Development of high efficiency Stirling cryocoolers for high temperature superconducting motor

CEC-ICMC2015
C1OrA-03
June 29, 2015

Kyosuke Nakano, Kenta Yumoto and Yoshikatsu Hiratsuka

Technology Research Center
Sumitomo Heavy Industries, Ltd.

Outline

- Introduction
- General design and measurement system
- Energy flow analysis
- Improvement results
- Summary

Outline

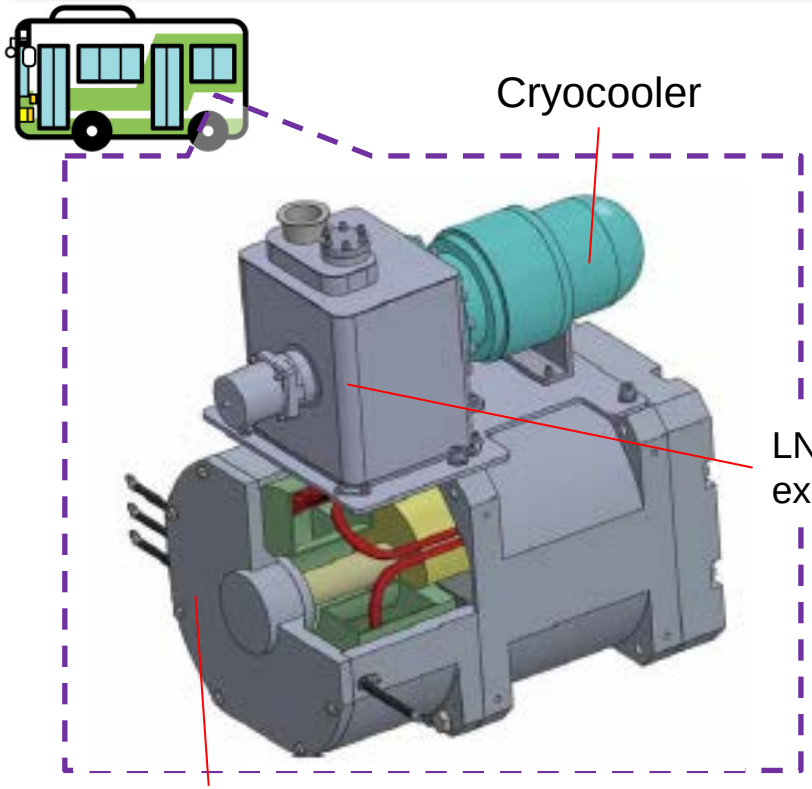
SHI Cryogenics Group

- Introduction
- General design and measurement system
- Energy flow analysis
- Improvement results
- Summary

HTS motor system

SHI Cryogenics Group

- Cryocoolers for electric vehicle driven by HTS motor system have been developed in a joint research with Sumitomo Electric Industries, Ltd.



The model of Superconducting motor unit

http://www.sei.co.jp/RandD/theme/automotive/

- In comparison with the conventional electric motor, the system can be expected about 20 percent fuel economy improvement.

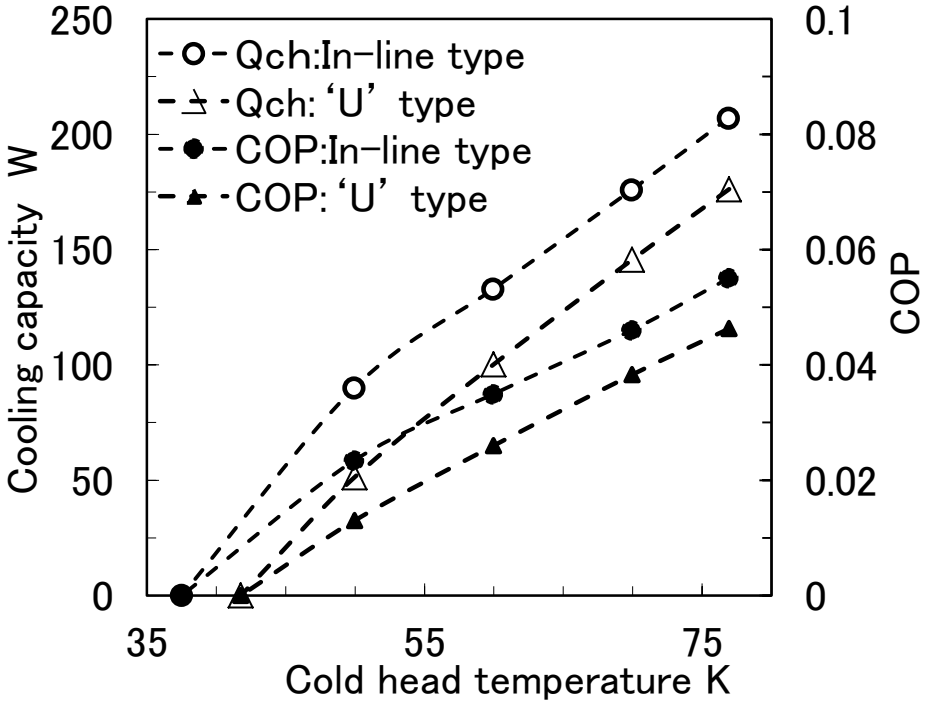
- High efficiency, reliability, compact cryocooler is needed.

