AN APPLICATION OF GAP REGENERATOR/EXPANDER

PRECOOLED BY TWO STAGE G-M REFRIGERATOR

Y. Matsubara and K. Yasukochi

Atomic Energy Research Institute
College of Science and Technology
Nihon University

ABSTRACT

The degradation of regenerator effectiveness below 10K is due to the imbalance of the heat capacity of the regenerator material and helium gas as a working fluid. One of the attractive methods to increase this efficiency could be realized by a gap regenerator system regarding helium gas property.

This paper describes an experiment using pressurized helium gas as a regenerator material. A two stage G-M cycle refrigerator has been used for precooling the gap regenerator system. With this method, minimum temperature below 5K has been obtained when the precooling temperature maintained at 10K.

INTRODUCTION

In order to obtain the liquid helium temperature effectively by a regenerative cycle cryocooler, such as Stirling cycle or Gifford-McMahon cycle, we need to know the thermal behavior of regenerator material and property of helium gas as a working fluid. One of the solutions to obtaining the liquid helium temperature is to use the gap regenerator method with plastic cylinder and displacer which has been successfully developed by Zimmerman, et al.(1).

This paper describes the experimental results of a gap regenerator /expander which is made of plastic piston and stainless steel cylinder with helium gas annulus, precooled by two stage Gifford-McMahon refrigerator.

REGENERATOR CONFIGURATION

One of the features of a gap regenerator, when compared to lead shot type regenerator, is that the contents of working gas in the regenerator can be kept to minimum. This effect is particularly noticeable at a temperature level below 10K where the volumetric specific heat of the helium gas increases, as pointed out by Radebaugh(2) and Daney (3).

On the other hand, the heat transfer area of a gap regenerator is limited to the finite displacer length and its cylinder surface, therefore, the regenerator heat capacity of wall materials becomes very small at a temperature level below 10K. For this reason, it then becomes necessary to balance the heat capacity ratio of the regenerator material and working gas.

Figure 1 shows the volumetric specific heat of helium gas below 15K, as compared to those of lead and G-10, explaining this fact very well. This also indicates that the high operating pressure may not be applicable due to the imbalance of the heat capacity ratio when lead or G-10 is used as a regenerator material.

To change the view point, high pressure helium gas seems to be a good regenerator material below 10K, if the thermal diffusion coefficient is maintained at a level high enough to create a reasonable operating cycle speed. This is because the low thermal diffusion coefficient would necessitate the cycle speed to be lowered to an unacceptable value for the regenerative cycle. Performance as a regenerator material when the operating speed is constant can be explained as follows:

Considering the sinusoidal temperature fluctuation on the surface of semi-infinite solid, the quantity of heat accumulated by the regenerative material during the half cycle is expressed as (4)

$$Q=\Delta T \cdot A \sqrt{\lambda C_p \rho \frac{2}{\pi} \tau_0} \ ,$$

where ΔT is the amplitude of temperature oscillation on the surface of the solid, A is the surface area, τ_0 is the period of oscillation, λ is the thermal conductivity, C_p is the specific heat and ρ is the density. Therefore, the value of $\sqrt{\lambda C_p \rho}$ represents the effectiveness of the material as a regenerator.

Fig. 2 shows this effectiveness of the helium gas compared to that of G-10, and it shows the pressurized helium gas ranging between 0.4-1.0 MPa becomes a regenerative material superior to G-10 in the temperature range below 8K.

EXPERIMENTAL APPARATUS

Fig. 3 shows the schematics of our experimental apparatus. The purpose of this study is related to the effectiveness of the regenerator operating below 10K. Therefore, we used two stage Gifford-McMahon cycle refrigerator as a precooler for the test section, which gives the warm heat station of 50K and cold heat station of 10K. With this arrangement, gap regenerator/expander system as a test section can be made with a pair of single cylinder and displacer. This precooler was also constructed in our laboratory, which has a pneumatically controlled displacer, electronically controlled valves, copper mesh regenerator for warm stage and lead-shot regenerator for cold stage.

Details of the test section are shown on Fig. 4. Cylinder of the test section is made of stainless steel having an outer diameter of 13 mm and a thickness of 0.5 mm. Displacer is made of cotton-cloth reinforced phenolic resin, which has a diameter of 11.9 mm and a total length of 65 cm. Between the cold heat station and the cold end of the test section, the cylinder is covered with another stainless steel tube which has an outer diameter of 15 mm, a thickness of 0.4 mm, and a length of 24.5 cm.

