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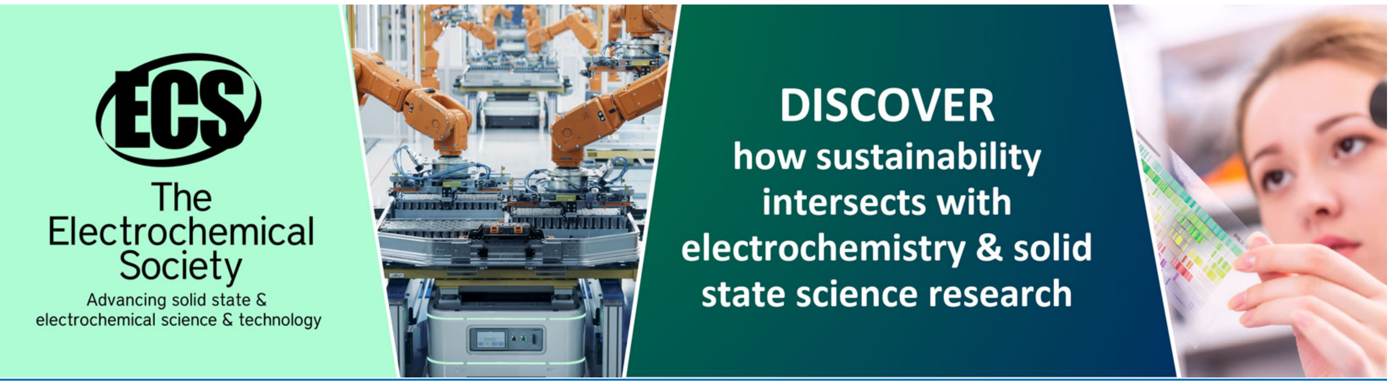

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A study on the interstage cooling capacity shifting of Stirling/pulse tube hybrid cooler based on an idealized model

Y X Guo[1,2], Y J Chao[1,2], B Wang[1,2], Z H Gan[1,2], and S Z Li[1,2]

[1] Institute of Refrigeration and Cryogenics, Zhejiang University
Hangzhou 310027, P.R. China
[2] Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, P.R. China

Email: gan_zhihua@zju.edu.cn

Abstract. A Stirling/pulse tube hybrid cooler is comprised of a Stirling cooler as the first stage and a pulse tube cooler as the second stage. Such a cooler is able to shift cooling capacity between stages by adjusting the phase of the displacer. Therefore, this hybrid cooler can adapt itself to time-varying heat loads at different temperatures. In this paper, an idealized model of the hybrid cooler is introduced, which is followed by a qualitative analysis on the mechanism of the hybrid cooler's ability of shifting cooling capacity between stages. It is found that such an ability of the hybrid cooler is conditional and the condition that enables this ability of the hybrid cooler is proposed. The analysis result is compared with numerical result from a Sage model and a good agreement is achieved. The understanding of the hybrid cooler's mechanism of inter-stage cooling capacity shifting would be beneficial to its proper design and optimization.

1. Introduction

Space detectors demand a low temperature environment to function properly. In general, stored-cryogen systems, such as liquid helium and liquid hydrogen storage tanks, are used to cool different types of space detectors working at different low temperatures. However, such systems have a limited lifetime due to the limited amount of stored cryogen, and their weight and size are excessively large. Nowadays, closed cycle cryocoolers, such as the Stirling cooler and the pulse tube cooler, are taking the place of the traditional stored-cryogen systems. Cryocoolers feature small weight and size, and can have a much longer lifetime than stored-cryogen systems. Yet, typical cryocoolers are unable to provide time-varying cooling capacities at different temperatures simultaneously, and cryocoolers of different low temperatures are needed to satisfy various types of space detectors. Therefore, the application of cryocoolers is still limited in space detector cooling.

A Stirling/pulse tube hybrid cooler, comprised of a Stirling cooler as the first stage, and a pulse tube cooler as the second stage, appears to be a more competitive candidate than the typical cryocoolers in space detector cooling. Keeping the input power constant, the cooling capacities of both stages can be shifted by adjusting the phase of the displacer in the first stage. Therefore, with a proper adjustment of the input power and the phase of the displacer, a Stirling/pulse tube hybrid cooler can overcome the shortage of typical cryocoolers by providing time-varying cooling capacities at different temperatures at the same time.

