

Development of a linear compressor for compact 2K Gifford-McMahon cryocoolers

SHI

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Introduction

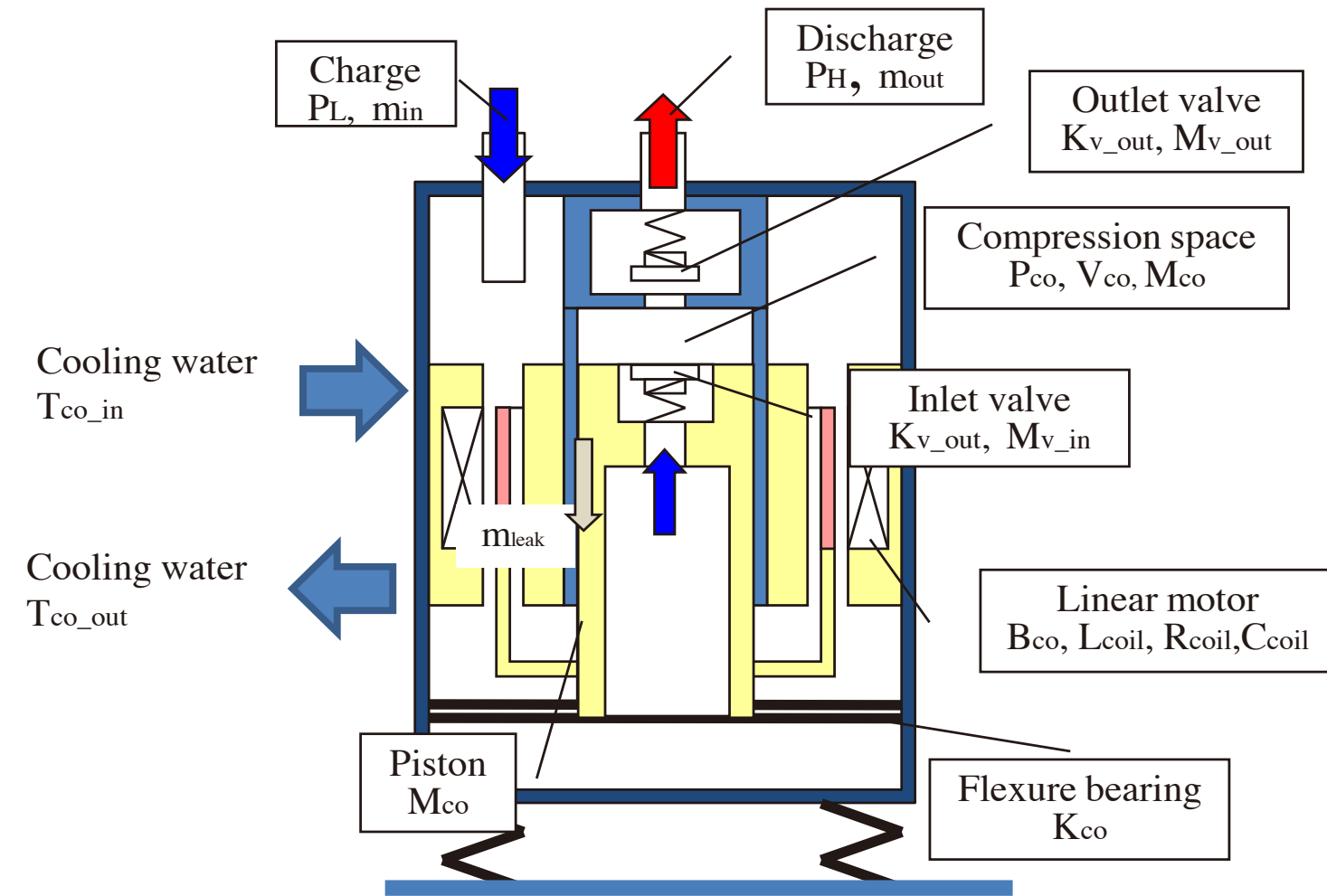
- In order to reduce the size of superconducting single photon detectors (SSPD) system, a compact GM expander together with a low bottom-temperature of about 2.3 K, has been developed.
- It is required to reduce the total volume of the compressor unit by 50% relative to the existing CNA-11 compressor.
- Considering the targeted cooling application, we set the design temperature targets of the first and the second stages under 1 W and 20 mW of heat load to be 60 K and 2.3 K, respectively.
- Recently, a new, compact valved non-lubricated linear compressor has been developed at SHI.
- It connected with 2K GM expander, the cooling capacity was measured, and the cryocooler performances with the CNA-11 compressor were compared.