Helium gas as a regenerator material is introduced from the capillary tube to this annular space where the carbon fiber was packed for the purpose of preventing convection. In this experiment, a small amount of lead-shots were also used as a regenerative material around 10K. Lead-shots of 0.3 mm diameter immersed in the epoxy resin were coated on the surface of the lower part of the displacer with its diameter rearranged to 11.9 mm by lathe.

A stepping motor was used to drive the displacer. The timing of the intake and exhaust valves were controlled by means of a computer using an input signal of the diaplacer position. Pressure change was measured by the strain guage bonded on the cold end cap.

RESULTS AND DISCUSSIONS

Fig. 5 shows the P-V diagrams obtained at the cold end volume with the displacer stroke of 8 mm and intake and exhaust pressure of 0.6 and 0.12 MPa, respectively. The reason of decreased pressure ratio of (b)-(e) compared to (a) is explained as follows:

This test section basically forms a G-M cycle which has a maximum refrigeration work per one cycle when it has a rectangular P-V diagram. This condition will result if the intake valve is opened when the expansion volume is at its minimum, and exhaust valve is opened when the expansion volume is at its maximum. However this condition increases the regenerator load due to the effect of the incomplete expansion of the excessive intaked mass of the helium gas. In the example of Fig. 5 to reduce this effect, early cut-off of the intake valve was executed.

When the expansion volume is maintained at room temperature, P-V diagram shows a rectangular shape, even when the early cut-off has been excuted. However, if the temperature of the expansion volume decreases, area of P-V diagram decreases due to the condensation of the gas at the expansion volume. The turning corner at upper right position on the P-V diagram is a point at which the exhaust valve is opened.

Mass velocity of the helium gas passing through the gap regenerator can be controlled by changing the valve timing with the appropriate displacer position. The difference between (c) and (d) is caused by this timing change.

Fig. 6 shows the minimum temperature, T_{min}, obtained at the cold end of the test section with an operating pressure of 0.6MPa-0.12MPa and constant temperature of the cold heat station at 10K. Fig. 6 (a) shows the effect of helium gas pressure inside of the annulas, P_{reg}, with a fixed cycle speed at 17rpm. This result indicates that the helium gas in the annulus acts as a regenerative material. The cold end temperature below 6K did not obtained without helium gas in this annulus space. Fig. 6 (b) shows the effect of cycle speed with a fixed P_{reg}.

As expected, optimum cycle speed is very low and we obtained minimum cold end temperature of 4.8K at 12rpm. Below this speed, cold end temperature increases again. The expander work calculated from the P-V diagram of Fig. 5 (e) is about 22mwatts. At this condition, a heat input of 8mwatts was added to the cold end. Cold end minimum temperature increased to 5.8K and expander work also increased to 24mwatts , therefore, thermal efficiency of the test section will be about 35% and main losses will be caused by shuttle loss, insufficient heat transfer area, and excess enthalpy flow into the expansion volume due to the non-ideality of helium gas.

CONCLUSION

While our data were not complete enough, our experimental results indicate that in the gap regenerator/expander system it is very effective to use pressurized helium gas as a regenerator material at a temperature level below 10K. We found a refrigeration temperature below 5K can be obtained under this method with the precooling temperature of 10K. Although, under the regenerator design as shown in Fig. 4, optimum cycle speed was as low as around 12 rpm, the highest possible cycle speed is desirable as regenerative cycle, as far as the pressure loss permits. We thus propose as follows:

The highest possible cycle speed should be obtained through the regenerator fabricated by putting the pressurized helium gas into fin- or wool-state of materials (such as copper, lead or other pure metal) which are high in its thermal conductivity, while low in its specific heat, in the temperature range below 10K. In our experiments, in order to know the optimum P-V diagram we employed such G-M cycle which can change the valve timing and we also used a different type refrigerator in the precooling system to avoid the effect on the upper stage to be caused by change in temperature.

Our experimental results suggest that we would be able to obtain the helium temperature from the room temperature by employing this system at the final stage of multistage Stirling cycle, without using the different type precooling system.

We wish to thank S.Uosaki and T.Munekata for technical assistance.

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DISCUSSION

Question by C. Winter, Simon Fraser University: Please descrive the mounting of the strain gage pressure transducer on the cold end cap. What was its sensitivity to pressure changes?

Answer by author: A foil strain gage is glued on the membrance of the cold end cap. Effective diameter and the thickness of the membrance is 8mm and 0.5mm respectively. This gauge (as shown in Fig. 7) consists of four different gauges which give signals proportional to a radial and a tangential strain of the membrance. Calibrated sensitivity of this pressure transducer was (3.48±0.02)KPa/Volt below 1MPa, using strain amplifier with the voltage gain of 350.

