Dynamic Simulation of 10 kW Brayton Cryocooler for HTS Cable

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Abstract. Dynamic simulation of a Brayton cryocooler is presented as a partial effort of a Korean governmental project to develop 1~3 km HTS cable systems at transmission level in Jeju Island. Thermodynamic design of a 10 kW Brayton cryocooler was completed, and a prototype construction is underway with a basis of steady-state operation. This study is the next step to investigate the transient behavior of cryocooler for two purposes. The first is to simulate and design the cool-down process after scheduled or unscheduled stoppage. The second is to predict the transient behavior following the variation of external conditions such as cryogenic load or outdoor temperature. The detailed specifications of key components, including plate-fin heat exchangers and cryogenic turbo-expanders are incorporated into a commercial software (Aspen HYSYS) to estimate the temporal change of temperature and flow rate over the cryocooler. An initial cool-down scenario and some examples on daily variation of cryocooler are presented and discussed, aiming at stable control schemes of a long cable system.

Keywords: Dynamic Simulation, Brayton Cryocooler, HTS Cable.
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INTRODUCTION

The high-temperature superconductor (HTS) cable project in Korea is underway towards a goal to install and demonstrate 1~3 km cables at transmission class in Jeju Island by 2016. For the purpose of closed-cycle refrigeration, a Brayton cryocooler with capacity of 10 kW at liquid-nitrogen temperatures is under development as well. Thermodynamic design of the Brayton-cycle refrigeration was completed [1], and the key components such as heat exchangers [2], cryogenic turbo-expander, and compressors were also selected with a basis of steady-state operation. As a next step, this work intends to investigate the dynamic behavior of a Brayton cryocooler with commercial software (Aspen HYSYS), taking into account the dimensions and specifications of the components employed for prototype construction. The Aspen HYSYS is a general purpose process simulator [3] widely used in plant and gas industries, which has been lately applied to cryogenic refrigeration systems [4,5] in order to predict the dynamic behavior for control strategies.

This dynamic simulation has two specific targets. The first is the cool-down process to predict how promptly the system will be ready for the power-on and how long it will take for the system to reach a normal operation after scheduled or unscheduled stoppage. In practice, rapid cool-down and recovery could be a crucial factor in power and utility services. The second is the transient behavior of the cryocooler, followed by external disturbances, such as cooling load and outdoor climate condition. The efforts are directed towards a reliable long-term operation of the cryogenic refrigeration system.

MODELING

Figure 1 is the simplified flow diagram of a 10 kW Brayton cryocooler [1] for sub-cooling liquid nitrogen (from 78 K to 67 K) in an HTS power cable system. The cycles of refrigerant (helium: He) and coolant (liquid nitrogen: LN) are also shown on the temperature-entropy diagram and phase diagram, respectively. The compressor (Comp) and after-cooler (AC) are operational at ambient temperature, and all other components are placed in a cryostat. HX1 is a (He-He) recuperator which has the major cold mass of the cryocooler, and HX2 is a (He-LN) sub-cooling heat exchanger. The turbo-expander (Exp) produces the coldest helium and plays a leading role in the transient behavior. Helium was selected as the refrigerant, because it is superior to neon in thermodynamic efficiency [1]. Liquid nitrogen is circulated by a cryogenic pump for delivering the thermal load in the HTS cable to the cryocooler.

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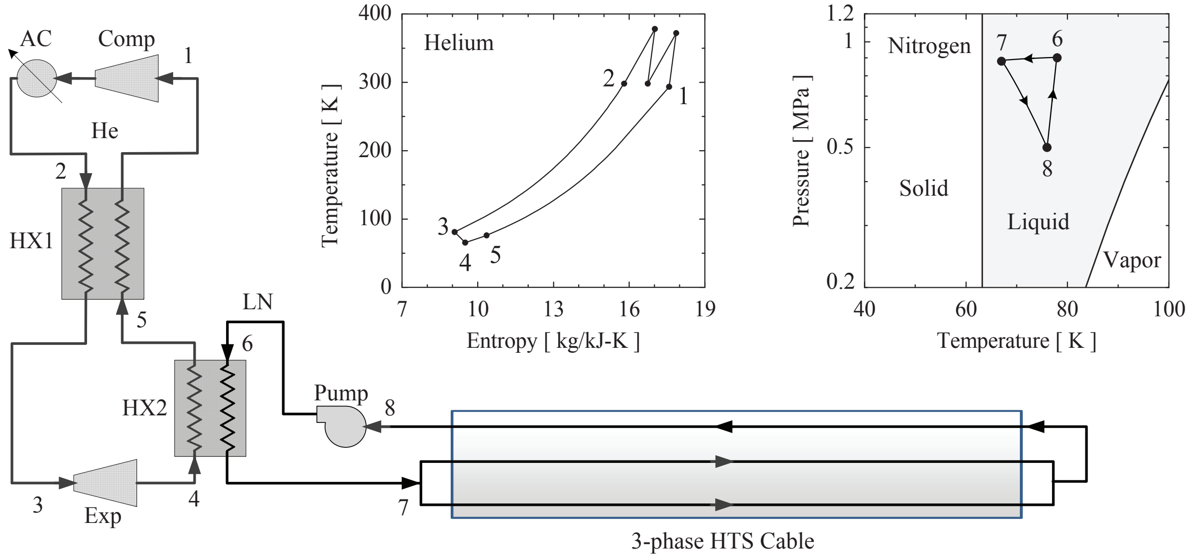