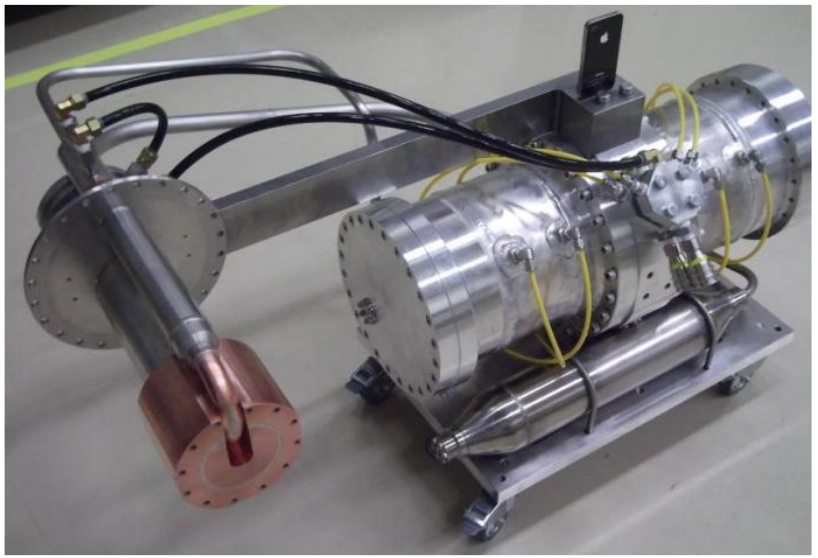
- The final target of the cryocooler performance is 150 W at 70 K and COP > 0.1

Stirling-type pulse tube cryocooler

SHI Cryogenics Group

- SHI developed high-power stirling-type pulse tube cryocoolers (STPCs) for cooling HTS vehicles from 2010 to 2012.



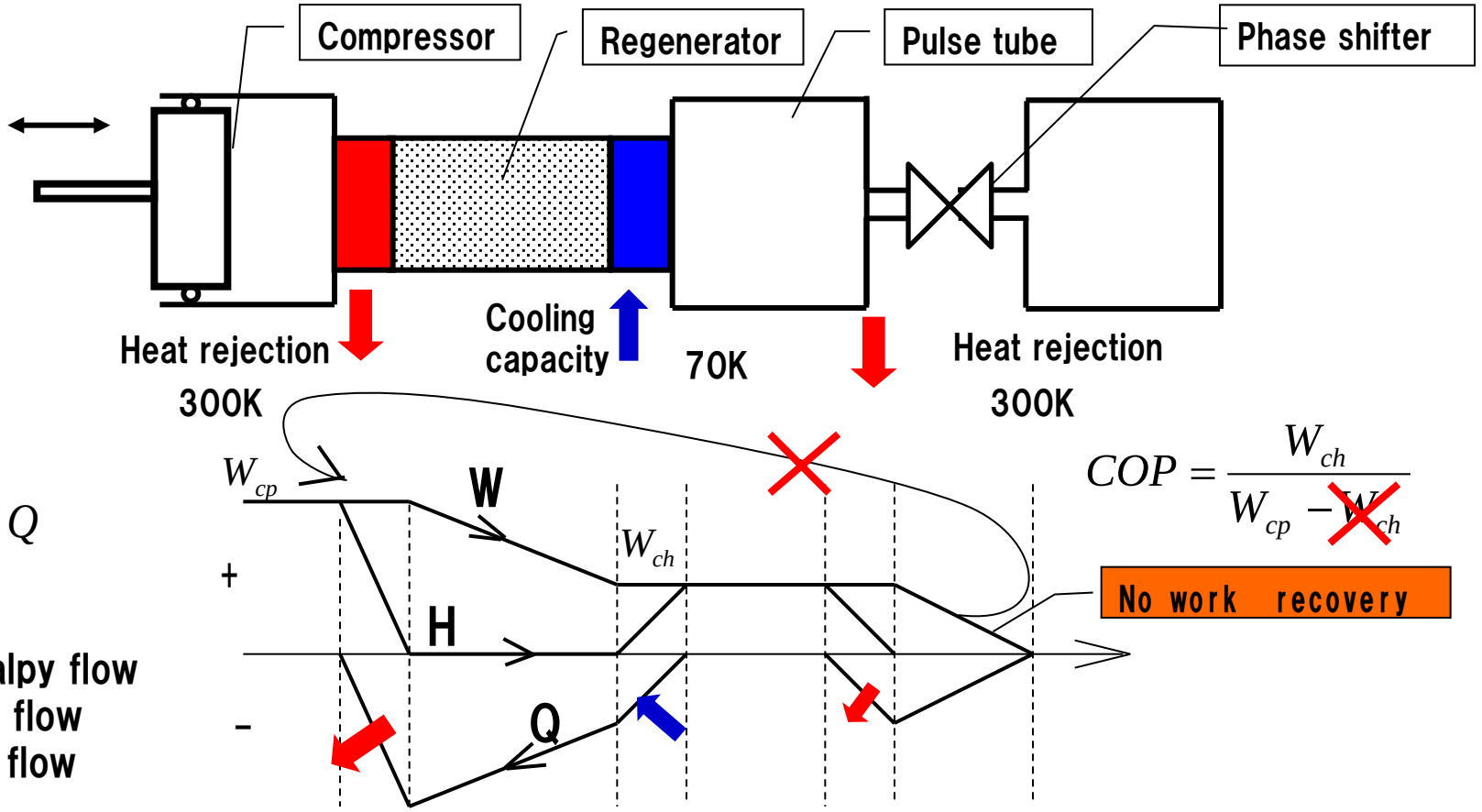


'U' type split STPC

- The cooling capacity of the in-line STPC is 175 W at 70 K (COP 0.046) and the 'U' type STPC is 145 W at 70 K (COP 0.038) .
- The efficiency of the cryocooler is required to be COP > 0.1.