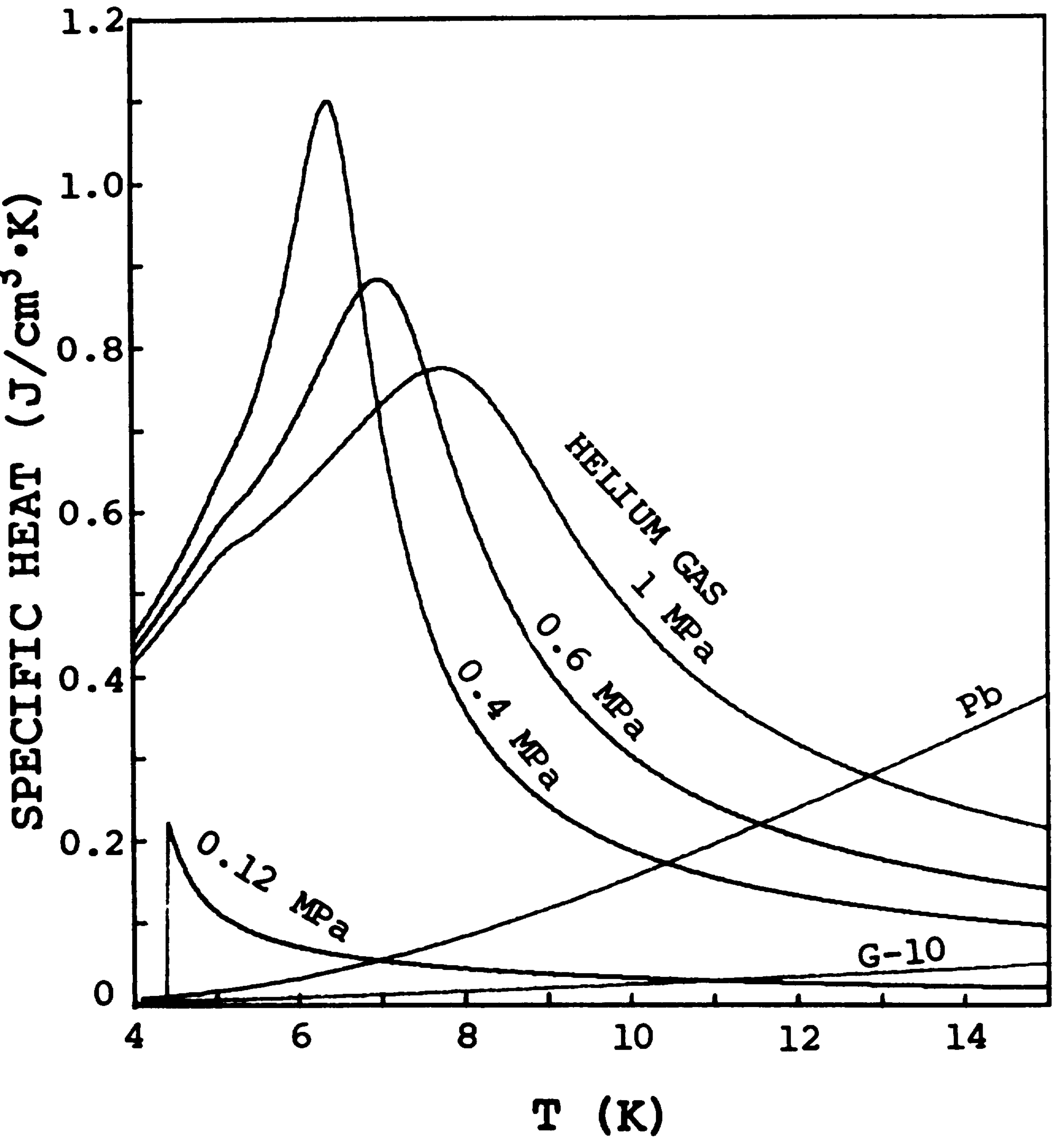

Figure 1. Volumetric heat capacity of helium, lead and G-10.