Design of the valved linear compressor

Design target of the linear compressor for 2K GM cryocooler.

First stage cooling capacity	1 W at 60 K
Second stage cooling capacity	20 mW at 2.3 K
Maximum electric input power	1.2 kW AC100 V
Operating frequency	40 ~ 70 Hz
Cooling temperature	Water 30 °C
Initial gas pressure	1.3 ~ 2.0MPa
High / Low pressure	2.25 / 0.85 MPa
Mass flow rate	> 0.8 g/sec
Compressor efficiency	> 60 %
Unit volume	< 35 L

Analysis model of a valved linear compressor.



- In order to design a valved non-lubricated linear compressor for a 2K GM cryocooler, the mass flow rate and the pressure ratio are set to be similar to the specification of a CNA-11 compressor.
- Furthermore, under these determined conditions, the movement of the compressor parts has been analyzed.
- In order to reduce the pressure drop loss as much as possible, the gas charging side was installed at the piston upper end.

Conclusion

- An experimental unit of a valved non-lubricated linear compressor for a 2K GM cryocooler, which can be used for cooling superconducting electronic devices, has been developed.
- Under no-load condition, a low temperature of 2.19 K has been achieved.
- With 1 W and 14 mW heat load, the temperature was 50 K at the first stage and 2.3 K at the second stage with an input power of about 1.2 kW.
- In the future, we plan to further improve the efficiency of the compressor, to reduce the size of the heat exchanger thus reduce the total volume of the compressor.

Motion analysis model and calculation results

Equation of state  $P_{co} = \rho_f R_g T_{co}$

Conservation of mass  $M_{co} = M_{out} - M_{in}$

Conservation of energy for Compressor

$$\frac{dQ_{co}}{dt} + m_{out} C_p T'_{out} - m_{in} C_p T'_{in} = \left( C_p P_{co} \frac{dV_{co}}{dt} + C_p V_{co} \frac{dP_{co}}{dt} \right) / R_g$$

Conservation of momentum for Compressor

$$i_{coil} B_{co} I_{coil} = M_{co} \frac{d^2 X_{co}}{dt^2} + C_{co} \frac{dX_{co}}{dt} + K_{co} (X_{co} + X_{offset}) + A_{co} (P_H - P_L)$$

Kirchhoff's law  $\frac{dE_{coil}}{dt} = \ell_{coil} B_{co} \frac{d^2 X_{co}}{dt^2} + L_{coil} \frac{d^2 i_{coil}}{dt^2} + R_{coil} \frac{di_{coil}}{dt} + \frac{i_{coil}}{C_{coil}}$

