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Experimental results of Stirling type Pulse Tube refrigerator with inertance tube

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Abstract-- **Pulse tube refrigerator, which has no moving parts at its cold section, is attractive for obtaining higher reliability, simpler construction and lower vibration than Stirling refrigerator or Gifford-McMahon refrigerator. Commonly used means to achieve optimum performance of Stirling type pulse tube refrigerator is an inertance tube. The use of inertance tube is a simple way to generate the phase shift needed to make pulse tube refrigerator operate as efficiently as Stirling refrigerator. In this study, the performance of the inertance pulse tube refrigerator (IPTR) was investigated experimentally. An in-line type IPTR consists of a linear compressor with two reciprocating pistons driven by linear motors, which makes pressure waves, a regenerator, a pulse tube with the inertance tube, and a reservoir. The dynamic pressures (the compressor, pulse tube, reservior) and the temperature at the cold heat exchanger are measured to explore the dependence of the inertance tube on the performance of the IPTR. The experimental results show the dependency of cool-down characteristics, no-load temperature and amplitude of the pressures on the length and diameter of the inertance tube.**

1. INTRODUCTION

The pulse tube refrigerator, which has no moving parts (displacer) at its cold section, is attractive for obtaining the higher reliability, simpler construction, lower vibration in the cold section, no performance degradation during long-life operation, and capability for wide range of the cooling temperature than the Stirling refrigerator or Gifford - McMahon (G-M) refrigerator.

The refrigeration in the pulse tube refrigerator is based on the cyclic process such that gas piston, which has replaced the displacer in the Stirling refrigerator or G-M refrigerator, is compressed, displaced to the warm end, expanded, and re-displaced to cold end. These successive processes are realized by providing the gas flows with different magnitudes and phases to the both ends of the pulse tube.

Since W. E. Gifford and R. C. Longsworth describe the first pulse tube refrigerator in 1964 [1], various types of the pulse tube refrigerator have been developed for the better thermal efficiency.

The orifice pulse tube refrigerator (OPTR) has an orifice to create phase shift between pressure and mass flow in the pulse tube [2,3]. The double inlet pulse tube refrigerator (DIPTR) has double-inlet connection that allow some of flow to bypass the regenerator and pulse tube [4].

The refrigeration power per unit mass flow rate through the regenerator was greatly increased in the DIPTR. But DC flow, which can substantially degrade the performance, in double inlet configuration has been experimentally demonstrated for low and high frequency pulse tube refrigerator [5]. In neither case does the efficiency quite reach that of the Stirling refrigerator [6].

Commonly used means to achieve the optimum performance of the Stirling type pulse tube refrigerator is the inertance tube [7]. The use of the inertance tube (inertance pulse tube refrigerator, IPTR) is a simple way to generate the phase shift needed to make pulse tube refrigerators operate as efficiently as the Stirling refrigerators.

A detailed analysis of the IPTR was reported by Zhu et al. [8]. They carried out analysis providing the performance as a function of the diameter and length of the long neck tube (inertance tube). The analysis was verified by an experiment in which a long tube was connected directly between the reservoir and compressor volume.

More recently, de Boer [9] showed that the performance of the IPTR is superior to that of the OPTR over a limited range of frequencies, and the rate of refrigeration of the IPTR is as a function of dimensions of inertance tube, volume of the pulse tube, the conductance of regenerator, the charging pressure, and the frequency.

Ravikumar et al. [10] showed as frequency increased the "inertance tube" phase shifter enhanced the cooler performance in a region where orifice or double-inlet deteriorated the performance and the dependency of frequency of operation, inertance tube diameter and length was experimentally investigated using rotary valve along with G-M compressor.

Hou et al. [11] demonstrated experimentally the effects of inertance tubes on the performance of a miniature

PTR with a rotary type compressor and showed the phase shifting effect is small using narrow inertance tube in miniature IPTR.

In this study, the thermal performance of the in-line type IPTR with a linear compressor was experimentally investigated.

The effects of inertance tube (diameter, length) and buffer volume on the thermal performance of IPTR were investigated, and the pressure in the pulse tube and phase angle of mass flow are measured to investigate the effects of the phase shifter.