The Stirling/pulse tube hybrid cooler was first proposed in 1999. [1] Since then, several prototypes have been fabricated and tested. In 2003, a Stirling/pulse tube hybrid cooler's ability of shifting cooling capacity between stages is verified by an experiment on a RSP2 cooler.[2] The

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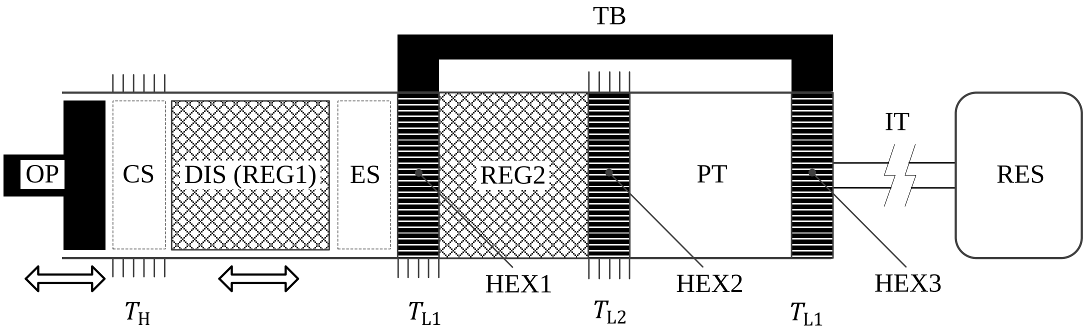
experiment shows that, as the phase difference between the power piston and the displacer increases, the cooling capacity of the first stage increases while the second stage decreases. Thereafter, more prototypes of the Stirling/pulse tube hybrid cooler have been fabricated and optimized, and their performances are significantly improved.[3,4]

Previous studies on the Stirling/pulse tube hybrid cooler focus on its performance enhancement and commercialization, and the study on the most distinguished feature of this cooler, the ability of inter-stage cooling capacity shifting, is very limited. In fact, the mechanism of this feature is of great importance to the proper design of a Stirling/pulse tube hybrid cooler. By introducing an idealized model of a Stirling/pulse tube hybrid cooler, this paper studies the mechanism of inter-stage cooling capacity shifting of a Stirling/pulse tube hybrid cooler qualitatively, based on which, the condition that enables this feature is proposed.

2. The idealized model of a Stirling/pulse tube hybrid cooler

2.1. Modeling object and assumptions

Figure 1 is a diagram of a typical Stirling/pulse tube hybrid cooler with cold inertance tube, and it is the object of the modelling. The regenerative material, such as the woven screen matrix, is filled in the displacer. Therefore, the displacer also works as the first stage regenerator. The movement of the displacer is controlled by a motor, which is omitted in the diagram for simplicity. The second stage is a typical pulse tube cooler. A thermal bridge connects the heat exchanger 1 and 3, keeping them the same temperature.



CS: compression space DIS: displacer ES: expansion space HEX1: heat exchanger 1
HEX2: heat exchanger 2 HEX3: heat exchanger 3 IT: inertance tube OP: piston
PT: pulse tube REG1: regenerator of the 1st stage REG2: regenerator of the 2nd stage
RES: reservoir TB: thermal bridge

Figure 1. A diagram of a Stirling/pulse tube hybrid cooler with cold inertance tube.

The idealized model is established upon several assumptions. Though these assumptions may cause a deviation from reality, they are helpful to reveal the thermodynamic principles of a Stirling/pulse tube hybrid cooler.

(1) Both of the two regenerators are ideal. The regenerative material is frictionless and there is a perfect heat transfer between the regenerative material and the working fluid.
(2) The temperature of the regenerator is considered as the average of the temperatures at both ends.
(3) There is not any irreversible loss inside any component.
(4) The pressure within the cooler, except the inertance tube and the reservoir, is uniform.
(5) All the clearance seals are perfect.
(6) The piston, the displacer, the pressure and the mass flow oscillate in harmonic manner. The displacer phase is the reference phase.
(7) The working fluid is an ideal gas.