Energy-flow of pulse tube cryocooler

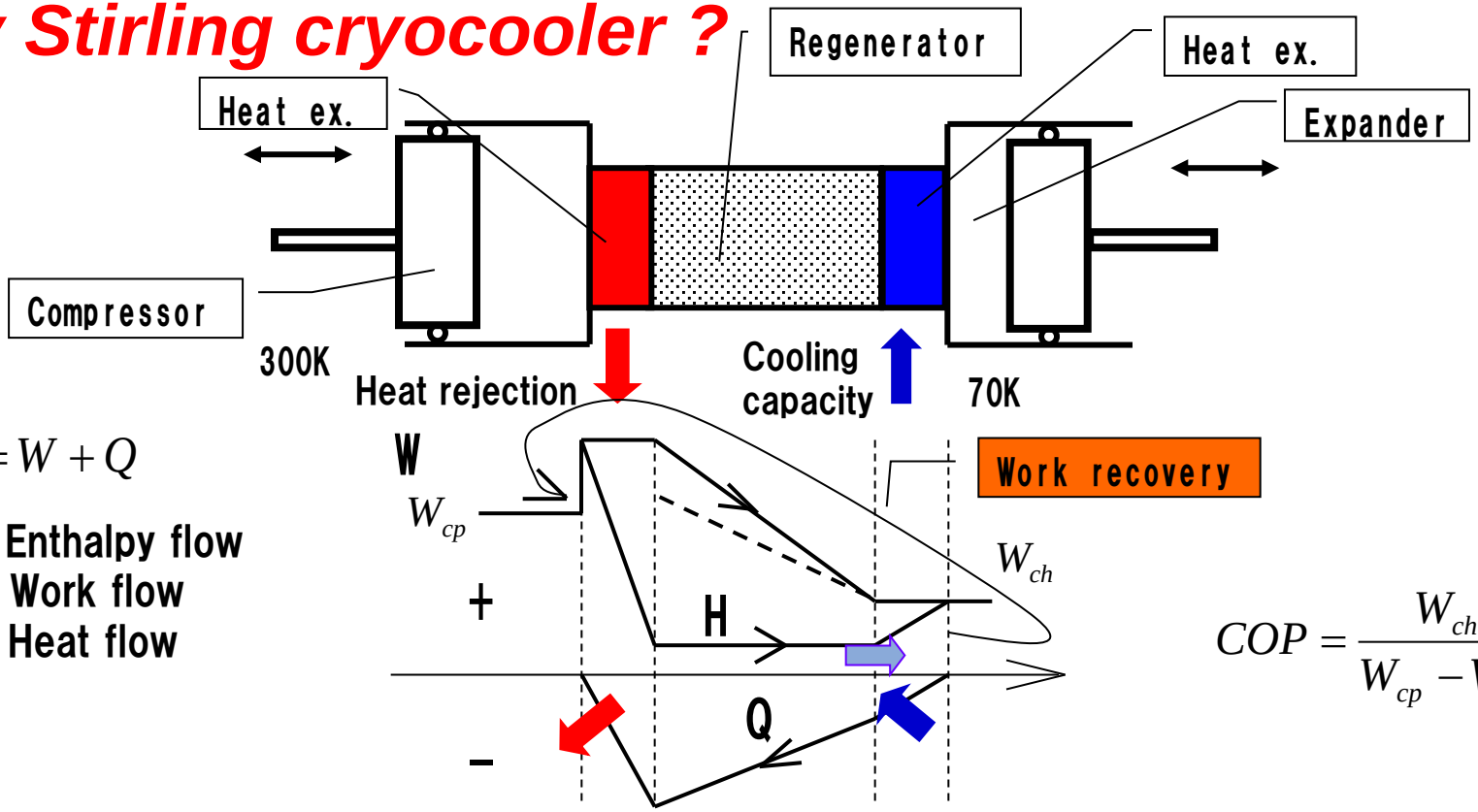
SHI Cryogenics Group



- It is difficult to further improve the efficiency of the pulse tube cryocooler because the work-flow generated from the hot-end of the pulse tube cannot be recovered.

Energy-flow of Stirling cryocooler

Why Stirling cryocooler ?



$$H = W + Q$$

H : Enthalpy flow
W : Work flow
Q : Heat flow

$$COP = \frac{W_{ch}}{W_{cp} - W_{ch}}$$

- Stirling cryocooler can meet the demand for high efficiency because the work-flow can be recovered.
- In order to improve the efficiency, we decided to change the expander from a pulse tube to a free-piston.

