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A pulse tube refrigerator below 2 K

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Abstract

Up to now, all pulse tube refrigerators operating at the liquid helium temperature range use ^4He as the working fluid. However, the lambda transition of ^4He is a barrier for reaching temperatures below 2 K. Theoretical analysis in this paper shows that, using ^3He, the temperature limit is below 2 K, and the efficiency of a 4 K pulse tube refrigerator can be improved significantly. A three-stage pulse tube refrigerator is constructed. A compressor with input power of 4 kW and a rotary valve are used to generate the pressure oscillations. With ^4He, a minimum average temperature of 2.19 K was reached. Replacing ^4He by ^3He, at the same valve settings and operating parameters, the minimum average temperature goes down to 1.87 K and the cooling power at 4.2 K is enhanced about 60%. After fine tuning of the valves, a minimum average temperature of 1.78 K was obtained. This is the lowest temperature achieved by mechanical refrigerators.

Keywords: Pulse tube refrigeration; Cryocooler; Cryogenics; Helium three; Refrigeration

1. Introduction

In 1994, Matsubara and Gao [1] obtained a temperature below 4 K using a three-stage pulse tube refrigerator and Er_3Ni as regenerator material in the coldest stage. The lowest temperature reported so far is by Giessen group [2]. They obtained 2.07 K with a nitrogen-precooled two-stage pulse tube refrigerator.

Up to now, all pulse tube refrigerators operating at the liquid helium temperature range use ^4He as the working fluid. However, the lambda transition of ^4He is a barrier for reaching temperatures below 2 K. In order to cool below 2 K, one possibility is to use ^3He as the working fluid [3]. Theoretical analysis in this paper shows that, using ^3He, the temperature limit is below 2 K, and that the efficiency of a 4 K pulse tube refrigerator can be improved significantly. A three-stage pulse tube refrigerator is constructed. It is found that replacing ^4He by ^3He, at the same valve settings and operating parameters, the minimum average temperature goes down from 2.19 to 1.87 K. The cooling power at 4.2 K is enhanced from 40 to 65 mW, so with about 60%. After fine tuning of the valves, a minimum average temperature of 1.78 K was obtained.

2. Theoretical analysis

A schematic diagram of a single-stage pulse tube refrigerator is given in Fig. 1. An extensive treatment of the thermodynamics of pulse tube refrigerators is given in previous publications of our group [4–8].

We will now derive the expressions for the cooling power $\dot{Q}_L$ for small pressure variations δp. The change in the molar enthalpy, H_m, depending on the molar volume V_m, the heat capacity at constant pressure C_P, the temperature T, and the volumetric thermal expansion coefficient α_V, is as follows:

$$\delta H_m = C_P\,\delta T + H_P\,\delta p \tag{1}$$

with

$$H_P = (1 - T\alpha_V)V_m. \tag{2}$$

The enthalpy flow is given by

$$\overset{*}{H} = \overset{*}{n} H_m, \tag{3}$$

where $\overset{*}{n}$ is molar flow rate. We split the enthalpy into a time average part and a varying part $H_m = \overline{H_m} + \delta H_m$. In the regenerator, we assume $\delta T = 0$, and use the fact

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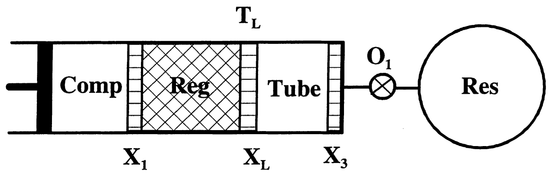


Fig. 1. Schematic diagram of a stirling type single-stage orifice pulse tube refrigerator. From left to right the system consists of a compressor (Comp), a room-temperature heat exchanger (X_1), a regenerator (Reg), a low-temperature heat exchanger (X_L), a tube (Tube), a second room-temperature heat exchanger (X_3), an orifice (O_1), and a buffer volume (Res).

that $\overline{\overset{*}{n}} = 0$. With Eqs. (1) and (2) we can express the average enthalpy flow in the regenerator as

$$\overline{\overset{*}{H}_{\mathrm{r}}} = (1 - T\alpha_{\mathrm{V}}) V_{\mathrm{m}} \overline{\overset{*}{n}_{\mathrm{r}}\,\delta p}, \tag{4}$$

where $\overset{*}{n}_{\mathrm{r}}$ is molar flow rate inside the regenerator. If Eq. (4) is evaluated at the cold side of the regenerator, we obtain the expression for the average enthalpy flow into X_L in the regenerator.

