Effects of DC Flow on a Three-Stage Stirling Pulse Tube Cryocooler Working at Liquid Helium Temperatures

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1. Motivation: DC Flow Studies on Liquid Helium Temperatures Pulse Tube Cryocooler.

A gas circulation called DC flow was found to exist in most double-inlet pulse tube coolers according to theoretical simulations. It was first brought up by Rott in the form of acoustic streaming. Gedeon developed it to DC flow, and formulated its mass flow and heat loss as followed,

$$M' = \frac{1}{2} Re[\tilde{\rho}_1 U_1] + \rho_m U_{2,0}$$

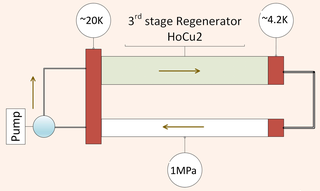
$$\frac{\dot{Q}_{loss}}{\dot{H}_{2,reg}} \sim \frac{\gamma}{\gamma-1}\frac{(T_0-T_C)}{T_0}\frac{\dot{E}_2}{\dot{H}_{2,reg}} \sim \frac{\gamma}{\gamma-1}\frac{(T_0-T_C)}{T_0}\frac{\dot{Q}_{C,gross}}{\dot{H}_{2,reg}}$$

where ρ and U are the density and volume flow rate, $\dot{E}_2$ is the usual acoustic power passing through the regenerator, $\dot{Q}_{C,gross}$ is the gross cooling power.

Researchers are trying to decrease loss in regenerator and increase expansion efficiency in pulse tube. Some researchers found a negative DC flow dissipating the enthalpy flow at the hot end of pulse tube and increasing cooling capacity of the pulse tube. Utilizing DC flow may be an effective method to improve performance of Stirling Pulse Tube Cryocoolers (SPTC) working at liquid helium temperatures. However, there has not been research on it.

2. Theoretical Calculation of DC Flow Effects on Performance of 4K SPTC

Fig.1 is the diagram of the model build by Sage.5 calculating DC flow and its effects in liquid helium temperature SPTC. A pump was used to induce a negative DC flow from pulse tube to regenerator at the hot end.



Third stage:
Frequency: 30Hz
Pressure: 1MPa
Pressure ratio: 1.46
T_H: 20K
Packing metierial:HoCu2

Fig.1 Sage model of DC flow in 3rd-stage of SPTC

⋆ DC mass flow rate check

Table.1 DC mass flow rate in SPTC comparing with Wangchao's in GMPTC[1]

	M1 (g/s)	M2(g/s)	M3(g/s)	M_{DC} (g/s)
4K SPTC	1.50	1.71	0.416	2.0×10^{-4}
4K GMPTC	6.823	8.743	0.119	6.96×10^{-3}

M1, M2, M3: time-averaged mass flow rates at the outlet of compressor, cold and hot end of the pulse tube, respectively; M_{DC}: average DC flow rate in one cycle.

From Table.1: M_{DC} in 4K SPTC (around 2×10^{-4}g/s) is around 1/10 of that in 4K GMPTC(1×10^{-3}g/s~7×10^{-3}g/s)[1], and M1, M2 in 4K SPTC are both around 1/10 of that in 4K GMPTC. The DC mass flow rate is in a reasonable range to effect the 4K SPTC.

⋆ DC flow rate effect on the cooling capacity

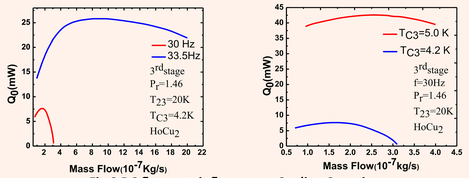


Fig.2 DC flow rate influence on Cooling Capacity

The cooling capacity with DC flow reached 26mW@4.2K, maximum 220% more than without DC flow. Fig.2 shows: a) there is an optimum DC mass flow related to operating frequency; b) the optimum DC mass flow grows when the temperature of the cold end increase.