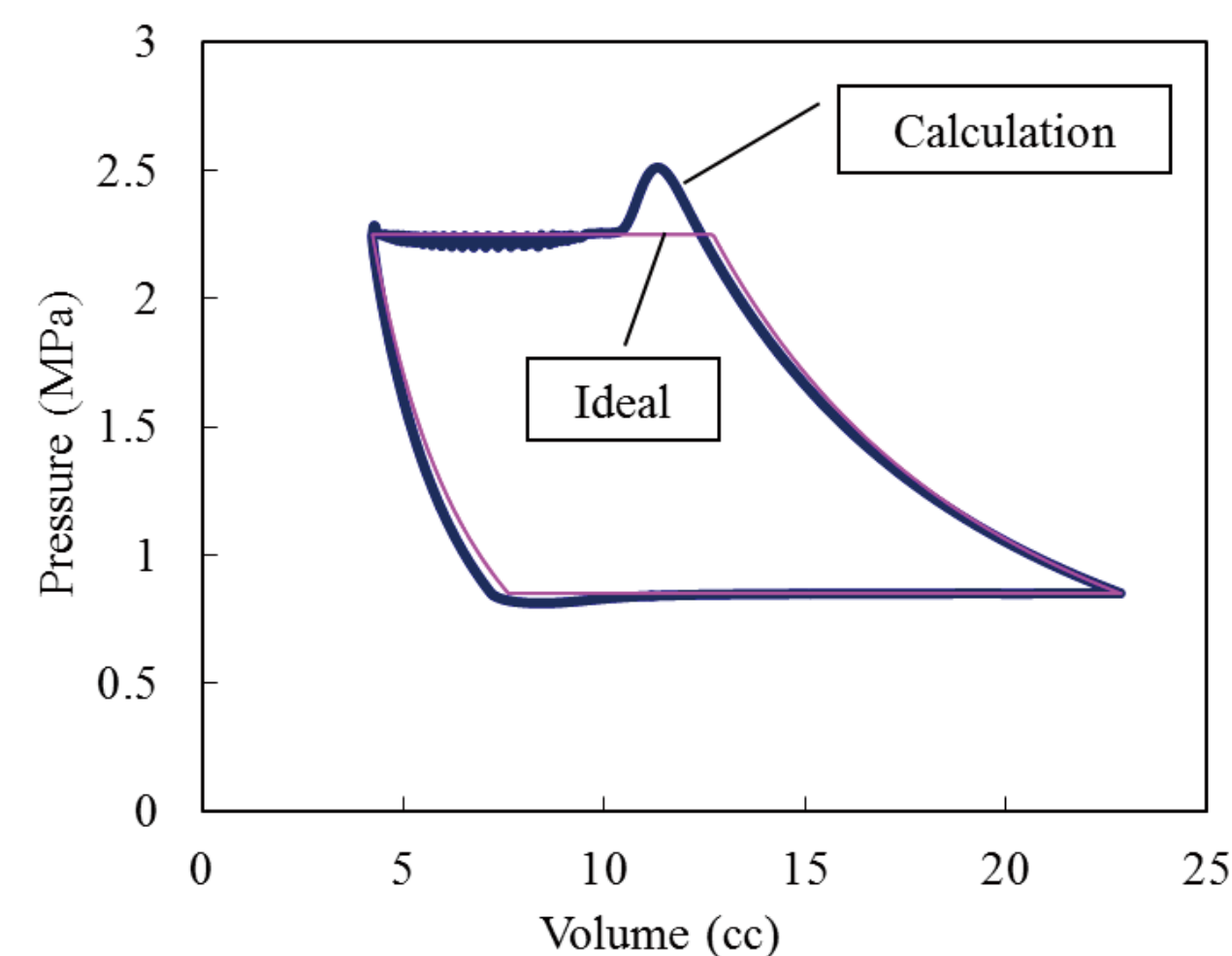
Conservation of momentum for Valve

$$0 = M_v \frac{d^2 X_v}{dt^2} + C_r \frac{dX_v}{dt} + K_v X_v + A_{vt} (P_{co} - P_H) \quad \frac{dX_v}{dt} = -C_r \frac{dX_v}{dt}$$