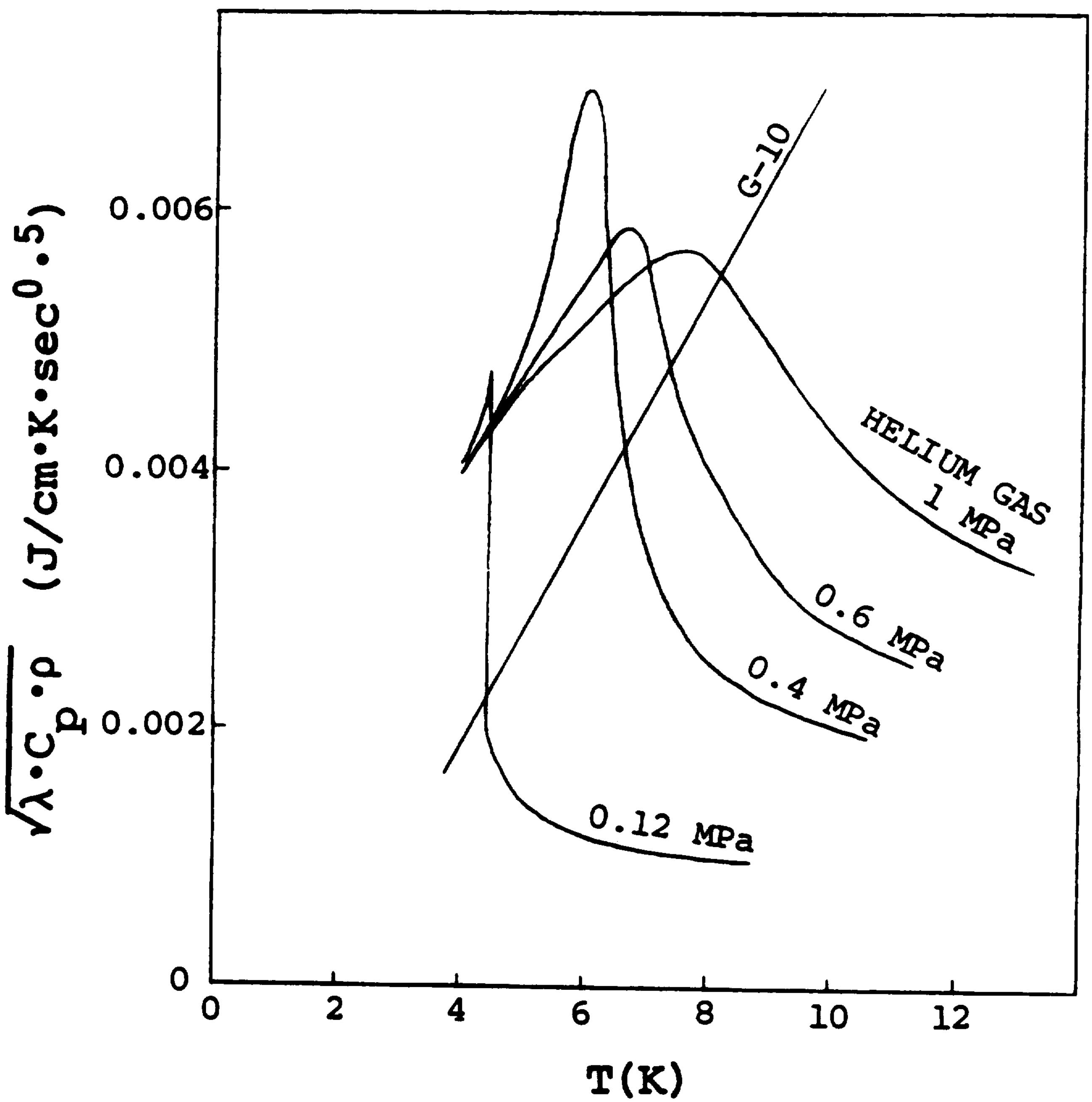

Fig.2 Performance of helium gas as a regenerative material.