The variation of the enthalpy can also be expressed as

$$\delta H_{\mathrm{m}} = T\,\delta S_{\mathrm{m}} + V_{\mathrm{m}}\,\delta p. \tag{5}$$

In the tube the gas elements move with constant entropy, so $\delta S_{\mathrm{m}} = 0$. Using Eq. (5) we get for the enthalpy flow in the tube

$$\overline{\overset{*}{H}_{\mathrm{t}}} = V_{\mathrm{m}} \overline{\overset{*}{n}_{\mathrm{r}}\,\delta p}. \tag{6}$$

We now consider the energy balance of X_L (Fig. 2)

$$\dot{Q}_{\mathrm{L}} + \overline{\overset{*}{H}_{\mathrm{r}}} + \dot{Q}_{\mathrm{c}} = \overline{\overset{*}{H}_{\mathrm{t}}}, \tag{7}$$

where $\dot{Q}_{\mathrm{L}}$ is the applied heating power and $\dot{Q}_{\mathrm{c}}$ the heat flow due to thermal conduction in the regenerator. With Eqs. (2) and (6) the cooling power can be written in terms of the expansion coefficient as

$$\dot{Q}_{\mathrm{L}} + \dot{Q}_{\mathrm{c}} = T\alpha_{\mathrm{V}} V_{\mathrm{m}} \overline{\overset{*}{n}_{\mathrm{r}}\,\delta p}. \tag{8}$$

All quantities in this expression must be evaluated near the cold heat exchanger X_L.

It is clear from Eq. (8) that the cooling power is zero if the thermal expansion coefficient is zero. This can also be understood from the expression for the change in the molar entropy

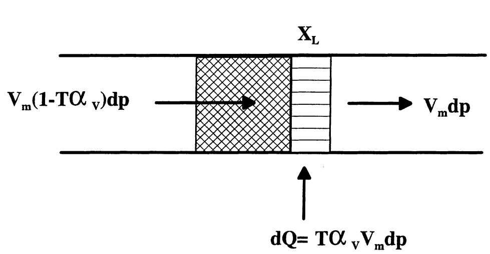


Fig. 2. Energy flows near the cold heat exchanger.

$$\delta S_{\mathrm{m}} = \frac{C_P}{T}\,\delta T - \alpha_{\mathrm{V}} V_{\mathrm{m}}\,\delta p. \tag{9}$$

If $\alpha_{\mathrm{V}} = 0$ then $(\partial T/\partial p)_{S_{\mathrm{m}}} = 0$, so adiabatic compression or expansion does not change the temperature. The thermal expansion coefficients of ^4He and ^3He are shown in Fig. 3. The thermal expansion coefficient of ^4He at 15 bar is zero around 2 K and even becomes negative at lower temperatures [9]. So it is impossible to cool below 2 K with ^4He. For ^3He, $\alpha_{\mathrm{V}} = 0$ at 15 bar at temperatures about 1 K [10]. Fig. 4 shows the $\alpha_{\mathrm{V}} = 0$ curve for ^3He. The λ-line for ^4He and the melting curves for ^4He and ^3He are also shown in Fig. 4. It is clear that, using ^3He, it is possible to cool below 2 K.

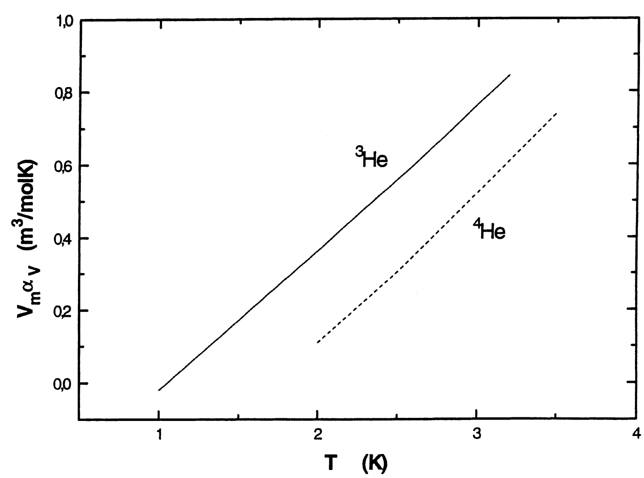


Fig. 3. $V_m\alpha_V$ of ^3He and ^4He versus temperature at 15 bar.