2.2. The phasor analysis

According to the classic theory of the pulse tube cooler, at the hot end of the second stage regenerator, the phase of the mass flow rate leads the phase of the pressure, and the second stage of the Stirling/pulse tube hybrid cooler can be considered as an acoustic load to the first stage. The equivalent impedance of this acoustic load is given by

$$\boldsymbol{Z_2} = \frac{\boldsymbol{p}}{\dot{\boldsymbol{m}}_{\boldsymbol{2}}} = |Z_2|\mathrm{e}^{\mathrm{j}\theta_2} \tag{1}$$

with $\boldsymbol{p}$ the pressure phasor, $\dot{\boldsymbol{m}}_{\boldsymbol{2}}$ the mass flow rate phasor at the hot end of the second stage regenerator, $|Z_2|$ and θ_2 the amplitude and the phase angle respectively of $\boldsymbol{Z_2}$.

According to assumption (8), the mass of the working fluid within the first stage is given by

$$m_1 = \frac{p}{R_\mathrm{g}}\left(\frac{V_\mathrm{C}}{T_\mathrm{H}} + \frac{V_\mathrm{R1}}{T_\mathrm{R1}} + \frac{V_\mathrm{E}}{T_\mathrm{L1}}\right). \tag{2}$$

with p the pressure, V_C and V_E the volume of the compression space and the expansion space respectively, V_R1 the void volume of the first stage regenerator, T_R1 the temperature of the first stage regenerator, R_g the specific gas constant, T_H the ambient temperature and T_L1 the cooling temperature of the first stage. With some mathematical deduction, equation (2) can be rewritten with phasors, which is

$$\boldsymbol{m_1} = B_1\boldsymbol{p} - B_2\boldsymbol{x_\mathrm{D}} - B_3\boldsymbol{x_\mathrm{C}} \tag{3}$$

in which

$$B_1 = \frac{1}{R_\mathrm{g}}\left(\frac{V_\mathrm{Cm}}{T_\mathrm{H}} + \frac{2V_\mathrm{R1}}{T_\mathrm{H} + T_\mathrm{L1}} + \frac{V_\mathrm{Em}}{T_\mathrm{L1}}\right) \tag{4}$$

$$B_2 = \frac{p_\mathrm{m}A_D}{R_\mathrm{g}}\left(\frac{1}{T_\mathrm{L1}} - \frac{1}{T_\mathrm{H}}\right) \tag{5}$$

$$B_3 = \frac{p_\mathrm{m}A_\mathrm{C}}{R_\mathrm{g}T_\mathrm{H}}. \tag{6}$$

with p_m the charge pressure, A_C and A_D the surface area of the piston and the displacer respectively, $\boldsymbol{x_\mathrm{D}}$ and $\boldsymbol{x_\mathrm{C}}$ the displacement phasor of the displacer and the piston respectively, V_Cm and V_Em the average volume of the compression space and the expansion space respectively, $\boldsymbol{m_1}$ the phasor form of m_1. Notice that the mass within the first stage is related with the mass flow rate at the hot end of the second stage regenerator by

$$\frac{\mathrm{d}m_1}{\mathrm{d}t} = -\dot{m}_2 \tag{7}$$

with $\dot{m}_2$ the mass flow rate at the hot end of the second stage regenerator. Combing with equation (1), equation (7) can be rewritten as

$$\boldsymbol{m_1} = -\frac{\dot{\boldsymbol{m}}_{\boldsymbol{2}}}{\mathrm{j}\omega} = -\frac{1}{\mathrm{j}\omega}\frac{\boldsymbol{p}}{\boldsymbol{Z_2}}. \tag{8}$$

with ω the angular frequency and j the imaginary unit. Combining equation (3) and (8) gives

$$\boldsymbol{p} = \frac{\boldsymbol{p_\mathrm{ST}}}{\boldsymbol{Y}} = \frac{B_2}{B_1}\frac{\boldsymbol{x_\mathrm{D}}}{\boldsymbol{Y}} + \frac{B_3}{B_1}\frac{\boldsymbol{x_\mathrm{C}}}{\boldsymbol{Y}} \tag{9}$$

in which

$$\boldsymbol{Y} = 1 + \frac{-\mathrm{j}}{\boldsymbol{Z_2}}\cdot\frac{1}{\omega B_1} = 1 + \frac{1}{\omega B_1|Z_2|}\mathrm{e}^{-\mathrm{j}\left(\theta_2 + \frac{\pi}{2}\right)}. \tag{10}$$

Equation (9) describes the relation between the movements of the two moving parts and the pressure, which is critical in describing the thermodynamic characteristics of the Stirling/pulse tube hybrid cooler. Figure 2 shows the typical phasor diagram of a Stirling/pulse tube hybrid cooler obtained by the equations above.