FIGURE 1. Simplified flow diagram of a Brayton cryocooler for sub-cooling liquid nitrogen in an HTS power cable system and cycles on temperature-entropy diagram of helium and on phase diagram of liquid nitrogen in steady state

The cycles of He and LN are designed with a basis of steady-state operation of cryocooler and cable system. For 10 kW of refrigeration, the flow rate of helium is 0.183 kg/s. The pressure drop of He in the two HX's is estimated in accordance with the designed specifications of heat exchangers. For 3-phase cable, it is assumed that LN goes in two branched streams and returns in one mixed stream. The total flow rate of liquid nitrogen is 0.451 kg/s.

Plate-fin heat exchangers are selected for both HX1 and HX2, as schematically shown in Fig. 2, and the detailed dimension is listed in Table 1. The convection heat transfer coefficient is estimated with the engineering correlations in terms of Reynolds number based on the hydraulic diameter and Prandtl number, as presented by Chang et al. [6]. The corrugated fins are considered a simple plate fin, having half height and adiabatic tips because of its symmetry. Material of all parts in the HX's is aluminum.

TABLE 1. Dimension of aluminum plate-fin heat exchangers for recuperation (HX1) and sub-cooling (HX2)

Corrugated Fins	Parting Plates	Recuperator (HX1)	Sub-Cooler (HX2)
Thickness $\delta = 0.1$ mm	Thickness $t = 2.5$ mm	Width $W = 0.50$ m	Width $W = 0.50$ m
Height $h = 3$ mm		Height $H = 0.33$ m	Height $H = 0.33$ m
Pitch $p = 2.54$ mm		Length $L = 2.00$ m	Length $L = 0.20$ m

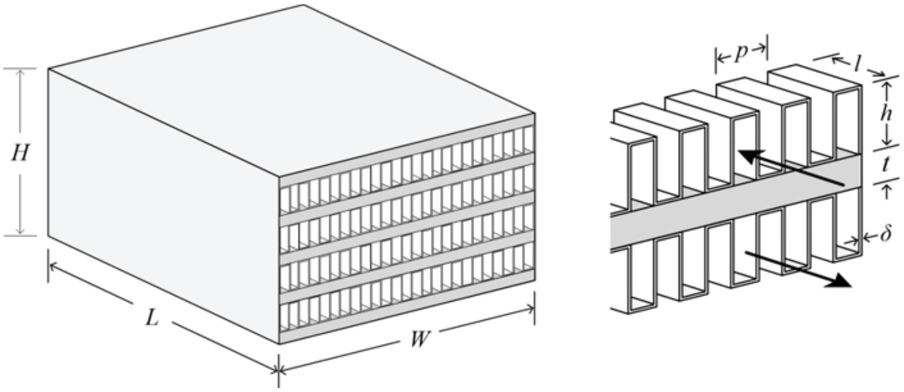


FIGURE 2. Schematic of counter-flow plate-fin heat exchanger and corrugated fins

To simulate the performance of the turbo-expander with Aspen HYSYS, two parameters should be incorporated: the volume flow rate at the inlet (Q_3) and the adiabatic efficiency (η_e). It is a good approximation in high-speed radial-flow turbines that the dimensionless flow rate ($\widehat{m}$) [7,8] is constant for a large pressure ratio. Since helium may well be considered an ideal gas in the operating condition,

$$Q_3 = \frac{\widehat{m} P_3}{\rho_3 \sqrt{\gamma R T_3}} \approx K_1 \sqrt{T_3} \tag{1}$$

where P, ρ, T are pressure, density, temperature at the inlet, respectively, and γ and R are specific heat ratio and gas constant of helium, respectively. The coefficient K_1 should be determined by hardware experiment, but is simply set to be a design value in this simulation.