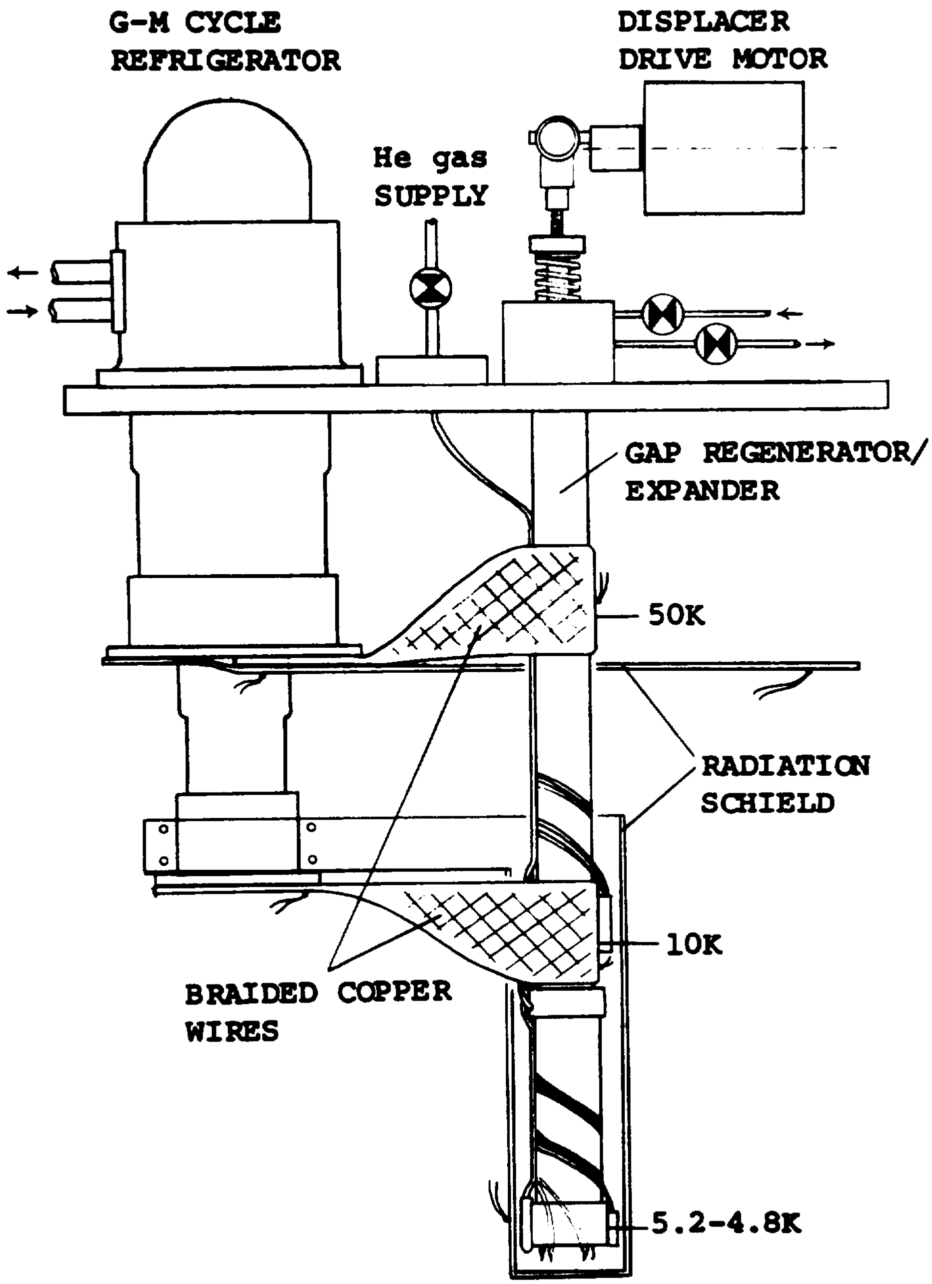

Figure 3. Schematic of experimental arrangement.