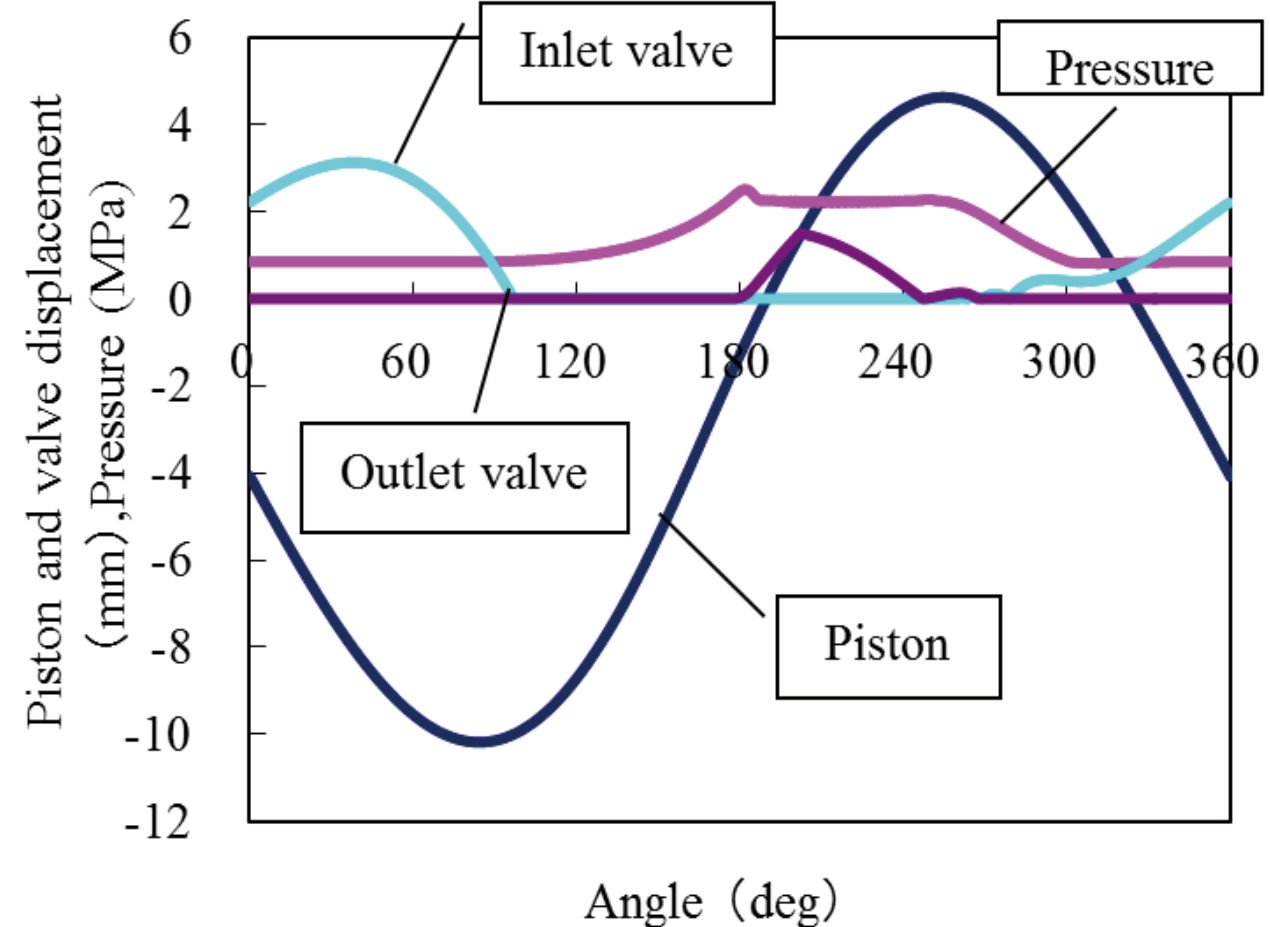
Mass flow rate of Valve, Piston leak

$$m_{leak} = CV \sqrt{P_H^2 - P_L^2}$$

Calculation results of the P-V diagram.



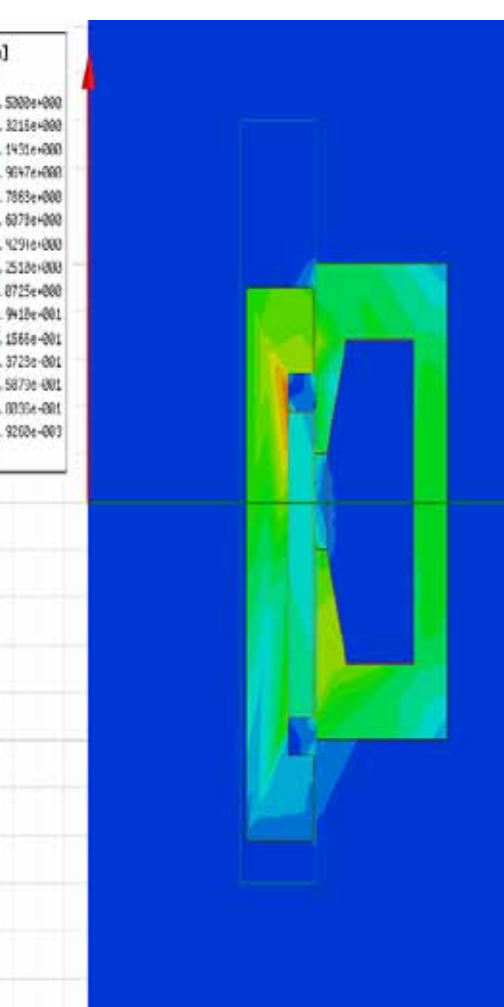
Calculation results of the pressure, and the displacement of the piston, the inlet and the outlet valve.