Outline

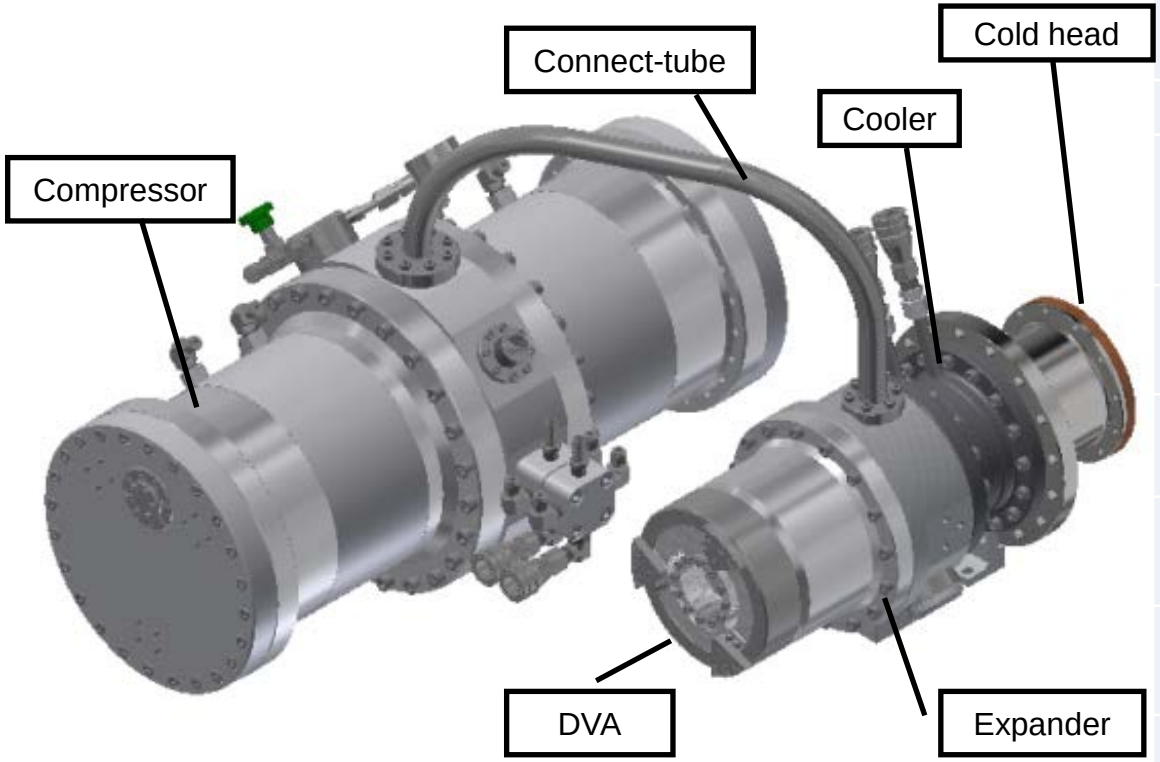
SHI Cryogenics Group

- Introduction
- General design and measurement system
- Energy flow analysis
- Improvement results
- Summary

Designed specification

SHI Cryogenics Group

- Details of the first prototype Stirling cryocooler (STC)



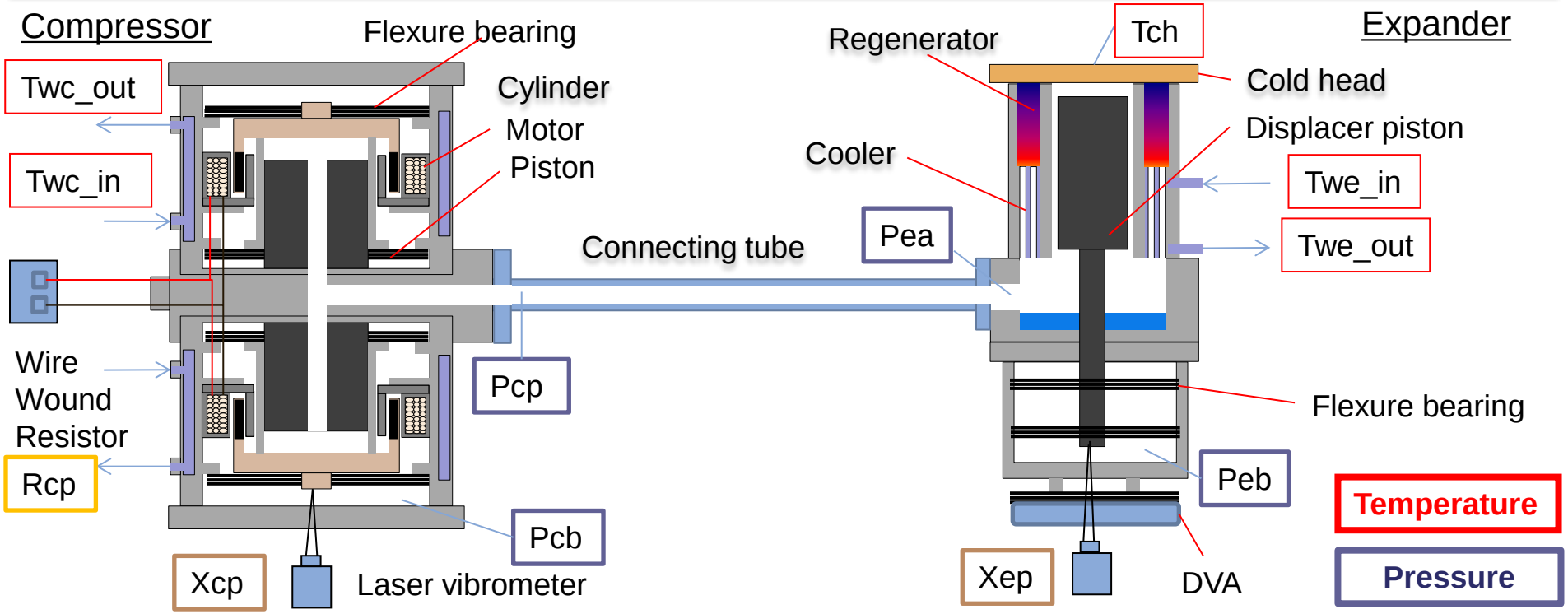
Cooling capacity	150 W at 70 K
First target COP	0.07
Maximum electric input power	2.15 kW
Operating frequency	47.0 Hz
Cooling water inlet temperature	30℃
Initial gas pressure	1.7 MPa Helium
Life Time (at design)	50000 hour
Weight	<150 kg

- Because it is very difficult to get COP > 0.1 with the first prototype unit, we set the performance target to be a cooling capacity of 150 W at 70 K, COP 0.07 at an inlet cooling water temperature of 30 ℃.