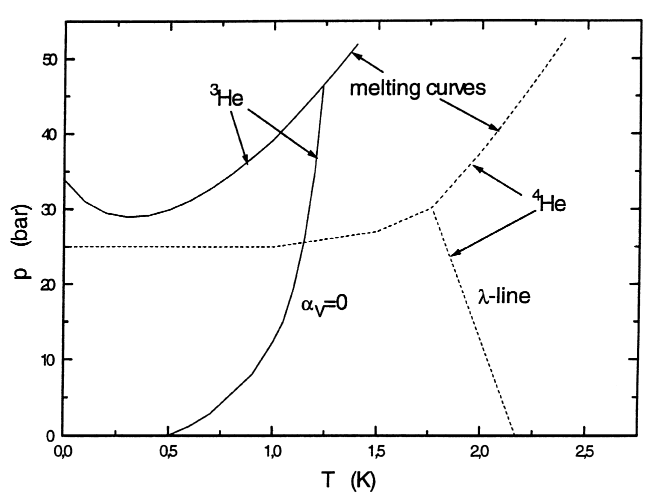


Fig. 4. The $\alpha_{\mathrm{V}} = 0$ curve for ^3He, the λ-line for ^4He and the melting curves for ^4He and ^3He.

3. Experimental set-up

Fig. 5 shows the schematic diagram of the three-stage pulse tube refrigerator. It was constructed according to the design presented by Matsubara and Gao [1]. The input power of the compressor is 4 kW. The openings of the orifice [11] and double-inlet [12] are adjusted by needle valves. Three needle valves are used as minor orifices [13] and connected to the high or low pressure side. The buffer volume of the first stage is 1 l, those of the second and third stages are 0.5 l, respectively.

The tubes and regenerators are fabricated from stainless steel. The sizes are listed in Table 1. The first-stage regenerator is filled with 200 mesh phosphor bronze screens. The second-stage regenerator is filled with lead spheres (diameter 0.2–0.3 mm). The third stage regenerator is filled with $Er_3Ni + ErNi + ErNi_{0.9}Co_{0.1}$ spheres.

Copper heat shields are mounted on the first- and second-stage cold end to reduce radiation losses.

The temperatures at the first-stage cold end are measured by means of platinum thermometers. Those at the second stage are measured by calibrated silicon diode thermometers. The temperatures near the hot end of the third-stage tube are measured by platinum thermometers. Those near the cold end are measured by silicon diode thermometers. The pressures in the inlet of the regenerator and each stage tube and buffer are measured using pressure transducers.

In our system, which is not optimized for using the minimum amount of ^3He, we need about 220 l NTP of ^3He to obtain an average pressure of 17 bar.

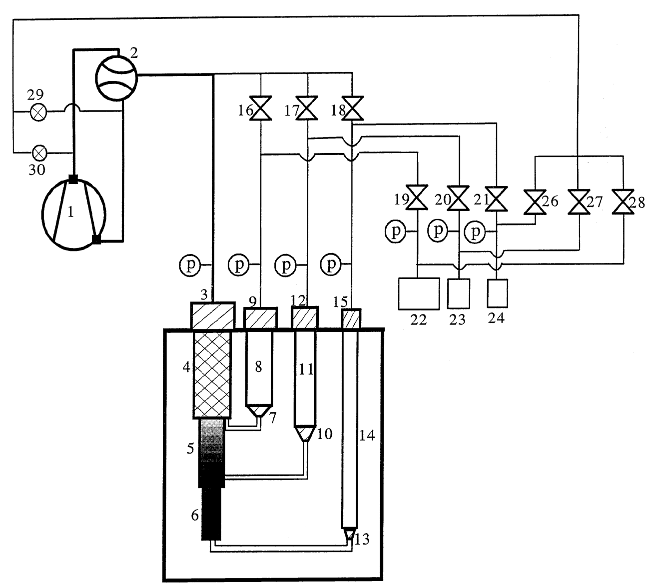


Fig. 5. Schematic of three-stage pulse tube refrigerator. 1 – compressor; 2 – rotary valve; 3, 9, 12, 15 – heat exchangers; 4 – 1st regenerator; 5 – 2nd regenerator; 6 – 3rd regenerator; 7 – 1st cold end; 8 – 1st tube; 10 – 2nd cold end; 11 – 2nd tube; 13 – 3rd cold end; 14 – 3rd tube; 16–18 – double inlet valves; 19–21 – orifice valves; 22–24 – buffers; 25 – vacuum chamber; 26–28 – minor orifices; 29, 30 – valves.

4. Experimental results and discussions

Unless stated otherwise, all the following results are obtained at an operating frequency of 1.2 Hz. All the valve settings for orifice, double inlet and minor orifice for ^4He and ^3He are the same.