- The neutral position of the piston is offset to the low pressure side by 3-4 mm due to the differential pressure of the upper and the lower pistons.

Design of motor and flexure bearing

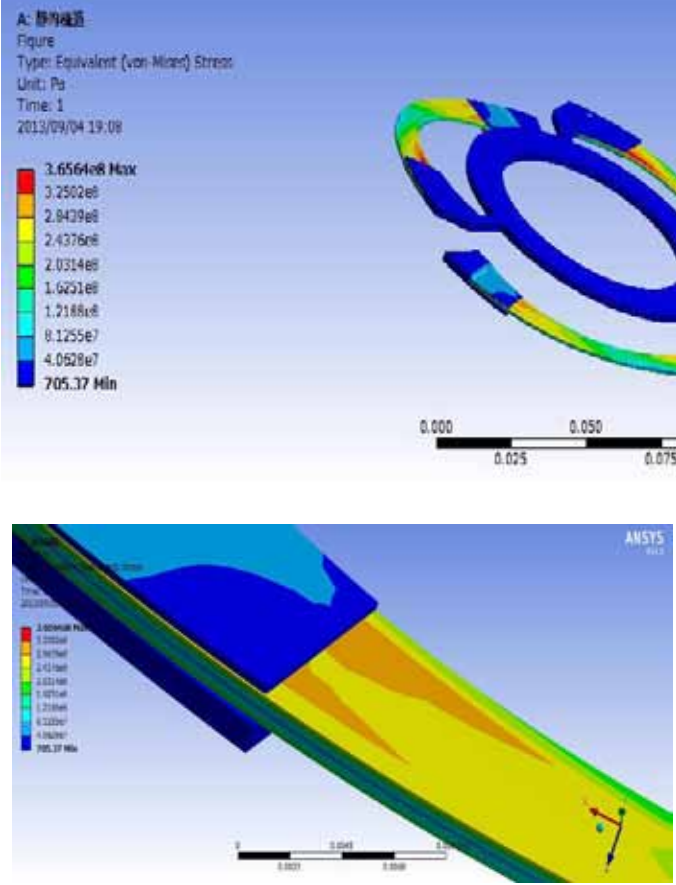
Analysis model of 1AirGap linear motor.



Calculation results of the transition analysis of a 1AirGap linear motor.

