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Effect of coupling position on a looped three-stage thermoacoustically-driven pulse tube cryocooler

Jingyuan Xu [a, b], Jianying Hu [a, **], Limin Zhang [a], Wei Dai [a], Ercang Luo [a, *]

[a] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[b] Chinese Academy of Sciences, Beijing 100190, China

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ABSTRACT

A looped three-stage thermoacoustically-driven cryocooler system is introduced. Based on classic thermoacoustic theory, simulations are performed to investigate the effects of three representative coupling positions (inlet, middle, and outlet) of the resonance tube. The total exergy efficiency is found to depend on the dimensions of the resonance tube, demonstrating the importance of this parameter. For the same resonance tube length, the highest exergy efficiency of 16.3% is achieved for the outlet coupling position, whereas the middle and inlet coupling positions only achieved highest exergy efficiencies of 9% and 14.93%, respectively. The distribution of the phase difference, acoustic power, and exergy loss ratios of the main components are then presented to clarify the coupling mechanism. The results show that better phase distribution in the regenerator and less exergy loss in the resonance tube contribute significantly to the superior performance of the outlet coupling position.

1. Introduction

THE (Thermoacoustic heat engines) and PTC (pulse tube coolers) have attractive application potential because of their mechanical simplicity and high reliability. Using the acoustic power spontaneously generated by the THE to drive the PTC results in a so-called thermoacoustically-driven cooling system with no moving mechanical components. The first thermoacoustically-driven system, developed in 1990, was capable of reaching a temperature of 90 K [1]. Since then, many efforts have been made to improve the performance of such systems and some important advances have been achieved [2–5]. However, most of the reported thermoacoustically-driven systems have two drawbacks: one is their non-compact size and shape, which incorporates a long and large-diameter standing-wave resonance tube; the other is substantial dissipation of acoustic power in the resonance tube, leading to low efficiency. In 2010, De Blok developed a four-stage looped traveling-wave THE, providing a possible solution to the problem [6]. Owing to its compact size and potential high efficiency, the looped multi-stage thermoacoustic system has been a focus of research ever since [7–9]. Fig. 1 shows a schematic of the three-stage system investigated in the present study. Following a theoretical analysis of its performance and mechanism, our research group conducted preliminary experiments on the looped three-stage cooling system and obtained a total exergy efficiency of 3.5% [10]. Later, an improved version achieved a total exergy efficiency of approximately 8% and a cooling capacity of more than 1 kW at 130 K [11], presenting exciting prospects for applications such as natural gas liquefaction and recondensation.

In Fig. 1, the acoustic power generated by the engine flows from one end of the resonance tube to the other. Simply considered, the PTC may be connected to any location of the resonance tube; however, owing to the strong acoustic characteristics of the system, the connection position affects the acoustic field both up- and downstream. The manner in which the coupling position affects the system performance remains a subject for further study. The present paper numerically investigates three representative coupling positions, as shown in Fig. 1: the inlet of the resonance tube (IR-coupling), the middle of the resonance tube (MR-coupling), and the outlet of the resonance tube (OR-coupling), which are all defined according to the direction of the acoustic power flow. The simulations firstly evaluate the effect of the dimensions of the resonance tube on system performance. Using the optimal dimensions of the resonance tube for each coupling position, the phase difference,

* Corresponding author. Tel./fax: +86 10 82543750.
** Corresponding author. Tel./fax: +86 10 82543733.
E-mail addresses: jyhu@mail.ipc.ac.cn (J. Hu), Ecluo@mail.ipc.ac.cn (E. Luo).

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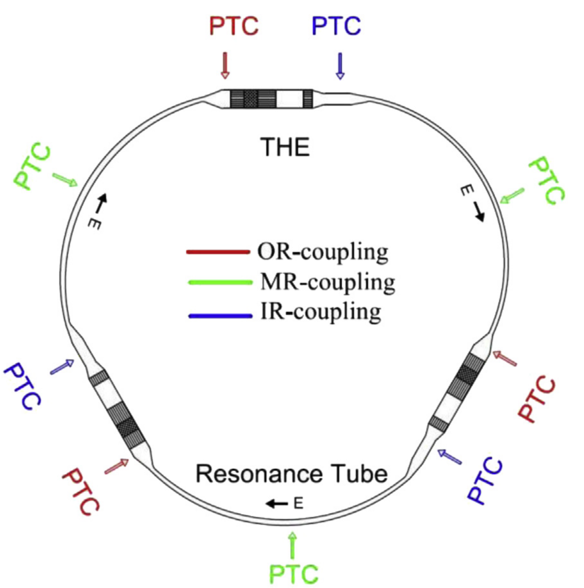

Fig. 1. Schematic view of the acoustically resonant cooling system.

acoustic power, and exergy loss are then investigated to clarify the performance differences. Finally, conclusions are given.

