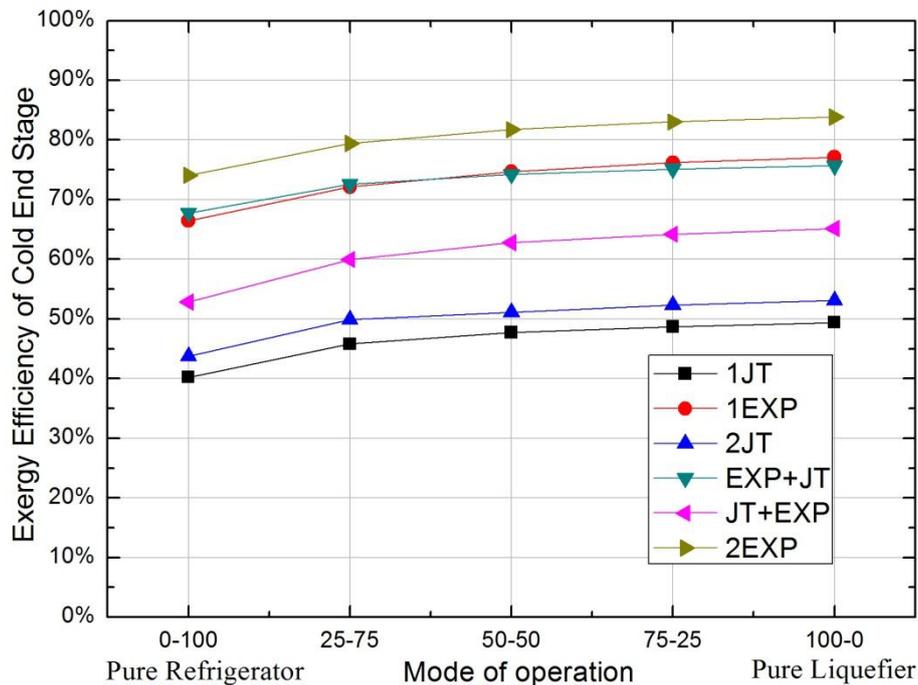


Figure 3. Exergy efficiency of cold end with helium with hot helium at 13 bara

Exergy efficiency of cold end with 1 EXP+1JT at different pressure is presented in figure 4. When helium cryoplant operates in mixed mode and pure liquefier mode, exergy efficiency increases with pressure. To obtain high efficiency in liquefier mode and mixed mode, the discharge pressure of compressors usually choose 20 bara. However in pure refrigerator mode, the optimum pressure is 14 bara due to sharp variety of helium properties near supercritical zone. For example, when the pressure

is 20 bara, the inlet temperature of the turbine with a expansion ratio of 5 is 5.5 K while the outlet temperature is only 5.143 K. The temperature difference is only 0.357 K.