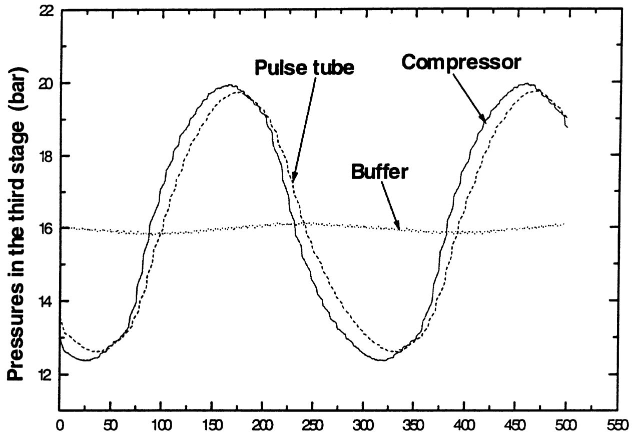
Fig. 6 shows the pressure curves when the system is at the steady state in the inlet of regenerator, the third stage tube and buffer with ^4He and ^3He. The average pressure p_{av} in the system and the pressure ratio, $\sigma = p_{max}/p_{min}$, in each stage tube are shown in Table 2. Most of the pressure drop is in the first- and second-stage regenerator. The pressure drop in the third-stage regenerator is rather small, because the viscosity and the volume flow rate in the third stage are much small.

The lowest temperatures at the first-, second- and third-stage cold end are shown in Table 3. Using ^3He, the lowest temperatures at the third-stage cold end is lower, while those at the first and second stage are higher. It is clear that, using ^3He, a pulse tube refrigerator can break the lambda transition barrier and go down below 2 K. Simply replacing ^4He by ^3He, the minimum average temperature goes down from 2.19 to 1.87 K.

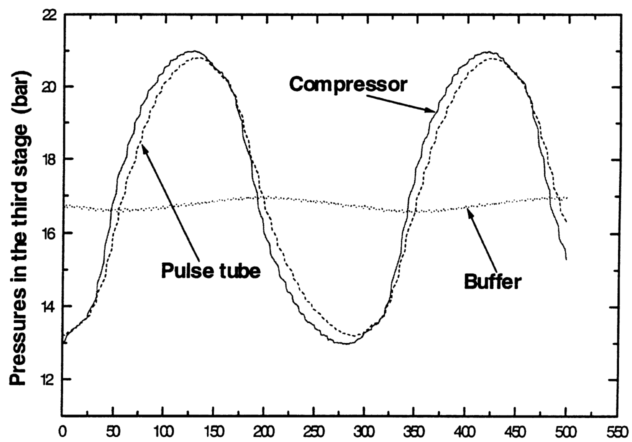
The cool down processes of the third-stage cold end are shown in Fig. 7. Using ^4He, the lowest temperature oscillates from 2.17 to 2.22 K. At the same settings, using ^3He, the lowest temperature oscillates from 1.82 to 1.91 K. After fine tuning of the valve settings, the lowest temperature oscillates from 1.72 to 1.83 K. The temperature variations are due to temperature difference of the gas going out and coming back the cold end. Compared with helium, the heat capacity of copper is very small, so it can easily follow the temperature variation of the gas.

Table 1
The sizes of the tubes and regenerators (in mm)

Stage	Tube			Regenerator		
	Inner diameter	Wall thickness	Length	Inner diameter	Wall thickness	Length
First	25	0.5	183	50	0.7	141
Second	18	0.5	203.5	29.7	0.6	130
Third	9	0.25	430	19.0	0.5	155



(a)



(b)

Fig. 6. Pressure oscillations in the inlet of regenerator, the third-stage tube and buffer using ^4He or ^3He. All the valves are optimized for the minimum average temperature for ^4He: (a) ^4He; (b) ^3He.

The relationship of cooling power $\dot{Q}_L$ versus refrigeration temperature T_L at the third stage is shown in Fig. 8. The cooling power at 4.2 K is 40 mW with ^4He and 65 mW with ^3He. The cooling power at 4.2 K is enhanced about 60% by using ^3He. Since the input power is the same, it means that the efficiency of pulse

Table 2
The average pressure and the pressure ratios[a]

	p_{av} (bar)	Pressure ratio			
		σ_c	σ_1	σ_2	σ_3
^3He	17.0	1.62	1.60	1.58	1.57
^4He	16.1	1.61	1.59	1.57	1.56

[a] p_{av}: average pressure; σ_c: pressure ratio at the inlet of regenerator; σ_1: pressure ratio in the first tube; σ_2: pressure ratio in the second tube; σ_3: pressure ratio in the third tube.