Measurement system

SHI Cryogenics Group

Experimental system and energy flow analysis



P-V work $W_{cp} = f_0 \cdot \oint P_{cp} \cdot dX_{cp} \cdot A_{cp}$

Heat rejection $Q_{cl} = C_w \cdot G_{cl} \cdot (T_{win} - T_{wout})$

Pressure drop loss of connecting tube $W_{ct} = f_o \cdot \oint \frac{1}{2} \cdot (P_{cp} + P_{ea}) \cdot d(V_{cp} - V_{ea})$

Outline

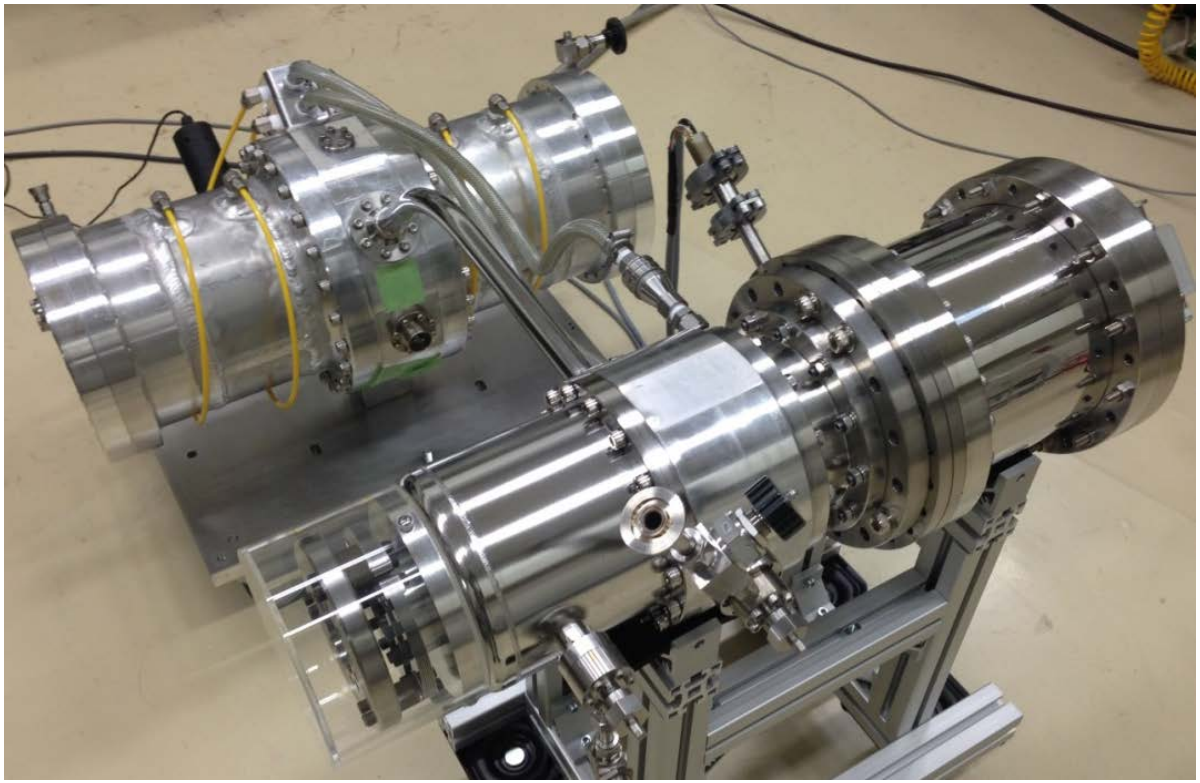
SHI Cryogenics Group

- Introduction
- General design and measurement system
- Energy flow analysis
- Improvement results
- Summary