In radial-flow turbines, the adiabatic efficiency can be expressed by a quadratic function of velocity ratio [7,8],

$$\eta_e = K_2 \left(\frac{U_3}{C_0} \right)^2 + K_3 \left(\frac{U_3}{C_0} \right) + K_4 \tag{2}$$

where U_3 is the rotor tip speed at the inlet, and C_0 is the spouting velocity, defined as the velocity whose kinetic energy is equal to the isentropic pressure drop.

$$C_0 = K_5 \sqrt{T_3 \left(1 - r_P^{(\gamma-1)/\gamma} \right)} \tag{3}$$

where r_P is the pressure ratio. The coefficients K's in Equations (2) and (3) are set again by the design specifications of prototype turbine such that the highest efficiency is 0.75 when the velocity ratio is 0.70 at steady-state [7,8].

The detailed thermal and hydrodynamic behavior of HTS cable is quite complicated and far beyond the scope of this work. In order to focus on the dynamic behavior of the cryocooler, the HTS cable is modeled simply as a distributed thermal mass that has a certain value of internal and external heat load per unit length. It is assumed that the heat capacity per unit length is 287 kJ/K-m including the conductor, former, and insulation, as estimated by the actual HTS cable in Icheon substation under long-run test [9]. The external load is equal to the heat leak from the ambient through conduction and radiation, which is assumed to be 1 W/m. The internal load is the heat by electrical current, such as ac loss and dissipation, which is assumed to be 2 W/m. As for thermal load at the terminals including the current leads, 1 kW is added so that the total load of 3 km cable system is thus 10 kW at steady state.

The compressors are selected as water-cooled reciprocating type for the first prototype. The pressure ratio is assumed to be constant at 2.5 over the entire operation [1]. The exit temperature of the after-cooler (T_2) is more or less dependent on outdoor conditions, such as temperature and humidity of ambient air. For simulation, it is assumed that T_2 is 298 K, and the effect of varying temperature is discussed later.

Thermodynamic properties of He and LN are calculated by the Peng-Robinson equation of state linked to Aspen HYSYS. Thermo-physical properties of materials and fluids are taken from the U.S. NIST and other standard data. In Aspen HYSYS, the transient terms are integrated by the implicit Euler method.

RESULTS AND DISCUSSION

Figure 3 shows the variation of the cycle on the temperature-entropy diagram of He, and Fig. 4 shows the variation of temperature and flow rate at the turbo-expander for the initial 30 min. At start-up, it is assumed that the entire cryocooler is at ambient temperature (298 K) and there is no LN flow in HX2 for this period. The helium temperature begins to drop at the exit of the turbo-expander, leading the overall cool-down. As temperature drops, the volume flow rate decreases according to Equation (1), but the mass flow rate increases. The cool-down is fast at the beginning, but as temperature decreases, the temperature drop across the expander becomes smaller, thus the cool-down becomes slower. The major cold mass is the two heat exchangers, since no circulation of liquid nitrogen is assumed for the initial period. The cool-down time to 77 K is estimated to be approximately 30 min.

