Thermoacoustic effect in a Gifford-McMahon refrigerator

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Abstract

We have studied the cooling power of a Gifford-McMahon refrigerator by varying the phase lead of pressure relative to displacement oscillations of working helium gas. The increase of the size of spherical regenerator materials results in the increase in the optimum phase lead, which represents the poor thermal contact in the regenerator filled with large particles.

Key words: thermoacoustics; regenerator; heat exchange process

1. Introduction

Experimental and theoretical studies so far revealed that thermoacoustic heat pumping effect originates from displacement ξ and pressure-induced entropy oscillations of gas parcels[1–3]; the gas absorbs entropy and hence heat from the passage wall at the cold end, and releases it at the hot end. Thus, the *bucket brigade* of the entropy produces the net entropy and heat flows. If the local equilibrium is always kept in the cross section of the gas passage, the gas entropy oscillates in phase with pressure P, and therefore, a maximum net heat flow occurs when a *traveling wave phase* [4,3,5,6] is achieved between P and ξ.

When the heat exchange process becomes irreversible[1,2], a thermal relaxation time τ[3] for thermal equilibrium over the cross section of the gas passage gives rise to a finite phase delay in the gas entropy relative to P. Here τ is given by $r_0^2/2\alpha$ and is closely related to thermal penetration depth δ as $\omega\tau = r_0^2/\delta^2$, where r_0 is the characteristic transverse length of the gas passage, and α is the thermal diffusivity of the gas. Under the existence of the phase delay due to the irreversibility, heat flow also occurs at a standing wave phase between P and ξ.

In a Gifford-McMahon refrigerator, one of representative thermoacoustic cooler, stacked spherical particles and screen meshes function as passage walls for oscillating helium gas. Recently, we reported the heat exchange process in a regenerator filled with 0.2 mm diameter spherical particles, by measuring the phase angle dependence of the cooling power[7]. In this work, we studied the regenerator performance filled with spherical particles of different diameters.

2. Experiments

We employed a second-stage GM refrigerator. The pressure and temperature oscillations of the helium gas at the second-stage expansion space are measured by using a pressure transducer and a Au(Fe)-Chromel thermocouple, respectively. The cooling power at a given temperature is measured by using the heat input fed through by a heater around the cold end. The hot end of the second regenerator monitored by a Si diode thermometer is kept at 85K throughout the experiments by using a temperature controller (Lake Shore 330).

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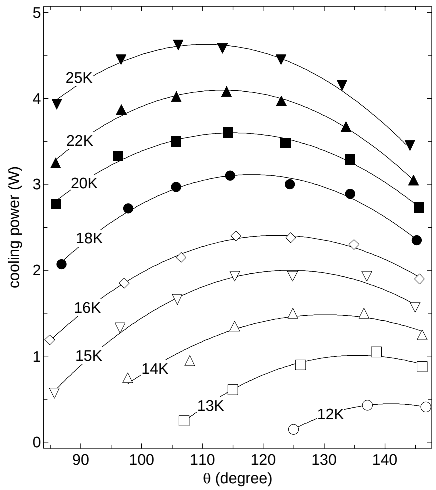

Fig. 1. The phase lead dependence of the cooling power in the present GM refrigerator.

3. Results

We operated the present GM refrigerator under the several phase angle θ between $P{=}p_0e^{i\omega t}$ and $\xi{=}\xi_0e^{i(\omega t-\theta)}$ with keeping their respective amplitudes almost independent of θ, and measured the temperature dependence of the cooling power. We plotted it as a function of θ in the temperature range from 12 to 27.5K in Fig. 1, when 0.2 mm diameter Pb particles are used as regenerator materials. The cooling power of the present GM refrigerator shows a broad maximum at about 100°, when the operating temperature is above about 20K. This assures almost isothermal heat exchange process within the regenerator in this temperature range. However, as the temperature decreases down to 12K, the optimum phase angle significantly increases and reaches 150°. The shift in the optimum phase angle represents that the heat exchange process in the regenerator filled with particles of 0.2 mm in diameter is no more isothermal, but irreversible at low temperatures below 20K. We had attributed this behavior to the strong decrease of thermal diffusivity α of helium gas with decreasing temperature[7].

Next we used the larger Pb particles with 0.5 mm and 1.5 mm diameter for the present GM refrigerator and similarly measured the cooling power. The optimum phase angle was determined from the obtained results. We plotted them as a function of the operating temperature in Fig. 3. As can be seen in the graph, the optimum phase angle decreases with decreasing temperature, regardless of the size of the particle. This also indicates the influence of the irreversibility due to the decrease of α on thermoacoustic heat pumping. Furthermore, we see that the use of larger spherical particles results in the increase in the optimum phase angle

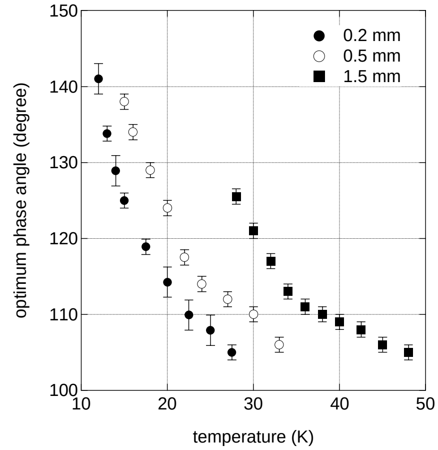

Fig. 2. The temperature dependence of the optimum phase angle for regenerators filled with 0.2, 0.5 and 1.5 mm diameter.

at a given temperature. This represents that the heat exchange process between the oscillating helium gas and the regenerator particles becomes more and more irreversible when the larger particles than 0.2 mm diameter are used. It should be noted here again that shift in the phase angle from 90°, corresponding to a traveling wave phase, is significant in low temperatures below 20K for 0.2 mm particles, because they are used as the ordinary regenerator particles; if smaller particles are used, the cooling power would be increased.

In summary, we measured the phase angle dependence of the cooling power of a GM refrigerator for regenerator spherical particles with different diameters. We found that the optimum phase angle increases when the size of the regenerator particles is increased. We conclude that choice of regenerator particles smaller than 0.2 mm in diameter should be effective to enhance the cooling power of the regenerative refrigerators working at about 10K.

References

[1] J. Wheatley, T. Hofler, G. W. Swift, A. Migliori, Phys. Rev. Lett. **50**, 499 (1983);J. Acoust. Soc. Am. **74**, 153 (1983); Am. J. Phys. **53**, 147, (1985).

[2] G. W. Swift, Phys. Today **48**, No. 7, 22 (1995); J. Acoust. Soc. Am. **84**, 1145, (1988).

[3] A. Tominaga, Cryogenics **35**, 427, (1995).

[4] P. H. Ceperley, J. Acoust. Soc. Am. **66**, 1508, (1979).

[5] T. Yazaki, T. Biwa, A. Tominaga, Appl. Phys. Lett. **80**, 157, (2002).

[6] Traveling and standing wave phases denote $\theta=$ 90° and 180°, respectively.

[7] S. Sunahara, T. Biwa, U. Mizutani, submitted to J. Appl. Phys.