Experimental result

SHI Cryogenics Group

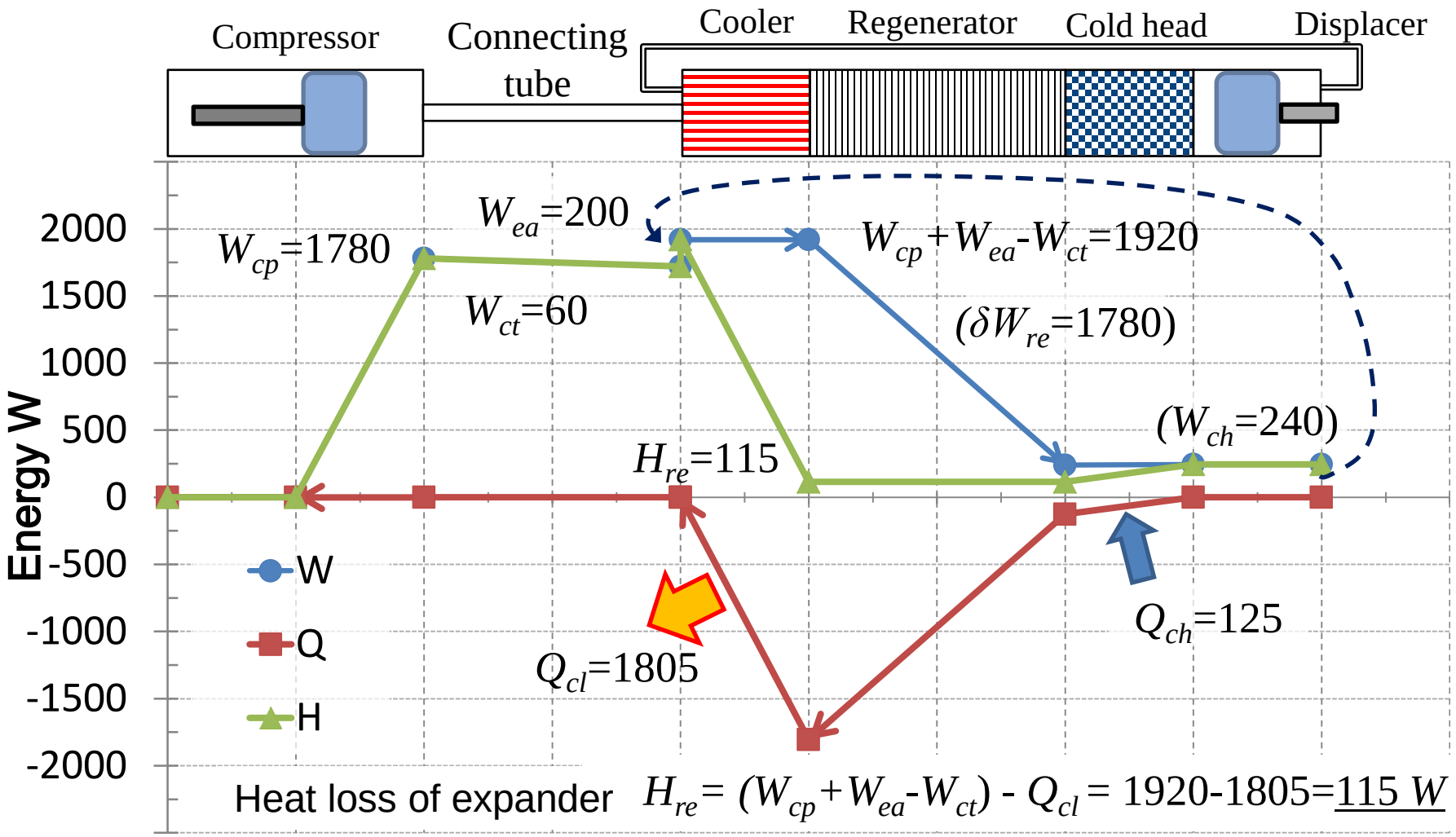
- In 2013, the first prototype unit was developed.



Cooling capacity Qch =125 W (COP 0.058) at 70 K
However, it's not enough compared with the first target….

Energy flow analysis

SHI Cryogenics Group



Experimental results

SHI Cryogenics Group

Compressor energy flow		
Compressor input power	Win	2150 W (V=145V, I=21A, P=0.072)
Compressor work flow	Wcp	1780 W
Compressor back space work flow	Wcb	80 W
Compressor copper loss	Qcc	160 W
Compressor iron loss	Qci	80 W
Mechanical loss of moving part.	Qcm	50 W (=Win-(Wcp+Wcb+Qcc+Qci))
Compressor heat rejection	Qcp	252 W

Expander energy flow		
Connecting-tube pressure loss	Wct	60 W
Expander hot-end P-V work	Wea	200 W
Expander buffer P-V work	Wcp	0.8 W
Cooler heat rejection	Qcl	1805 W
Expander cold head P-V work	Wch	240 W (calculated)
Expander heat loss	Hre	115 W (calculated)

・The heat loss of expander ,E_{re} ,was calculated as $115\ W$, and can be reduced. Therefore, the cooling performance was further improved by optimizing the regenerator ratio, clearance of displacer, and by reducing the conduction loss.

Outline

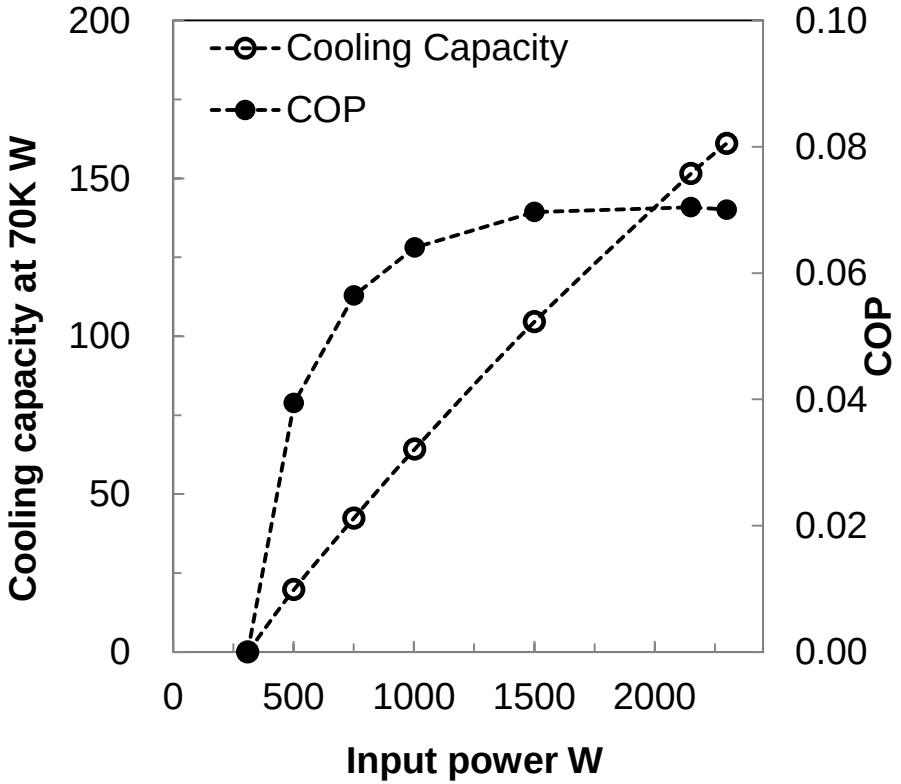
- Introduction
- General design and measurement system
- Energy flow analysis
- Improvement results
- Summary