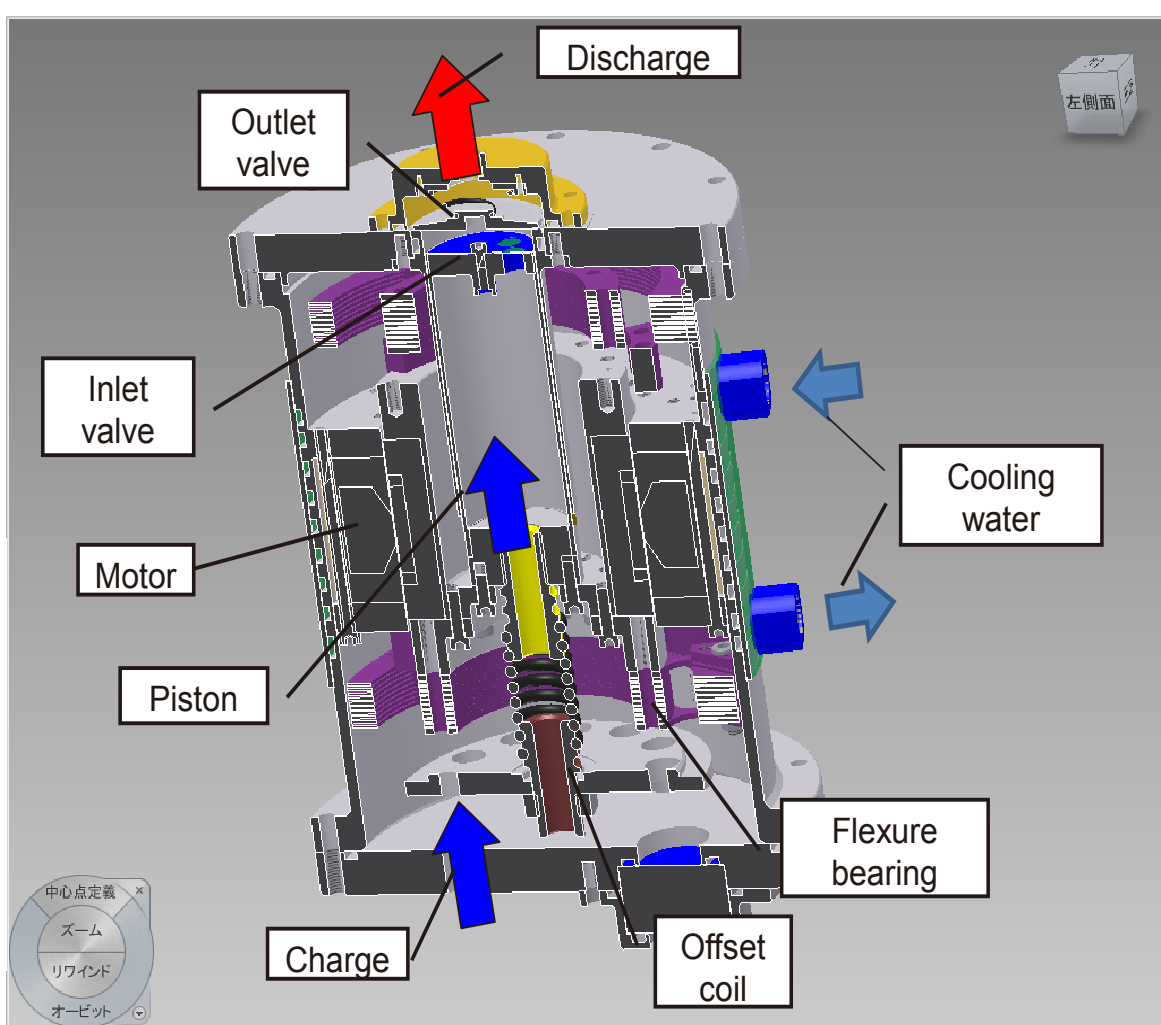
Operating frequency	50 Hz
Capacitor	0.22 mF
Turn number of coil	190 turn
Voltage	95 V
Current	14.4 A
Force	708.6 N
Force constant	49.3 N/A
Copper loss	140.3 W
Iron loss	123.0 W
Power factor	0.99
P-V work	1101.1 W
Input power	1364.4 W
Motor efficiency	0.81

Calculation results of a flexure bearing with a sub-spring using contact stress analysis.



- It is possible to reduce stress by 5~10% when using this concept.

