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Experimental study of a gas clearance phase regulation mechanism for a pneumatically-driven split-Stirling-cycle cryocooler

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ABSTRACT

A concept for a new type of pneumatically-driven split-Stirling-cycle cryocooler with clearance-phase-adjustor has recently been described, along with a theoretical model for simulating its operation and performance (Zhang, in preparation, 2003). This paper describes experiments that have been carried out to systematically validate the model, and to characterize the performance of the cryocooler in several key areas. These include: oscillatory flow within the cooler, correlation between the compression piston and the free displacer, the impact of the cold-tip temperature and phase-adjusting clearance gaps on cooler performance. The minimum cold-tip temperature is used as primary gauge of refrigeration performance. Real-time measurements of gas pressures in different chambers, displacements of the compression piston and the free displacer have been performed to reveal the internal physical processes. The experimental results are found to be in good agreement with the simulated ones.

1. Experimental apparatus

An experimental apparatus has been constructed to investigate the performance and theoretical modeling of a pneumatically-driven split-Stirling-cycle cryocooler with clearance-phase-adjustor [1], whose simplified experimental sketch is shown in Fig. 1. The important components are illustrated in detail. The experimental apparatus is comprised of two systems: refrigeration and measurement systems.

The refrigeration system (pneumatically-driven split-Stirling-cycle cryocooler with clearance-phase-adjustor) includes a linear compressor, a connecting hose and a pneumatically-driven gas expander. The gas expander consists of a hot chamber, a displacer/regenerator, a cold chamber, a cold end exchanger and a spring chamber. The refrigeration system was constructed at Cryogenic Laboratory in Shanghai Institute of Technical Physics (SITP). The main parameters are listed in Table 1.

Different phase-adjusting clearance gaps can be achieved by installing different diameter phase-adjusting parts in spring chamber. For testing, the expander cold finger is located in a cylindrical vacuum vessel, in which a low pressure of $1 \times 10^{-4} \sim 1 \times 10^{-5}$ Pa is maintained for thermal isolation from the environment. The thermal isolation is improved by the installation of radiation screens composed of 12 layers of aluminized polyester films. Some grams of dry activated carbon are placed in vacuum container to absorb vapor in residual gas.

The measurement system includes devices to measure pressure, temperature, net cooling power and displacement. It also includes measurement devices for input current, voltage and power of the linear compressor. As shown in Fig. 1, dynamic pressures in the compressor, the hot chamber and the upper spring sub-chamber were measured with three piezoelectric transducers and charge amplifiers. The displacements of the compression piston and the free displacer were measured with a linear variable-differential position transformer and an electric eddy displacement transducer, respectively. These are used to investigate the volume change generated by the drive mechanism. The cold-tip temperature was measured with a platinum resistance thermometer. A computer data-acquisition system is used for the real-time measurements of the dynamic temperatures, displacements and pressures. A resistor of 116 Ω attached to the cold end copper block is utilized to supply heating power to the cold end heat exchanger. When the temperature of the cold end block is stabilized, the heating power provided by the heater is equivalent to the net cooling power of the cooler. The pressure–volume (p–V) of the linear compressor and power supply parameters can be recorded with a digital oscilloscope.

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Nomenclature

D	velocity influencing coefficient
E	energy
f	frequency
p	pressure
Q	heat energy
S	displacement influencing coefficient
u	velocity
V	volume
x	displacement
Greek letter	
τ	time
Subscripts	
C	compressor piston vibration system
d	displacer vibration system
dd	displacer influencing on itself
dp	displacer influencing on compressor piston
in	inlet
n	natural vibration
out	output
pd	compressor piston influencing on displacer
pp	compressor piston influencing on itself
Superscripts	
-	mean value
.	variation with time

2. Results and discussions

Several series of experiments have been carried out with the experimental apparatus described above. These include:

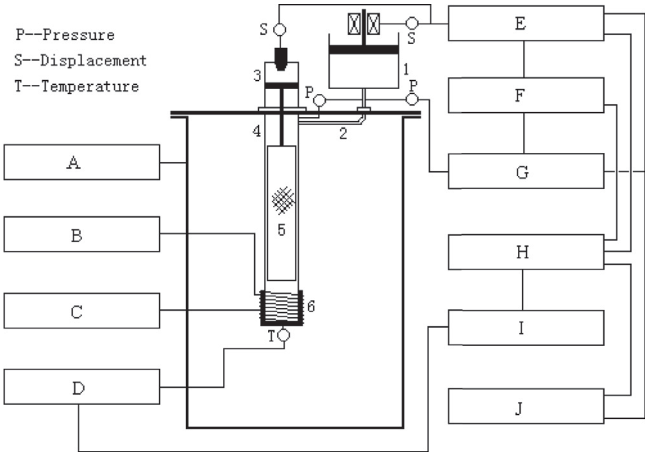
(1) characterizing the oscillatory flow within the cooler;
(2) determining the correlation between the compression piston and the free displacer;
(3) determining the influence of cold-tip temperature on cooler performance;
(4) determining the influence of phase-adjusting clearance gap on cooler performance; and
(5) examining overall cooler performance.

As we study the influences of one parameter, all the other parameters are kept constant. In the experiments except the cooler cool-down, when the cold-tip temperature is stabilized, we note the temperature and record the pressures and the displacements. Then we change only one parameter and repeat the process after the cold-tip temperature is stabilized once again.

2.1. Oscillatory flow within the cooler

Fig. 2A shows the displacement variations vs. time for the compressor piston and the displacer. The measured results indicate that compression period is about 1.2 times longer than the expansion period. The results also show a deviation from sinusoidal displacement variations for the compressor piston and the displacer. More practical displacement and pressure variations are gained by using the equation from fitted curves of experimental results. According our experimental results while cold-tip temperature is maintained at 80 K, the rectified displacement equation can be written by [2]

$$x_C = \begin{cases} \bar{x}_C + X_C \sin(1.80\pi f\tau) & (\dot{x}_C \geqslant 0) \\ \bar{x}_C + X_C \sin(2.20\pi f\tau) & (\dot{x}_C < 0) \end{cases} \qquad (1)$$



1. Compressor; 2. connecting hose; 3. linear motor; 4. expander cylinder; 5. displacer; 6. cold-end heat exchanger.

A. Vacuum system; B. constant current power supply; C. stable voltage power supply; D. digital multimeter;

E. displacement transducer; F. oscillograph; G. pressure transducer; H. cooler controller; I. computer; J. DC power supply.

Fig. 1. Simplified experimental sketch for the pneumatically-driven split-Stirling-cycle cryocooler with clearance-phase-adjustor.