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Progress in Development of a 10 kW Brayton Cryocooler for HTS Cable in Korea

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Abstract

Recent progress in the development of a 10 kW Brayton cryocooler is presented for HTS cable systems under installation in Jeju Island, Korea. The role of this cryocooler is to continuously cool a liquid-nitrogen flow from 78 K to 67 K, and the liquid is pumped to three-phase 154 kV cable over a length of 1 km. The refrigerant of cryocooler is helium, whose operating pressure and flow rate was determined earlier from a thermodynamic study on reversed-Brayton cycle. As main components, heat exchangers and turbo-expanders are designed and fabricated by custom orders. The heat exchangers are made of aluminum-brazed plate-fins, and the coldest part is arranged as two-pass cross-flow in accordance with our experimental study for preventing the freeze-out of liquid nitrogen. Two identical turbo-expanders are employed in parallel at the cold end, where the maximum rotating speed with gas bearings reaches 180,000 rpm and the output power is dissipated with eddy current brakes. The assembly is completed and the refrigeration capacity will be shortly measured with a dummy thermal load on the liquid-nitrogen stream. Details of thermal performance and short-term plans are reported towards and immediate application to the HTS Cable systems.

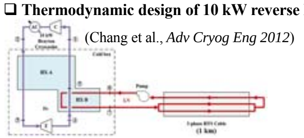
Introduction

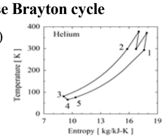
❑ Korean HTS Power Cable Project (2011 ~ 2016)

- Transmission Class at 154 kV
- Installation and demonstration at **Jeju Island**
- 3-phase and 1 km length
- Cooling by 10 kW Brayton cryoooler

❑ Thermodynamic design of 10 kW reverse Brayton cycle

(Chang et al., *Adv Cryog Eng* 2012)

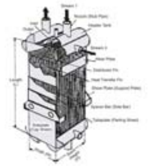




Design and Fabrication of Heat Exchangers

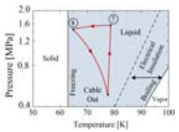
❑ Aluminum plate-fin heat exchanger

- Construction : Core, Header, Nozzle, Side bar Cap sheet, Parting sheet
- For flow direction : Parallel, Counter, Cross, etc.
- Variety of pins : Plain, Wavy, Serrated, etc.
- Mostly use heat exchangers in cryogenics
- Good performance in limited heat transfer area

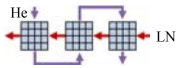


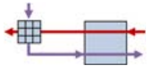
❑ Anti-freezing schemes of liquid nitrogen

- **Possibility of freeze-out of LN in long-length cable**
  - Long-length (1 km ↑) HTS cable
  - **Freeze-out of LN @ 63.3 K**
    - ✓ May block the LN circulation
    - → **Preparation for unusual decrease of thermal load**



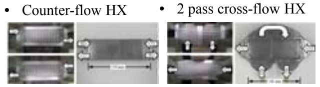
- (Chang et al., *Cryogenics* 2013)
  - Multi-pass cross-flow
  - cross-flow + counter-flow HX

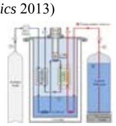




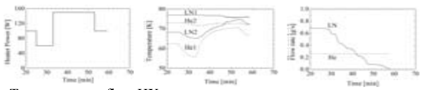
- ✓ 2-D temperature distribution
- ✓ Multi-pass : Increase ε
- ✓ Pressure drop problem
- ✓ Cold part → Cross flow
- ✓ Warm Part → Counter flow
- ✓ High ε and Anti-freezing

- **Experimental verification** (*Chang et al., Cryogenics* 2013)
  - Counter-flow HX
  - 2 pass cross-flow HX

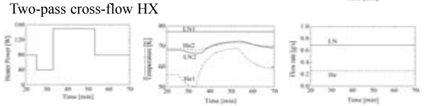




- Counter-flow HX



- Two-pass cross-flow HX



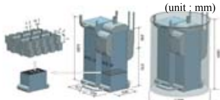
→ **Cross-flow HX's more robust against the freeze out**

❑ Compactness

- **Heat exchange design** (Chang et al., *Proceeding of ICEC25-ICMC 2014*)

HX-A : 141 kW (He-He)

HX-B : 66 kW + 10 kW (He-He)+(He-LN)



- **Prevention excessive size of HX-A**

→ **Two-pass cross flow heat exchanger design**

❑ Final product (DongHwa Entec, Korea)

- **Actual heat exchanger and size**

- Serrated Fin
- Stacked HX-A
- Stacked HX-B

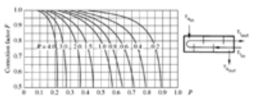
	HX-A	HX-B	
Material	Aluminum 3003		
Number of layers	39 (Warm) + 65 (Cold)	35 (Warm) + 45 (Cold)	
Height	425 mm	309 mm	309 mm
Length	1680 mm	970 mm	446 mm
Width	500 mm	500 mm	500 mm

❑ Two-pass cross-flow heat exchanger model

- **Using LMTD method and correction factor (F)**
  - For inlet and exit temperature

$$\Delta T_{LM,A}=\frac{(T_2-T_1)-(T_3-T_6)}{\ln\left(\frac{T_2-T_1}{T_3-T_6}\right)},\quad \Delta T_{LM,B}=\frac{(T_6-T_7)-(T_5-T_8)}{\ln\left(\frac{T_6-T_7}{T_5-T_8}\right)}$$