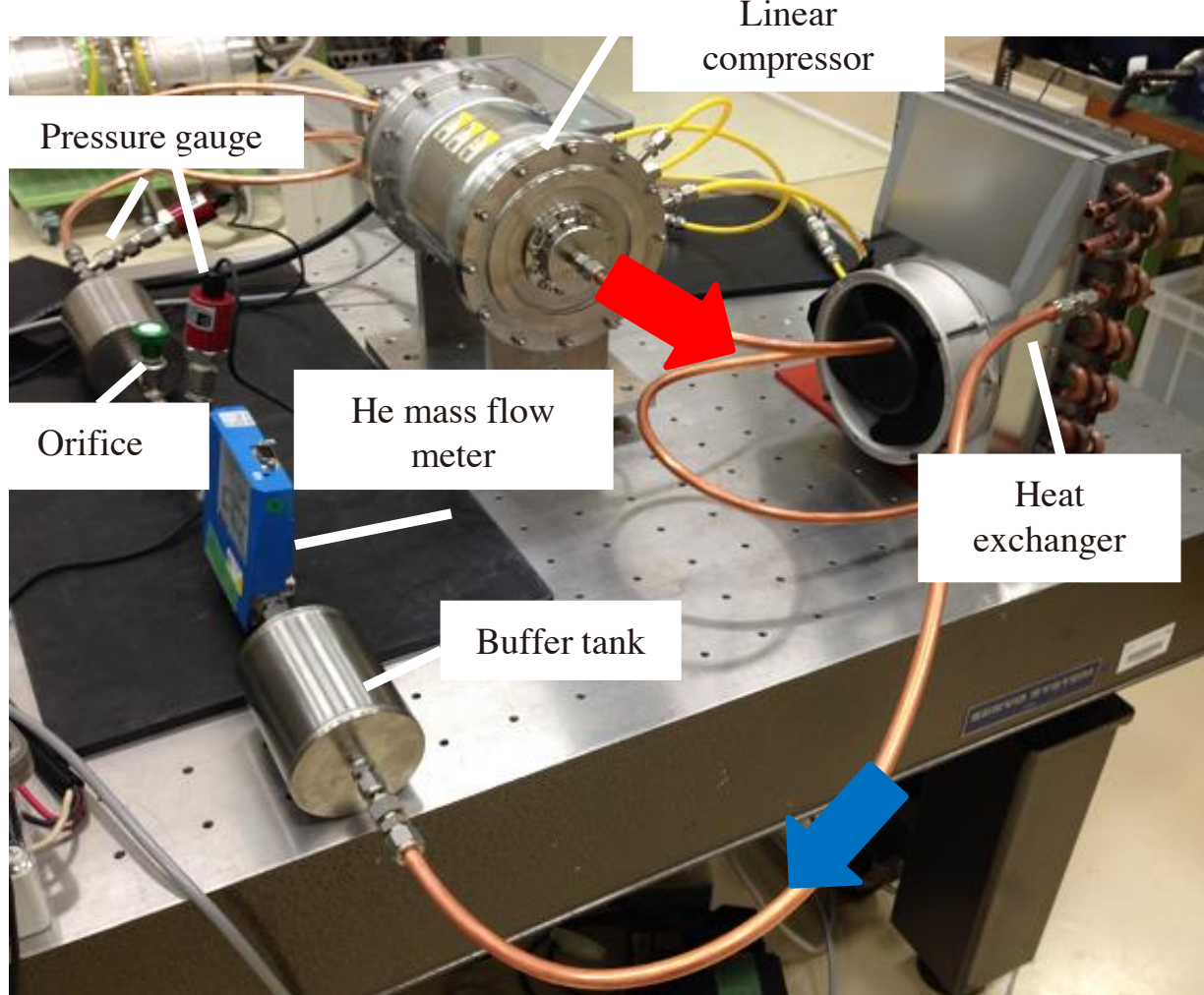
Cross section of an experimental unit of a valved linear compressor.



- It is possible to further improve the efficiency of the motor by reducing this air gap between the yoke and the magnet.
- In order to reduce the number of gaps, the yoke was designed to be integrated with the magnet.

The Estimate of compressor performance

Photograph of an experimental unit of the linear compressor.



- The low volume efficiency was caused by the gas leakage between the piston and the cylinder was too large.
- The motor efficiency was low because of the measured iron loss was larger than the calculation one.

Comparison between the experimental and the calculation results of the compressor.