Table 3
The lowest temperatures at each stage cold end[a]

	The lowest temperature (K)		
	First stage	Second stage	Third stage
^4He	79.5	26.1	2.19
^3He			
1	80.6	27.6	1.87
2	80.9	29.2	1.78

[a] 1: valve settings are the same for ^3He and ^4He; 2: valve settings are optimized for ^3He.

tube refrigerator at 4.2 K is improved about 60% using ^3He.

Fig. 9 shows the temperature profile along the third-stage tube wall. Using ^3He, the temperature near the hot end increases. It is due to a small change in the DC-flow. It means that the valve settings should be changed a

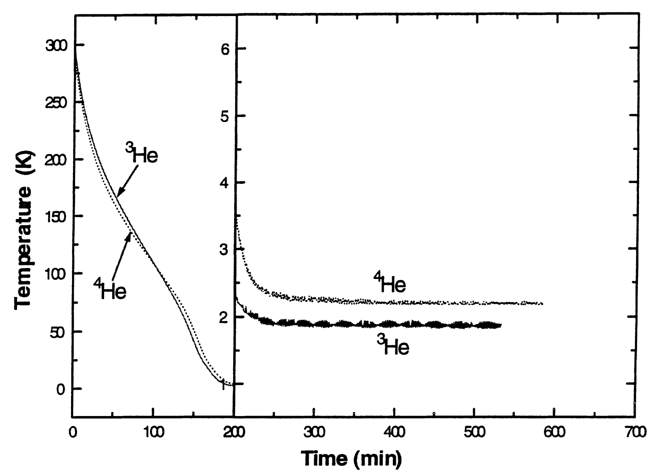


Fig. 7. The cool down process at the third stage. The openings of all the valves are the same for ^4He and ^3He.

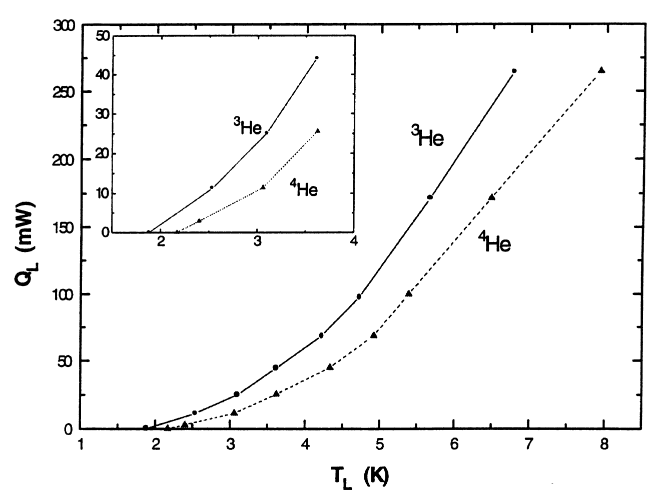


Fig. 8. The cooling power versus temperature. The openings of all the valves are the same for ^4He and ^3He.

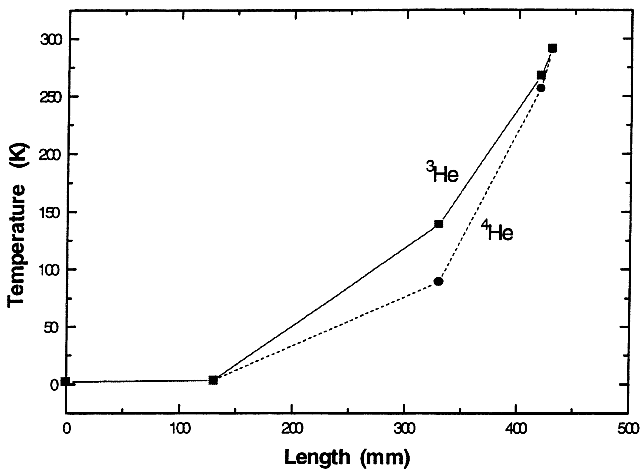


Fig. 9. The temperature profile along the third-stage tube wall. The openings of all the valves are the same for ^{4}He and ^{3}He.

little. So it is possible to get lower temperature after fine tuning the valve settings for ^{3}He.

5. Conclusions

Using ^{3}He, the temperature limit is below 2 K, and the efficiency at 4.2 K can be improved significantly. Replacing ^{4}He by ^{3}He, at the same valve settings and operating parameters, the minimum average temperature goes down from 2.19 to 1.87 K. The cooling power at 4.2 K is 40 mW with ^{4}He and 65 mW with ^{3}He. The cooling power at 4.2 K is enhanced about 60% using ^{3}He. Since the input power is the same, it means that the efficiency of a pulse tube refrigerator at 4.2 K is improved about 60% using ^{3}He. After fine tuning of the valves, a minimum average temperature of 1.78 K was obtained.

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