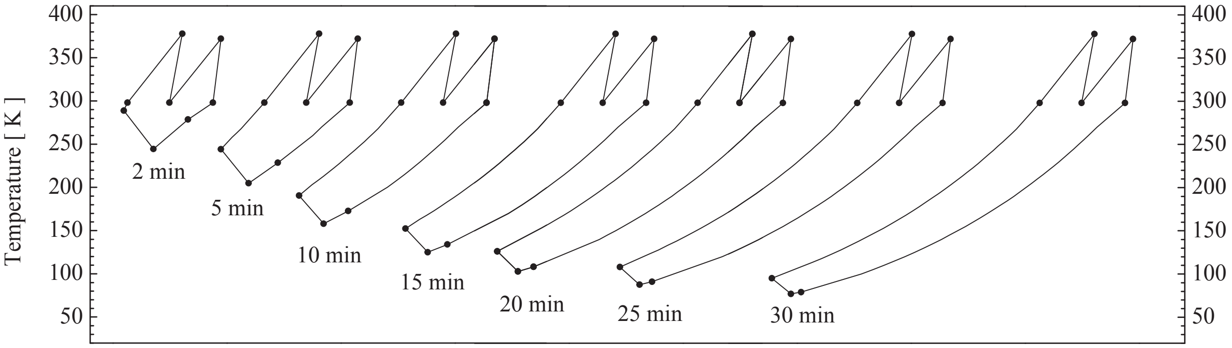


FIGURE 3. Simulated temperature-entropy diagram of helium for initial 30 minutes

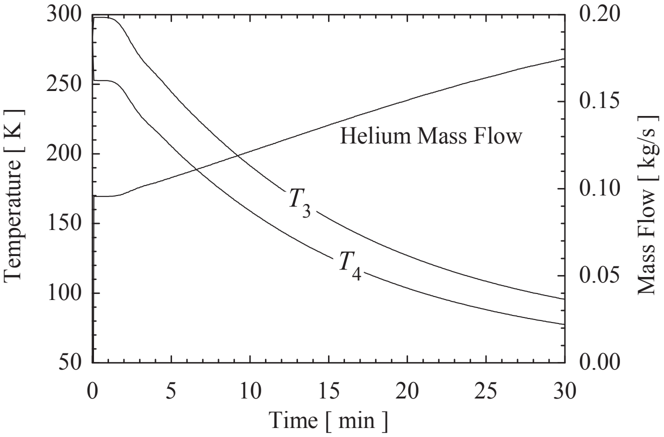


FIGURE 4. Simulated temperature and flow rate of helium at turbo-expander for initial 30 minutes

Figure 5 shows the simulated dynamic behavior of the cool-down process, assuming that LN begins to circulate when the He reaches 77 K, and that the current is on when the LN reaches 69 K. As LN begins to circulate, the incoming LN temperature (T_6) increases due to the external thermal load of the HTS cable, while the outgoing LN temperature (T_7) keeps decreasing. In this cool-down scenario, the LN reaches 69 K at the time of 2 hr 10 min, at which point the cable current is powered on. Since the internal load is added after this point, the temperature of LN and He gradually increases during the next 1~2 hr, and then decreases again. The period of this temperature oscillation is approximately 3 hr in the presented simulation model, but may be strongly dependent on the actual thermal load and detailed flow characteristics of LN. The overall time until the temperature fluctuation becomes less than 0.5 K is estimated to be 30 hr.

Another issue of dynamic simulation is the transient behavior in accordance with external disturbances, such as the variation in cooling load of the HTS cable or outdoor climate condition. Figure 5(a) shows an example to demonstrate the effect of the amount of cooling load. In practice, the internal cooling load may change to a certain degree because of the unsteady level of electrical current, and the external cooling load may also change due to the thermal radiation from variable ambient temperature. The top curve in Fig. 6(a) is a simple model of variable load between 11 kW (at peak) and 9.5 kW (at off-peak) over a day, and the bottom curves are the simulated temperature variation according to the variable load. The temperature fluctuation in this simulation is estimated to be about 2 K in both He and LN temperatures. It is noted that the temperature variation has a time lag of 5~6 hours. This delayed response will play a significant role in control strategy, especially for preventing the freeze-out of liquid nitrogen, as discussed below.