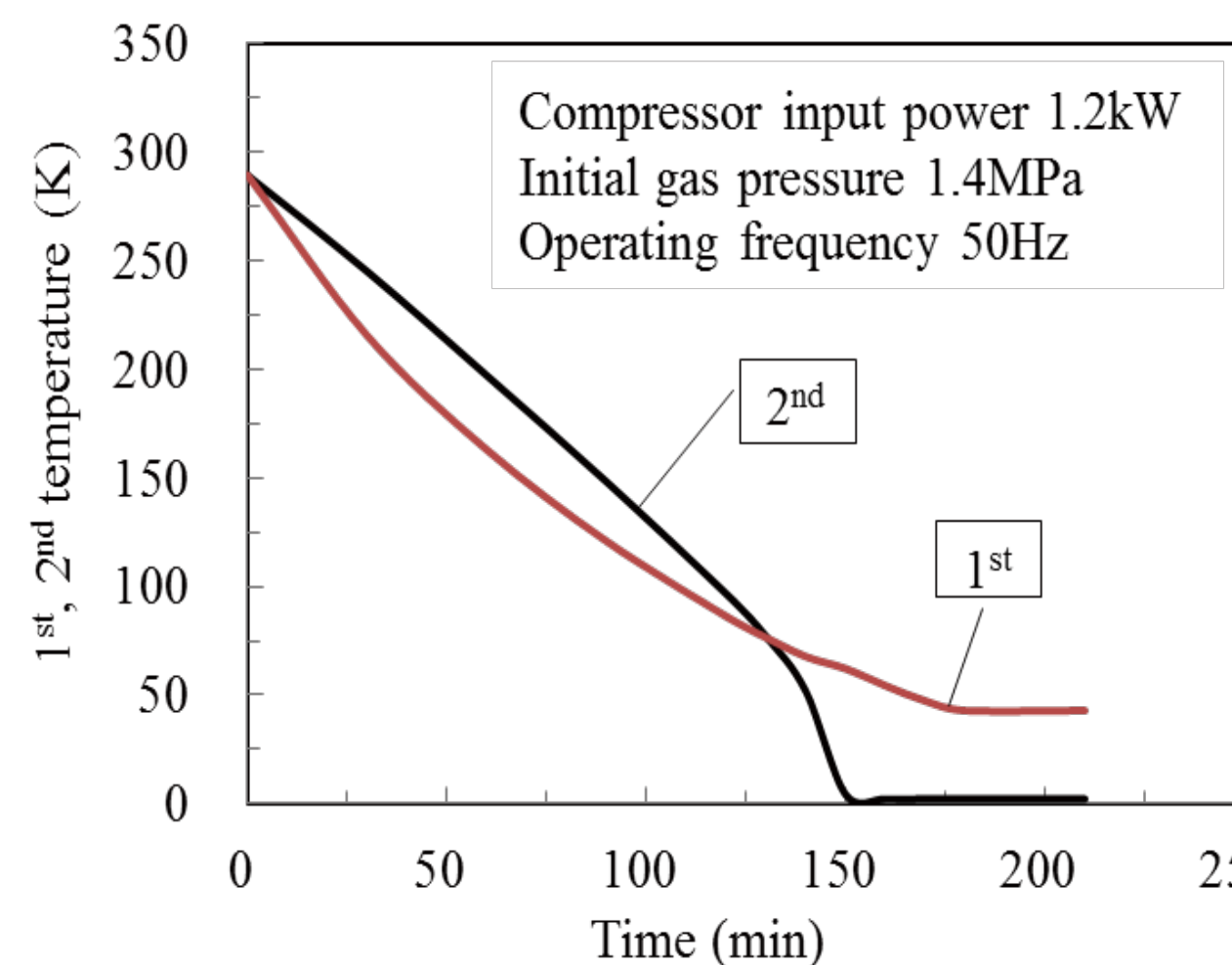
Item	Measurement	Calculation
Operating frequency	50 Hz	50 Hz
High / Low pressure	2.27 / 1.09 MPa	2.25 / 0.85 MPa
Discharge temperature	133.3 °C	125 °C
Charge temperature	25 °C	28 °C
Mass flow rate	0.89 g/sec	0.93 g/sec
Piston stroke	13.1 mm	13.5 mm
Input power	1.2 kW	1.2 kW
P-V work	0.86 kW	0.81 kW
Ideal P-V work	0.76 kW	0.81 kW
F-X work	0.91 kW	0.99 kW
Volume efficiency	0.64	0.87
Indicated efficiency	0.88	0.99
Motor efficiency	0.75	0.82
Indicated efficiency	0.88	0.99
Mechanical efficiency	0.95	0.95
Compressor efficiency	0.40	0.62

2K GM cryocooler with the linear compressor

Experimental results for a compact 2K GM cryocooler with the linear compressor.

Item	With CNA-11 compressor	Measured results
First stage temperature with 1 W	45 K	50 K
Second stage temperature at 2.3 K	20 mW	14 mW
No-load second stage temperature	2.18 K	2.19 K

Cool down curves of a compact 2K GM cryocooler with a linear compressor.



- With an input power of about 1.2 kW, a cooling capacity of 1 W at 48 K at the first stage and 14 mW at 2.3 K at the second stage has been achieved.
- The operation frequency was 50 Hz and the initial pressure was 1.4 MPa.

- The second stage temperature reaches 2.3 K in about 3 hours.

Acknowledgements

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