  - Correction factor (F)



$$P=\frac{T_6-T_5}{T_7-T_5}$$

$$R=\frac{(\dot{m}C_p)_{LN}}{(\dot{m}C_p)_{He}}$$

- **Using ε-NTU method for effectiveness**

$$\mathrm{NTU}=\frac{U_oA_o}{C_{\min}},\quad C_R=\frac{C_{\min}}{C_{\max}},\quad \varepsilon=1-\exp\left[\left(\frac{\mathrm{NTU}^{0.22}}{C_R}\right)\left\{\exp\left(-C_R\mathrm{NTU}^{0.78}\right)-1\right\}\right]$$

Design and Fabrication of Turbo Expanders

❑ Radial flow turbo-expander

- Small wheel, fast rotor velocity are important
- Lubrication is depended on bearing type
  - → Hydrostatic, Magnetic, Gas bearing, Etc.
- Output power dissipation
  - → Alternator, Compressor, Brake, Etc.
- Objectives : for 0.21 kg/s Helium, for 10 kW

❑ Final product (ATEKO, Czech)

- **Two identical turbo-expander**
  - Wheel diameter : 30.5 mm / Cooling power : 10 kW
  - Rotor velocity : 180,000 RPM / Pressure ratio : 2.07
- **Bearing type : gas bearing**
- **Output power dissipation : Eddy current brake**

❑ Test and Evaluation

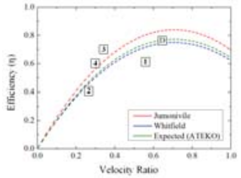
- **Lab test and similarity evaluation**
  - Different test condition from actual operating

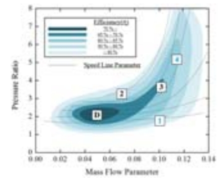
	Actual	Lab test
Working fluid	Helium	Air
Rotor velocity	180,000 RPM	100,000 RPM
Temperature	Cryogenic	Ambient
Pressure	High	Low

- Lab test data

		Date	Inlet		Exit		Speed [rpm]	Fluid	Efficiency
			P [bar]	T [K]	P [bar]	T [K]			
Design		2013	11.9	80.9	5.76	65.4	180,000	He	0.75
Test	1	2014. 01. 17	1.70	321	1.10	298	97,000	Air	0.61
	2		3.50	321	1.20	285	70,000	Air	0.43
	3	2014. 02. 12	3.50	354	1.03	287	82,350	Air	0.65
	4	2014. 09. 23	5.40	376	1.02	290	100,000	Air	0.61

- **Non-dimensional performance curve**
  - U/C curve





$$\eta=f\left(\frac{U}{C}\right),\quad U=\frac{D}{2}\left(\frac{2\pi N}{60}\right),\quad h_i=h_{e,s}+\frac{1}{2}C_0^2$$

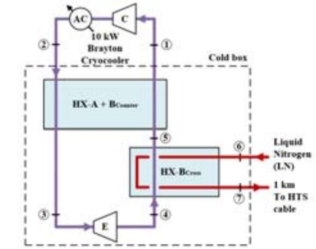
$$\eta=f\left(\frac{\dot{m}\sqrt{C_pT_i}}{D^2P_i},\frac{ND}{\sqrt{\gamma RT}},\frac{P_i}{P_e}\right)$$

- **Turbo-expander performance model**

Expected Performance

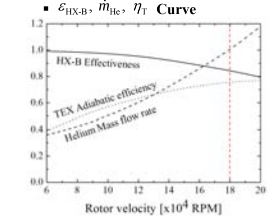
❑ Cooling capacity of refrigerator

- **Simulated cycle on T-s and P-T diagram**

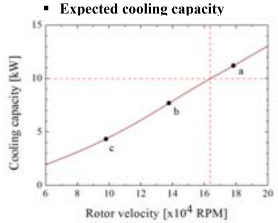


- The mass flow rate is estimated with a relative value with design condition (0.209 kg/s)
- If the speed is 180,000 RPM, the expected cooling capacity could be 11.2 kW.
- Should be >164,000 RPM in order to achieve 10 kW

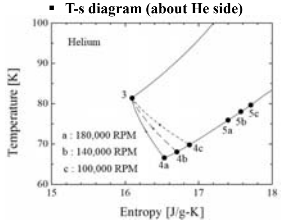
- $\varepsilon_{\text{HX-B}}$, $\dot{m}_{\text{He}}$, η_{T} Curve



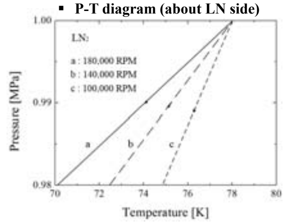
- Expected cooling capacity



- T-s diagram (about He side)



- P-T diagram (about LN side)



Summary and Future Plans

❑ Korean ongoing HTS power cable project is underway to develop a 10 kW Brayton cryocooler for 1 km HTS transmission cable.

❑ Assembly is completed, but additional jobs are needed, including the oil removal system(ORS), the safety valve, and a control system.

❑ The cooling performance will be tested shortly, and the cryocooler will be moved to Jeju Island for installation and demonstration by 2016.

This research is supported by a grant of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) for Power Generation & Electricity Delivery Program (No. 2014101050231B), funded by the Ministry of Trade, Industry and Energy of Korean Government.