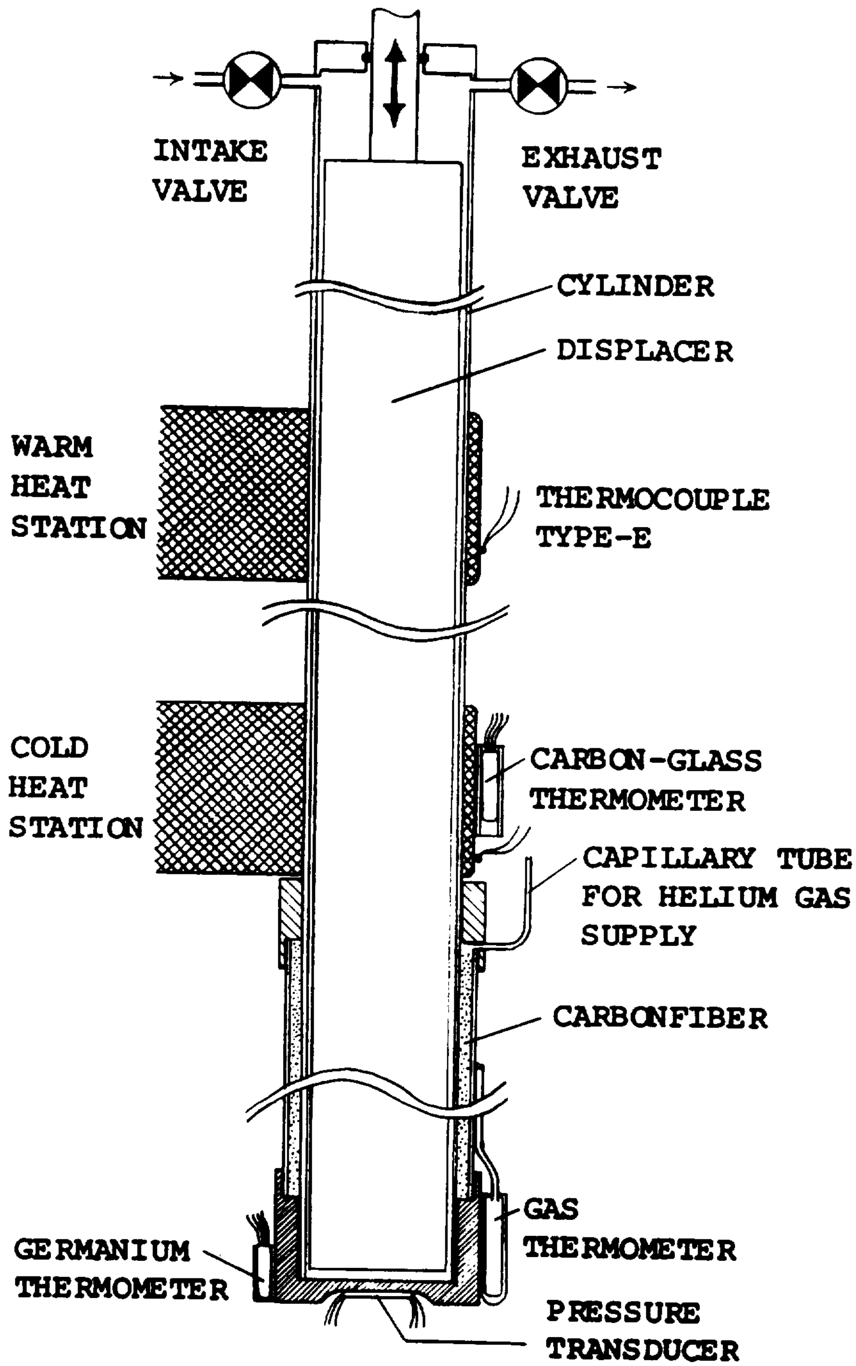

Figure 4. Gap regenerator/expander with pressurized helium gas annulus.