2.3. The thermodynamic analysis

If the expansion space and the heat exchanger 1 are included in a control volume, named CV1, the application of the first and second law of thermodynamics on CV1 would give

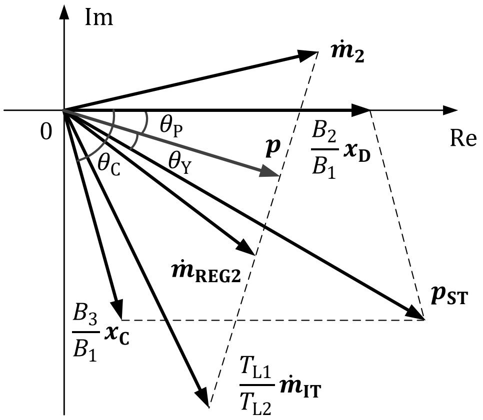


Figure 2. A typical phasor diagram of the Stirling/pulse tube hybrid cooler.

$$\langle W_{DL}\rangle = \langle Q_{pre}\rangle + \langle Q_{L1}\rangle \tag{11}$$

$$\frac{\langle Q_{pre}\rangle + \langle Q_{L1}\rangle}{T_{L1}} + \langle S_{R1}\rangle = \langle S_{R2}\rangle. \tag{12}$$

with $\langle W_{DL}\rangle$ the expansion work by CV1 on the displacer, $\langle Q_{pre}\rangle$ the precooling capacity needed by the second stage, $\langle Q_{L1}\rangle$ the cooling capacity of the first stage, $\langle S_{R1}\rangle$ and $\langle S_{R2}\rangle$ the entropy flow in the first stage and the second stage, respectively. If the compression space is defined as another control volume, named CV2, the application of the first and second law of thermodynamics on CV2 would give

$$\langle W_{DH}\rangle + \langle W_C\rangle = \langle Q_H\rangle \tag{13}$$

$$\frac{\langle Q_H\rangle}{T_H} = -\langle S_{R1}\rangle. \tag{14}$$

with $\langle W_{DH}\rangle$ the compression work by the displacer on CV2, $\langle W_C\rangle$ the compression work by the piston on CV2, $\langle Q_H\rangle$ the dissipated heat at T_H.Also, the classic theory of pulse tube cooler gives

$$\langle Q_{L2}\rangle = \langle Q_{pre}\rangle = \langle PV_{R2L}\rangle = -T_{L2}\langle S_{R2}\rangle \tag{15}$$

$$\langle PV_{R2H}\rangle = -T_{L1}\langle S_{R2}\rangle = \frac{T_{L1}}{T_{L2}}\langle PV_{R2L}\rangle. \tag{16}$$

with $\langle Q_{L2}\rangle$ the cooling capacity of the second stage, $\langle PV_{R2L}\rangle$ and $\langle PV_{R2H}\rangle$ the acoustic work at the cold end and the hot end of the second stage regenerator.

Summarizing the above results would give the cooling capacity of both stages, which is

$$\langle Q_{L1}\rangle = \frac{1}{4}\frac{\omega V_D}{|Y|}|p_{ST}|\sin[-(\theta_{PST}-\theta_Y)] - \frac{1}{2}\frac{R_g T_{L2}\cos\theta_2}{p_m|Y|^2|Z_2|}|p_{ST}|^2 \tag{17}$$

$$\langle Q_{L2}\rangle = \frac{1}{2}\frac{R_g T_{L2}\cos\theta_2}{p_m|Y|^2|Z_2|}|p_{ST}|^2. \tag{18}$$

with V_D the swept volume of the displacer, $|Y|$ and θ_Y the amplitude and the phase angle of the phasor $\boldsymbol{Y}$ respectively, $|p_{ST}|$ and θ_{PST} the amplitude and the phase angle of the phasor $\boldsymbol{p}_{ST}$.

3. The mechanism of inter-stage cooling capacity shifting

With the expression of the cooling capacity of both stages, the mechanism of inter-stage cooling capacity shifting can be analysed. This section will study the effect of the phase difference between the piston and the displacer on the cooling capacity of both stages.