⋆ Influence on phase angle and mass flow at the cold end

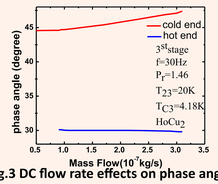


Fig.3 DC flow rate effects on phase angle

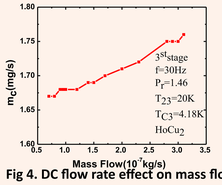


Fig 4. DC flow rate effect on mass flow at cold end

Fig.3 and Fig.4 shows: DC flow is not only an enthalpy flow in regenerator and pulse tube, but also affects the phase differences and the time-averaged mass flow at the cold end, which should be considered in DC flow affecting mechanism studies.

References:

1. Effects of DC gas flow on performance of two-stage 4K pulse tube coolers: C. Wang et al.

3. Experiments of Third Stage Pulse Tube Cryocooler Introduced DC flow

Liquid helium temperature SPTC uses a low-temperature inertance tube and reservoir instead of double-inlet valve as its phase shifter.

Small-diameter tubes were added between the inlet of regenerator and the hot end of pulse tube in the 3rd stage to induce DC flow.

The SPTC operated at conditions showed in Table.2. Pressure and temperature was measured at position as Fig.5 shows.

Table.2 Experiments operating conditions

	1st Stage	2nd Stage	3rd Stage
Compressors	CFIC 175		Leybold Polar
Regenerators	90-300K	20-90K	4-20K
	400# SS	500# SS, 635#SS	HoCu2
Frequency	40.5 Hz		28 Hz
Initial Pressure	2.1 MPa		1.3 MPa
Input Power	880 W		90W

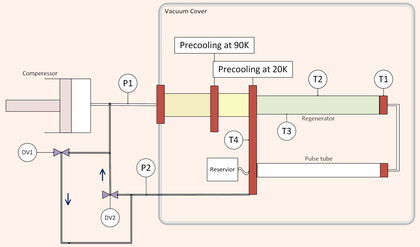


Fig.5 Diagram of 3rd-stage cryocooler with DC flow section

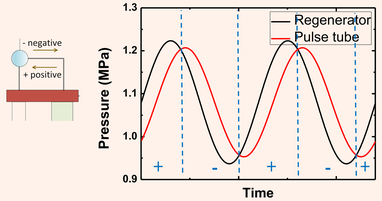


Fig.6 Pressure wave measured and DC flow direction

As showed in Fig.6, double-inlet valve (DV) was used for direction controlling. DC flow was driven by pressure difference.

Positive direction (+) is from the inlet of regenerator to the hot end of the pulse tube, and otherwise is the negative direction (-).

4. Preliminary Experiment Results of No Load Cold End Temperature

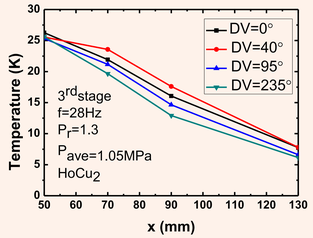


Fig 7. Temperature along 3rd stage regenerator

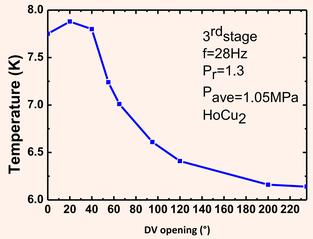


Fig 8. Cooling temperature–DV openings relation schema

In the experiments, as we open the DV, the temperature of the 3rd-stage react immediately.

Fig.7 indicates the temperature near the hot end of the 3rd-stage regenerator is higher when DC flow happening, but the temperature at the cold end is lower.

The no load cold end temperature with maximum DV opening reached 6.19K, 1.56K lower than without DC flow(7.75K) as showed in Fig.8.

5. Conclusions

⋆ Effects of DC flow introduced to a SPTC working at liquid helium temperatures were theoretically analyzed and experimentally tested.

⋆ Calculation results showed that a negative DC flow distinctly increased cooling capacity by 220%, maximum 26mW@4.2K.

⋆ Preliminary experiment results proved a well used DC flow in liquid helium temperature SPTC can lower the no load cold end temperature from 7.75K to 6.19K.

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