Improvemet results

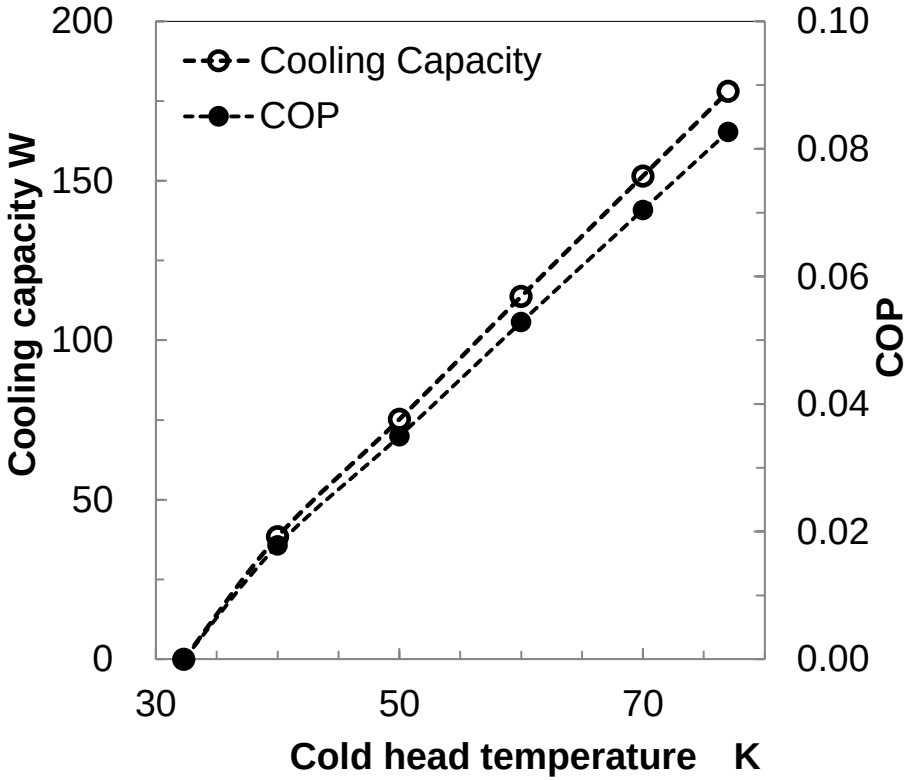
SHI Cryogenics Group

- In 2014, the second prototype unit was developed.

The cooling capacity at 70K vs. input power.



The cooling capacity vs. cold head temperature with an input power of 2.15 kW.



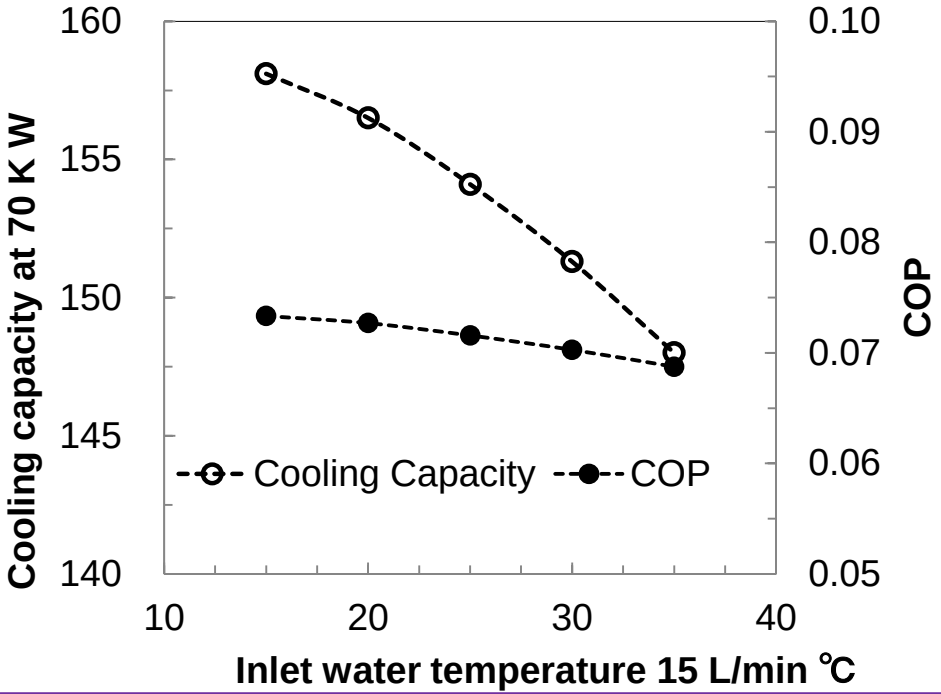
- A cooling capacity of 151 W at 70 K with an input power of 2.15 kW and COP of 0.07 respectively, were obtained.