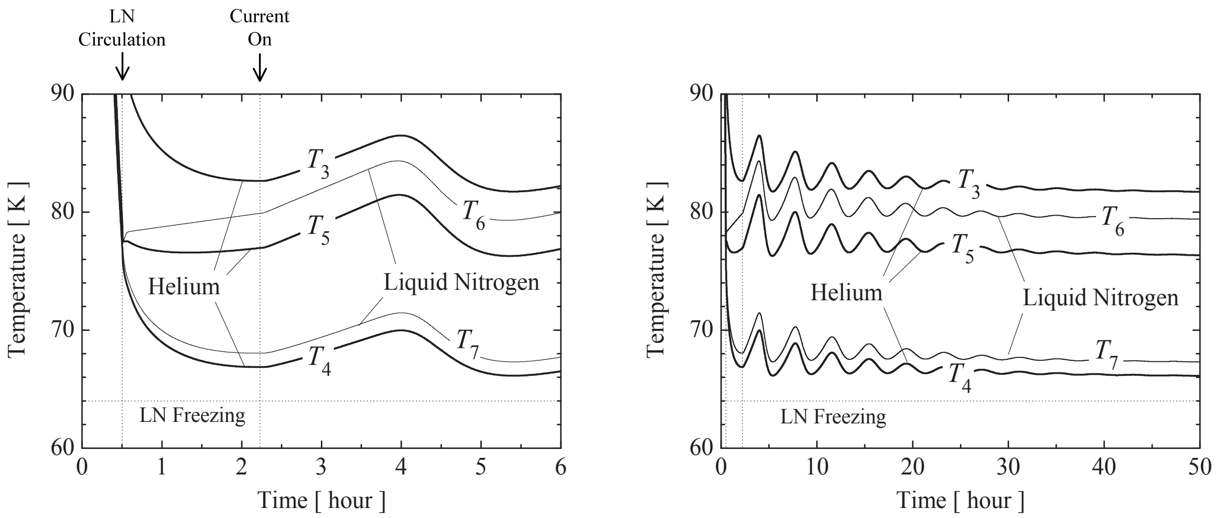
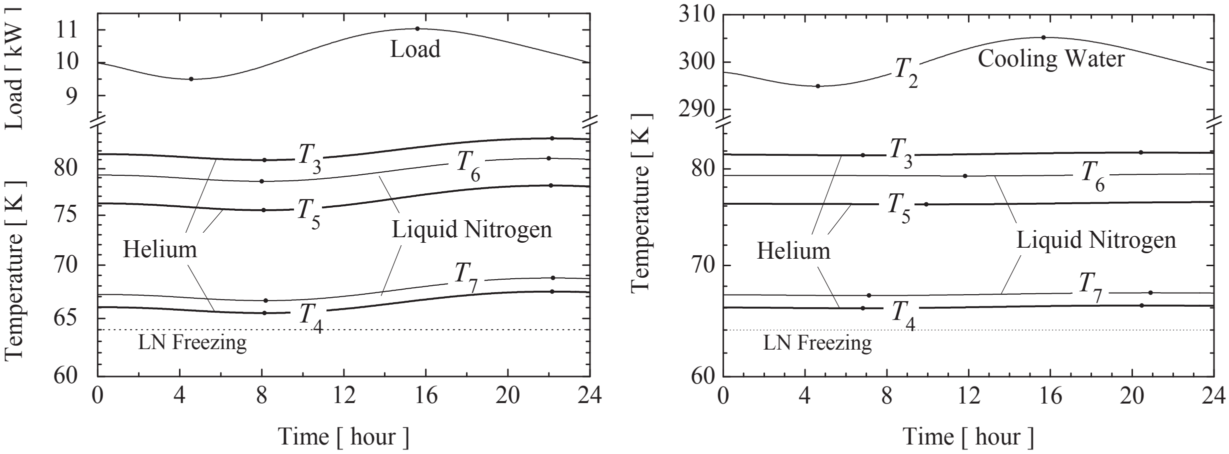


FIGURE 5. Simulated temperature variation over entire cool-down process



(a) Effect of variable cooling load

(b) Effect of variable cooling water temperature

FIGURE 6. Simulated temperature variation according to external disturbance

The ambient temperature of the cryocooler affects the refrigeration performance of the cryocooler more directly. Since the compressed He is water-cooled and the cooling water is cooled by the air-chiller, the after-cooler temperature (T_2) may change considerably, especially in the humid summer season. The top curve in Fig. 6(b) shows a simple model for daily variation of cooling water temperature between 305 K (at peak) and 295 K (at off-peak), and the bottom curves are simulated temperature variation of the process fluids. The temperature fluctuation of He and LN at the cold end of the cryocooler is estimated to be less than 1 K, and the response time is only 2~4 hours, which may be compared with the delayed response to the cryogenic load. It may be stated that the effect of outdoor climate on the cryocooler performance is not so significant.

As the cable length between cooling stations increases, the supply temperature of liquid nitrogen gets closer to its freezing temperature (63.3 K indicated by a dashed line in Fig. 5 and 6), and the possibility of freeze-out of LN emerges as a crucial design issue [10,11]. Yoshida et al. presented two design ideas to avoid the freeze-out of LN flow, including a tube-in-bath type HX and a two-stage type of plate-fin HX [10]. Chang et al. experimentally demonstrated that cross-flow heat exchangers are effective in avoiding the complete clog-up of all passages, mainly because the temperature distribution is two-dimensional [11]. In any case, a control strategy for the cryogenic system is indispensible for preventing the disastrous freeze-out, and this dynamic behavior should provide useful information for the design of the control system.

CONCLUSIONS

The transient behavior of a Brayton cryocooler is investigated for sub-cooling liquid nitrogen in a long HTS cable system. The detailed specifications of a 10 kW cooler under development in the Korean project are incorporated into the simulation software (Aspen HYSYS), including the plate-fin heat exchangers and radial-flow turbo-expander. It is predicted that the cool-down time to liquid-nitrogen temperature is less than 1 hr and that the HTS cable can be ready for power-on in about 2 hr after the initial cool-down. A slow temperature fluctuation of refrigerant (helium) may occur at the beginning period of circulating the coolant (liquid nitrogen). The variation of cooling load in HTS cable does affect the operating condition of the cryocooler to a degree, but a time lag of 5~6 hr is predicted because of the long-length and large capacity of the distributed cold mass. The outdoor condition may affect the cryocooler more directly, but its impact on thermal performance is less significant.

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