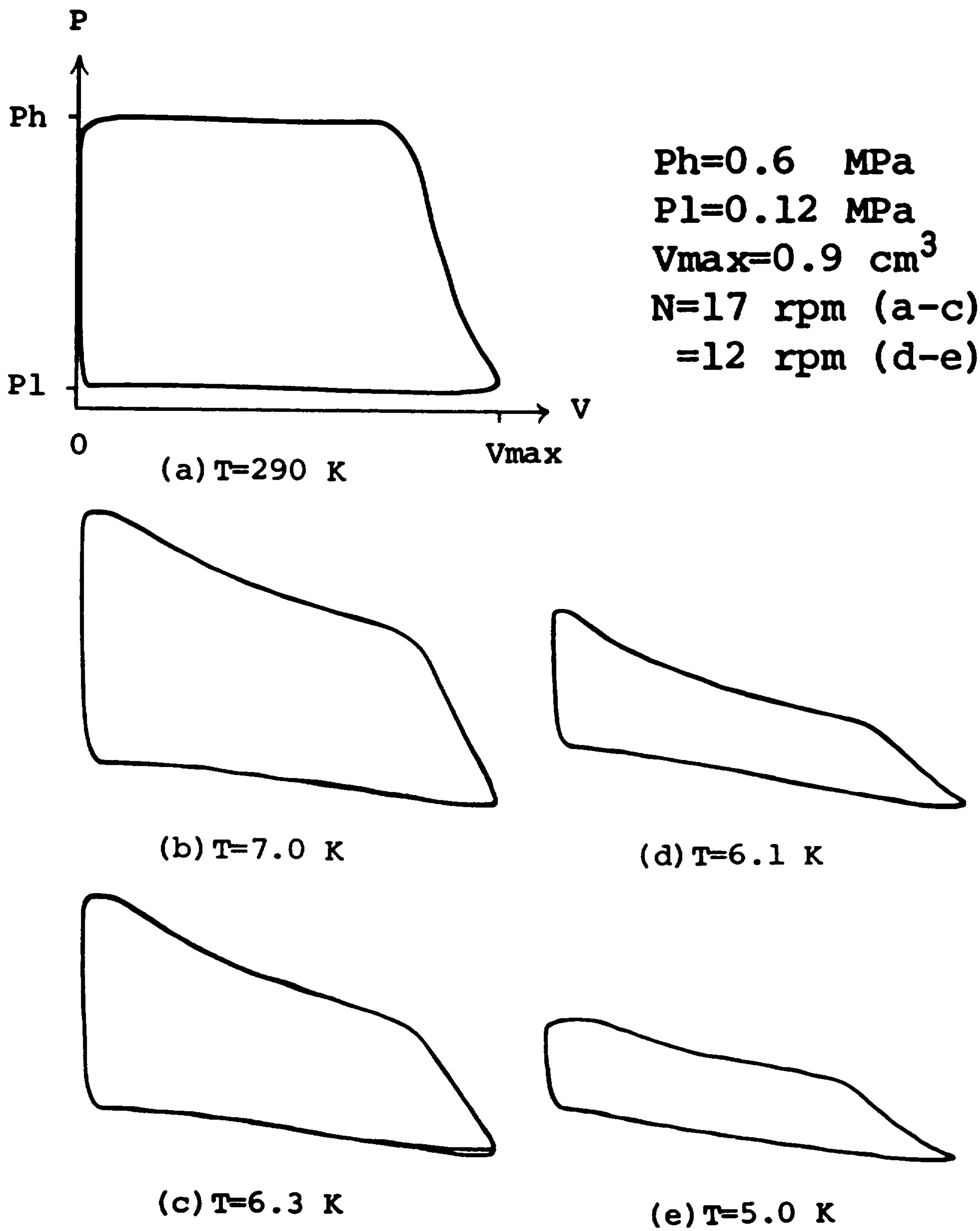

Figure 5. P-V diagrams of the expander.

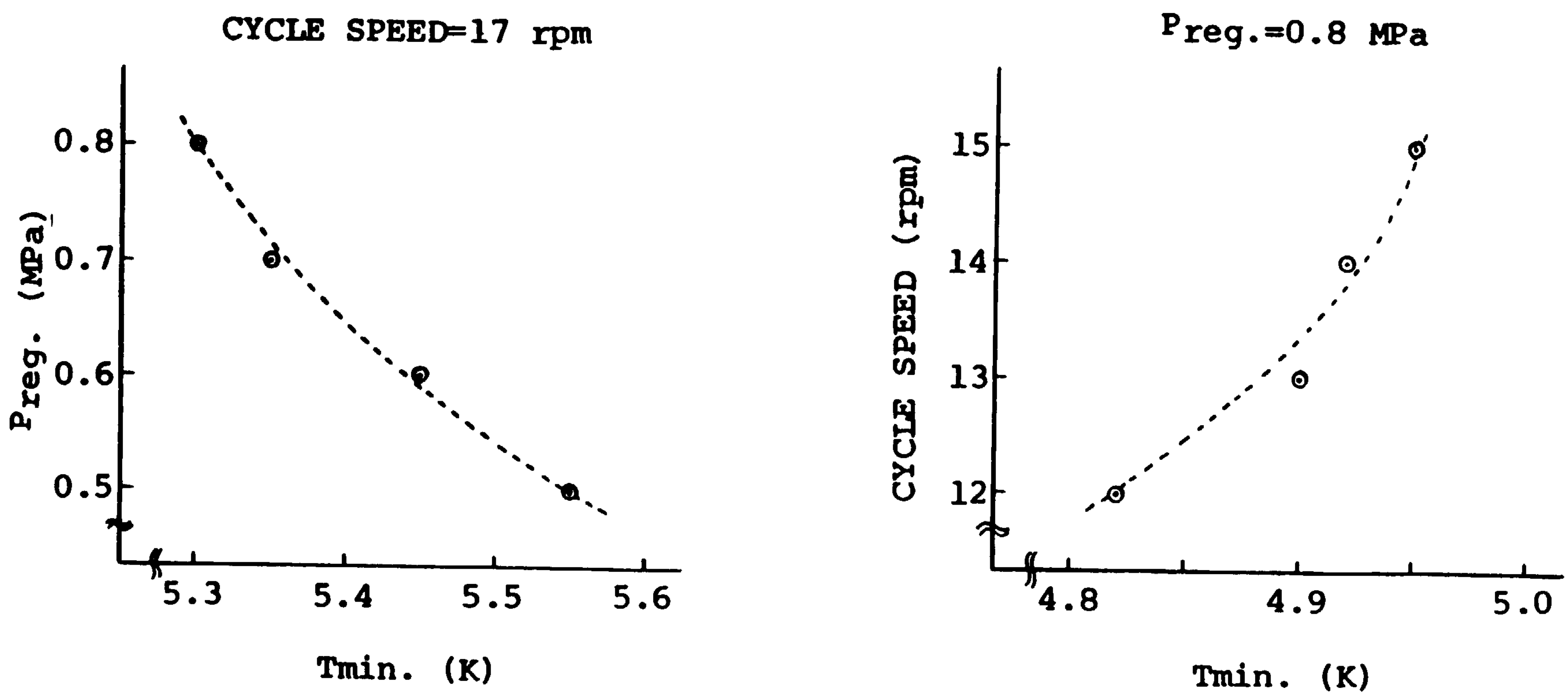

Fig.6 Measured minimum temperature at the cold end of the expander.