2. Numerical simulation and analysis

2.1. Looped three-stage thermoacoustically-driven cryocooler

Although there is no theoretical limit on the number of subunits, a three-stage system was chosen as a typical example here, based on a compromise between considerations of the total power scale and the efforts required in the construction of the experiments. As mentioned above, we have carried out several theoretical and experimental studies of the three-stage system and have achieved some progress, which inspired us to further investigate such systems. Fig. 1 shows the system configuration with three different PTC connection positions. Fig. 2 presents an enlarged view of one of the three identical subunits, which includes a THE and a PTC. The THE includes two water-cooled ambient heat exchangers, a regenerator, a heater block, a thermal buffer tube, and a resonance tube. The PTC includes an ambient heat exchanger, a regenerator, a cold head, a pulse tube, flow straighteners, and a phase shifter (comprising an inertance tube and a gas reservoir). Dimensions of the THE and PTC are presented in Table 1.

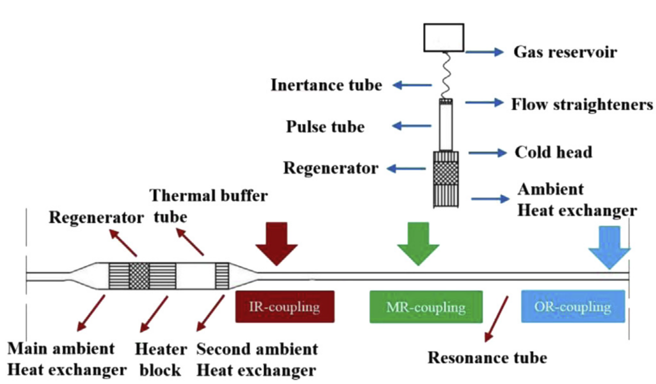

Fig. 2. Enlarged view of one subunit of the acoustically resonant cooling system.

Table 1
Geometrical parameters of the THE and PTC.

THE	Regenerator	80 × 60 (150#)
	Thermal buffer tube	80 × 120
	Heater block	80 × 80
PTC	Regenerator	75 × 70 (300#)
	Pulse tube	37 × 150
	Cold head	75 × 30

Dimensions: inner diameter × length (all in millimeters).

2.2. Numerical model

The simulations were conducted using DeltaEC [12], which is thermoacoustic software that is based on classical thermoacoustic theory [13]. The software provides a series of modules, such as DUCT, HX, STKSCREEN, and STKSCREEN, for the simulation of different thermoacoustic components and systems. Some parameters, such as the gas temperature, pressure amplitude, and phase, are set and initialized by the users. A shooting method is introduced in the software to satisfy the boundary conditions set by the user. A turbulence algorithm is employed for the resonance tube [12]. According to thermoacoustic theory, the momentum, continuity, and energy equations are [13]:

$$\frac{dp_1}{dx} = -\frac{i\omega\rho_m}{1-f_\nu}\frac{U_1}{A} \tag{1}$$

$$\frac{dU_1}{dx} = -\frac{i\omega A}{\gamma p_m}\left[1+\frac{(\gamma-1)f_\kappa}{1+\xi}\right]p_1 + \frac{(f_\kappa - f_\nu)}{(1-f_\nu)(1-\sigma)(1+\xi)}\frac{U_1}{T_m}\frac{dT_m}{dx} \tag{2}$$

$$\frac{d\dot{H}_2}{dx} = \dot{q} \tag{3}$$

$$\begin{aligned}\dot{H}_2 = {} & \frac{1}{2}\mathrm{Re}\left[p_1\tilde{U}_1\left(1-\frac{f_\kappa-\tilde{f}_\nu}{(1-f_\nu)(1-\sigma)(1+\xi)}\right)\right] \\ & + \frac{\rho_m c_p|U_1|^2}{2A\omega(1-\sigma)|1-f_\nu|^2}\frac{dT_m}{dx}\mathrm{Im}\left[\tilde{f}_\nu + \frac{\left(\tilde{f}_\kappa-\tilde{f}_\nu\right)(1+\xi f_\nu/f_\kappa)}{(1+\xi)(1-\sigma)}\right] \\ & - (Ak + A_s k_s)\frac{dT_m}{dx}\end{aligned} \tag{4}$$

whereP_1, U_1, H_2, q and dT_m/dx are the pressure wave, volume flow rate, total energy flow, heat absorbed or released from/to the heat sinks, and mean temperature gradient, respectively; ω,A,γ,P_m,ρ_m are the angular frequency, cross-sectional area, specific heat ratio, average pressure, and density, respectively; and f_ν f_k are viscosity and thermal functions, respectively.

In the calculation, the mean pressure is set as 6 MPa and the heating temperature as 923 K. Generally, the system performance is reflected by two important parameters: the cooling power and total exergy efficiency. To appropriately compare the three coupling positions, the cooling power is set as 750 W at a cooling temperature of 110 K and the total exergy efficiency, defined by

$$\eta_{ex} = \frac{Q_c\left(\frac{T_0}{T_c}-1\right)}{Q_h\left(1-\frac{T_0}{T_h}\right)}, \tag{5}$$