Effect of environment factors

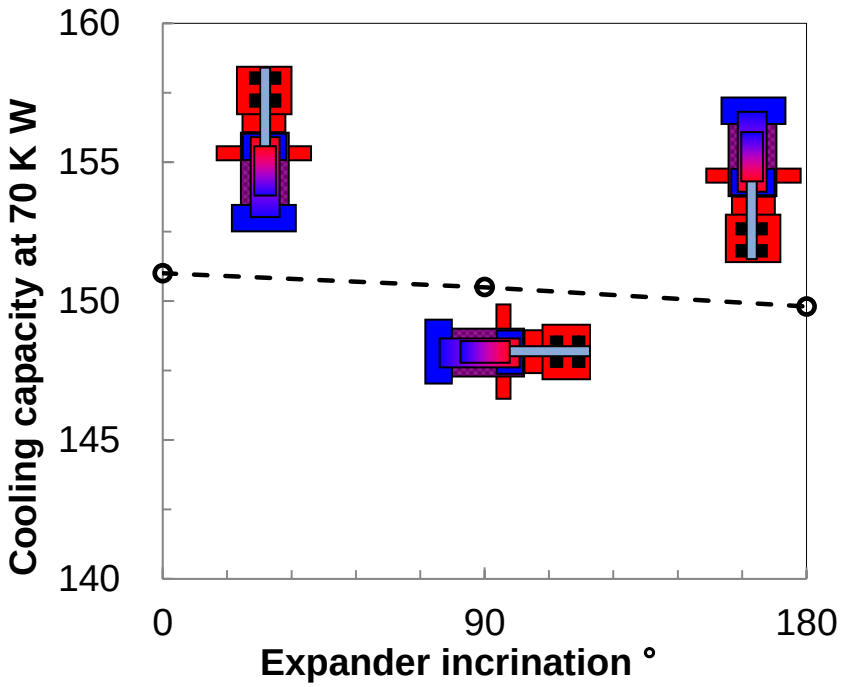
SHI Cryogenics Group

- To simulate the vehicle enviroment

Cooling capacity at 70 K vs. cooling water inlet temperature.



Effect of inclination



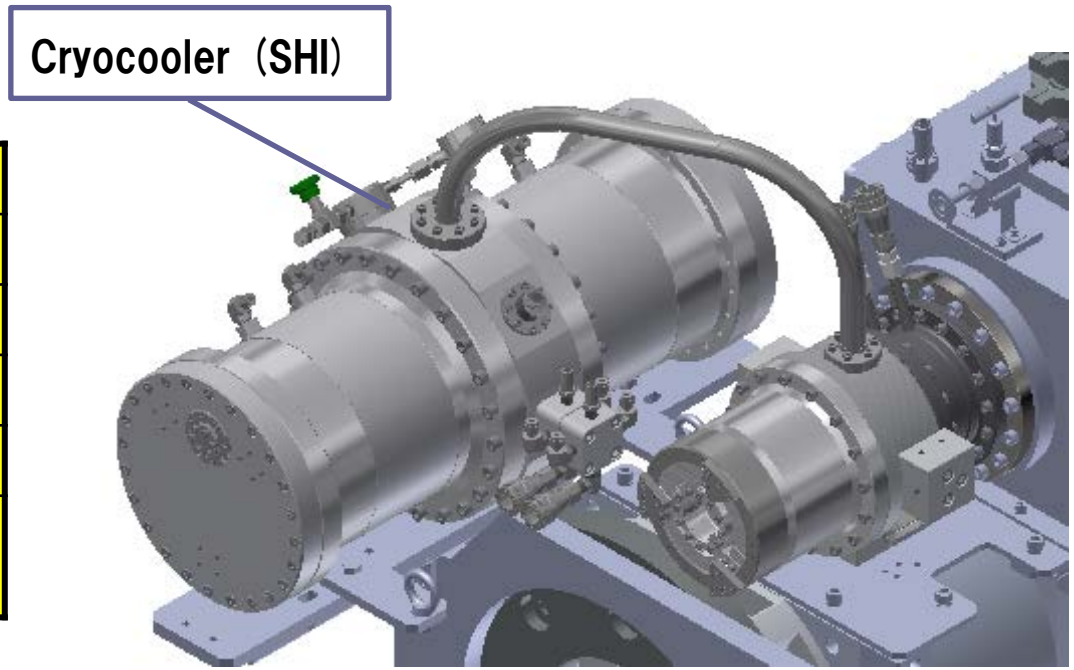
- The effect on the cooling capacity by the difference in the inlet cooling water temperature decreased about 0.5 W/℃.
- The effect of inclination is negligible.

HTS vehicle test

SHI Cryogenics Group

- May in 2015, HTS vehicle test was conducted.

Parameter	Target
Torque of motor	650Nm
Power of motor	100kW
Rev speed	4000rpm
Size of motor	100L
Efficiency	10% improve Compare a EV



- No obvious failure or performance degradation under the HTS vehicle environment was observed.

Outline

- Introduction
- General design and measurement system
- Energy flow analysis
- Improvement results
- Summary

Summary

The significant results of our research are:

- A prototype STC has been developed, and a cooling capacity of 151 W at 70 K and COP 0.07, respectively, were obtained.

- A prototype unit of the developed STC was installed in an HTS motor system of an electric vehicle, and a trial running test has been conducted. The prototype unit has been operated without failure or obvious performance degradation.

- It is necessary to further improve the efficiency and reliability, and to reduce the size and weight of cryocooler for practical use of HTS motors.

Acknowledgement

SHI Cryogenics Group

This work was supported by Strategic Innovation Program for Energy Conservation Technologies Project of the New Energy and Industrial Technology Development Organization (NEDO) of Japan and a joint research with Sumitomo Electric Industries, Ltd.

Thank you for your kind attention.

If you have any questions, please send me an e-mail.
Kys_nakano@shi.co.jp