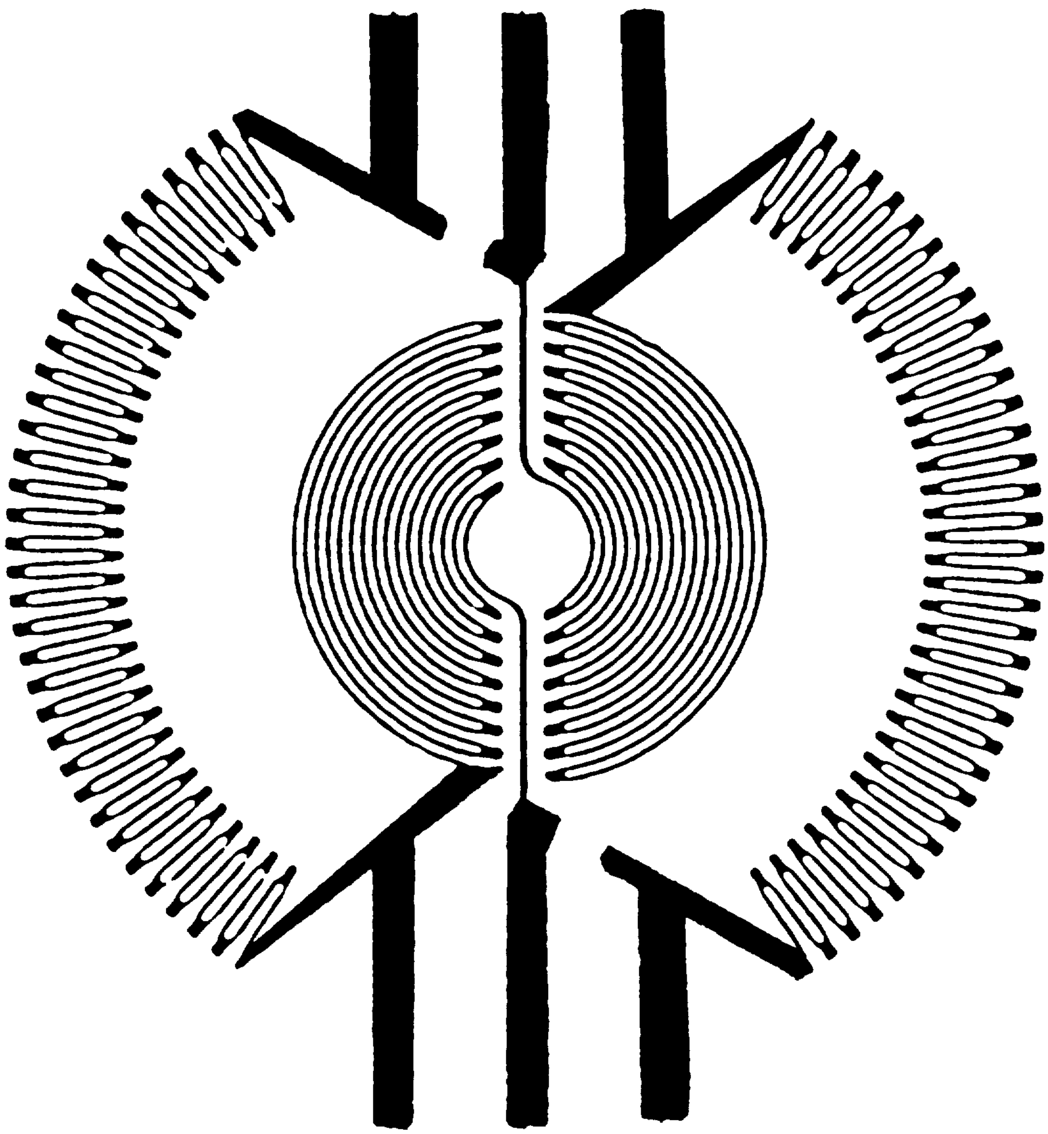

Figure 7. Strain gauge pressure transducer.