It can be inferred from Figure 2 that the phase difference between the piston and the displacer is actually the phase angle of the phasor $\boldsymbol{x}_C$, or θ_C. Equation (17) shows that $\langle Q_{L1}\rangle$ is positively associated with $|p_{ST}|\sin[-(\theta_{PST}-\theta_Y)]$ and negatively associated with $|p_{ST}|$, and equation (18) shows that $\langle Q_{L2}\rangle$ is positively associated with $|p_{ST}|$. Figure 3 shows that in process A-B, as θ_C

increases, $|p_{ST}|\sin[-(\theta_{PST}-\theta_Y)]$ increases and $|p_{ST}|$ decreases, therefore, $\langle Q_{L1}\rangle$ increases and $\langle Q_{L2}\rangle$ decreases. However, in process B-C, as θ_C increases, both $|p_{ST}|\sin[-(\theta_{PST}-\theta_Y)]$ and $|p_{ST}|$ decreases, therefore, $\langle Q_{L1}\rangle$ may increase or decrease and $\langle Q_{L2}\rangle$ decreases.

Notice that in Figure 3, B is the case when the phasor $\boldsymbol{x}_C$ is perpendicular to the phasor $\boldsymbol{Y}$, and it is the critical point for the feature of inter-stage cooling capacity shifting. Therefore, this feature of a Stirling/pulse tube hybrid cooler is conditional, and it can be proposed that the condition that a Stirling/pulse tube hybrid cooler is able to shift cooling capacity between stages is

$$|\theta_C| < |\theta_{crit}| = -\left(\theta_Y - \frac{\pi}{2}\right) \tag{19}$$

This theory can be verified by the cooling capacity vs θ_C curve from a Stirling/pulse tube hybrid cooler Sage model, as shown in Figure 4. The result is calculated with a charge pressure of 1.6 MPa and a frequency of 38 Hz. The cooling temperature of the first and the second stages is 60 K and 20 K, respectively. $|\theta_{crit}|$ is calculated and is equal to 106 deg, which is very close to 110 deg, the actual critical value of $|\theta_C|$ obtained from the curve.

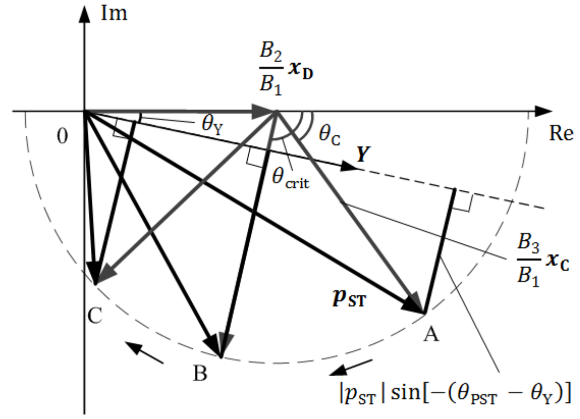


Figure 3. A phasor diagram of the Stirling/pulse tube hybrid cooler with various θ_C.

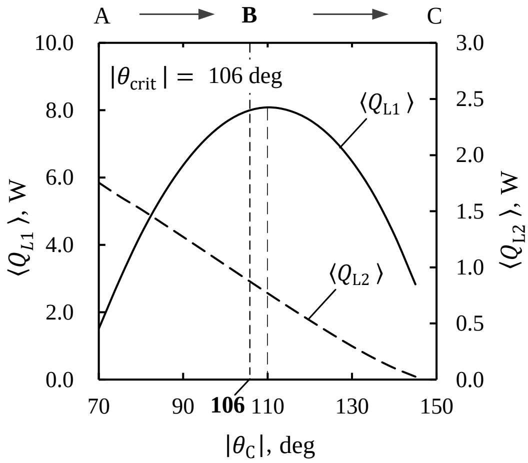


Figure 4. Cooling capacity vs θ_C curve of a Stirling/pulse tube hybrid cooler Sage model

4. Conclusion

A Stirling/pulse tube hybrid cooler features the ability of providing time-varying cooling capacity at different temperatures simultaneously. By establishing an idealized model, the mechanism of such a feature is revealed. It is found that such a feature of a Stirling/pulse tube hybrid cooler is conditional, and the condition that enables this feature is proposed. This theory is verified by a Sage model and will benefit the proper design of a Stirling/pulse tube hybrid cooler.

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Acknowledgments

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