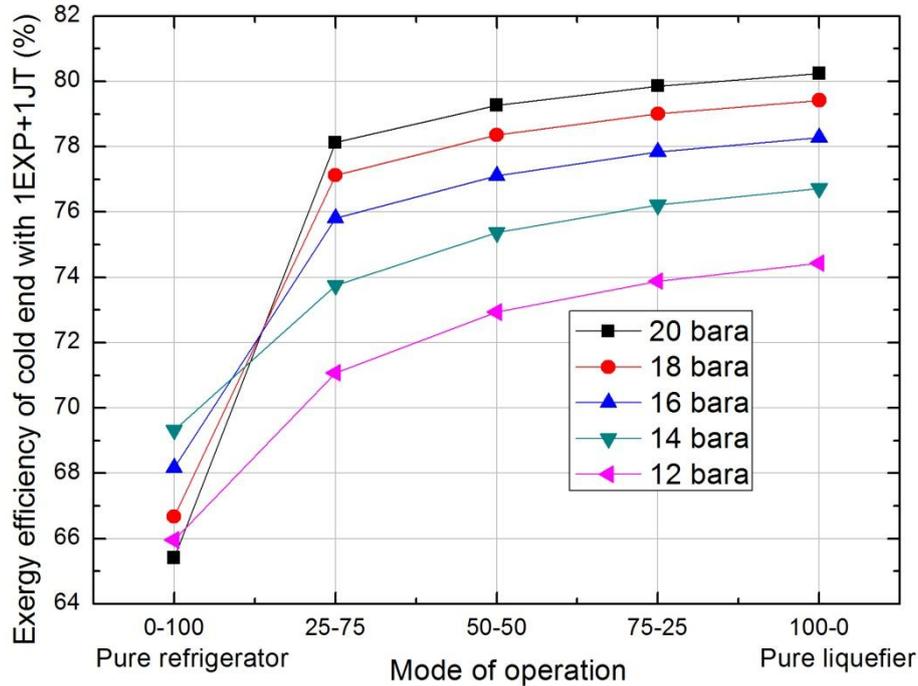


Figure 4. Exergy efficiency of cold end with 1 EXP+1JT at different pressure

Though cold end with 2JT has lower efficiency than 1EXP+1JT, it is also employed in some helium cryoplant. Exergy efficiency of cold end with 1 JT+1JT at different pressure is showed in figure 5. Higher pressure leads to higher exergy efficiency.

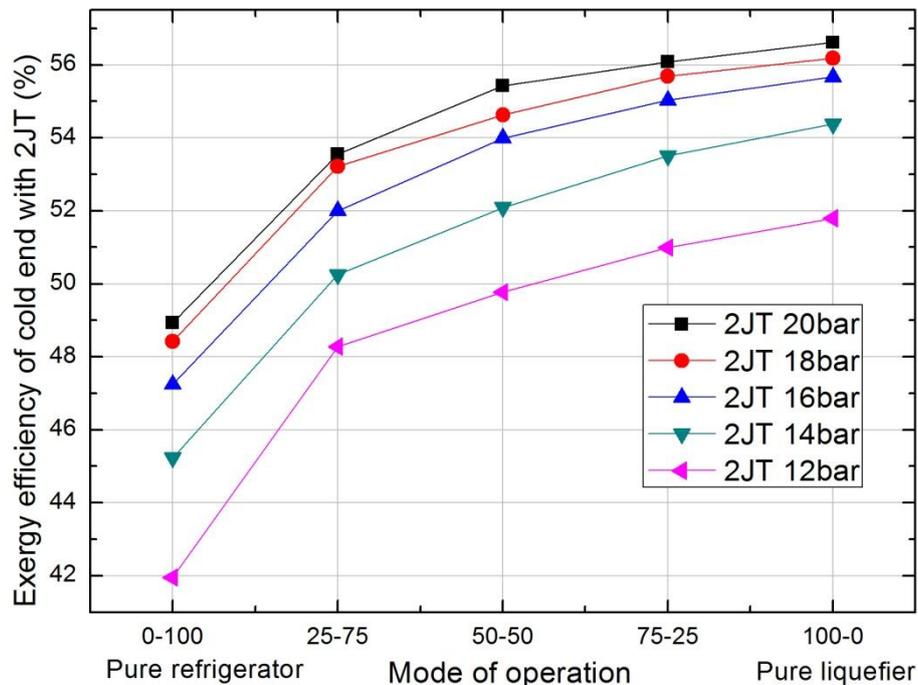


Figure 5. Exergy efficiency of cold end with 2 JT at different pressure

#### 4. Conclusions

Though the cold ends have high exergy efficiency when in mixed liquefier-refrigerator, wet expanders are usually not adopted due to difficulty in design and operation, poor stability and reliability, mode. Employing 1EXP+1JT is a good choice because of relatively high exergy efficiency, low cost and high reliability. For cold end with 1EXP+1JT or 1JT+1JT, higher discharge pressure of compressors are usually chosen to obtain high efficiency in liquefier mode and mixed mode.

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