2. EXPERIMENTAL DESCRIPTION

An experimental apparatus of the in-line type IPTR is shown in Fig. 1. The IPTR cconsists of a linear compressor with two reciprocating pistons driven by linear motors, which make pressure waves, a regenerator, a pulse tube with the inertance tube, and a buffer(reservoir) volume and vacuum chamber. The pressure oscillation is generated by linear compressor (Leybold Polar SC-7 COM).

The detail specifications of the IPTR are presented in Table. 1. The hot end heat exchangers (aftercooler) of the regenerator is cooled by circulating cooling water.

An AC power supply is used to supply and control the operating frequency and input voltage of the linear compressor.

The silicon diode thermometer is attached to measure the temperature at cold end, and the heater is provided at the cold end of the pulse tube to measure the cooling capacity. The cold end is installed to vacuum chamber, and the pressure of the vacuum chamber is maintained below 10^{-5} Torr to reduce the thermal loss during measurements.

After the regenerator of the pulse tube refrigerator is cleaned by evacuating and purging with clean high-pressure helium gas, the pulse tube refrigerator is connected to the compressor. Then, the system is charged up to 25 kg_f/cm^2G.

The piezoelectric pressure sensors to explore the dependence of the inertance tube on the performance of the IPTR are installed on transfer line (TL) between the exit of the compressor and aftercooler, hot end of the pulse tube (PT) and reservoir (BF) to measure pressure oscillations.

In the PTR, the gross refrigeration power at the cold end of regenerator is given by product of amplitude of pressure, mass flow rate and phase angle [12]. If the pressure oscillation in the IPTR has only 1st order harmonic function, the mass flow rate through the regenerator is expressed as follows.

$$\dot{m}_R = \alpha_R\left(P_{TL} - P_{PT}\right) = m_{R,O}\sin\left(\omega t + \theta_R\right) \tag{1}$$

$$P_{TL} = P_{TL,O}\sin\left(\omega t\right) \tag{2}$$

$$P_{PT} = P_{PT,O}\sin\left(\omega t + \theta_{PT}\right) \tag{3}$$

where α is the conductance, ω is the angular velocity, and θ is the phase angle. The subscript o means the amplitude of the sinusoidal oscillation, and subscript R means the regenerator.

The non-dimensional pressures at the pulse tube and buffer volume, the phase angle between pressure and mass flow rate are defined as follows.

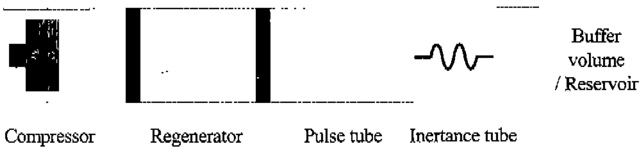

Fig. 1. Experimental apparatus of the IPTR

TABLE I
SPECIFICATION OF IPTR

Item		Value
Compressor		Polar SC-7
Charging pressure		25 kg_f/cm^2G (Helium)
Regenerator	Mesh	#400
	Volume	38 cc
Pulse tube	Diameter	1.32 cm
	Volume	8.867 cc
Inertance tube	Diameter	1.3/1.93/2.7/3.0/4.2 mm
	Length	0.475/0.950/1.9 m
Buffer volume		75/150/300/1000 cc

$$\pi_P = P_{PT,O}/P_{TL,O} \tag{4}$$

$$\pi_B = P_{BF,O}/P_{TL,O} \tag{5}$$

$$\phi = \theta_{PT} - \theta_R \tag{6}$$

where the positive phase angle means that the pressure oscillation in the pulse tube is lead to the mass flow rate.

3. EXPERIMENTAL RESULTS

3.1. Performance of IPTR

The thermal performance of IPTR can be evaluated from the no load temperature. The operating frequency of linear compressor has significant effects to the input power characteristics, and the compressor with the high charging pressure of working fluid has the high pressure ratio [13].

In this study, the linear compressor has the optimum performance about operating frequency 25-30 Hz at the charging pressure 25 kg_f/cm^2G, and the experiments were performed at given applied voltage and operating frequency (35 V_{RMS}, 30 Hz, respectively). The volume of reservoir, the length and diameter of ineratance tube were changed respectively for other fixed conditions.

Fig. 2 shows the variation of no load temperature of IPTR with buffer volume for the fixed inertance tube. A much lower no load temperature was obtained when the buffer volume is increased. The results show the volume of reservoir above 300 cc is sufficient for the present study.

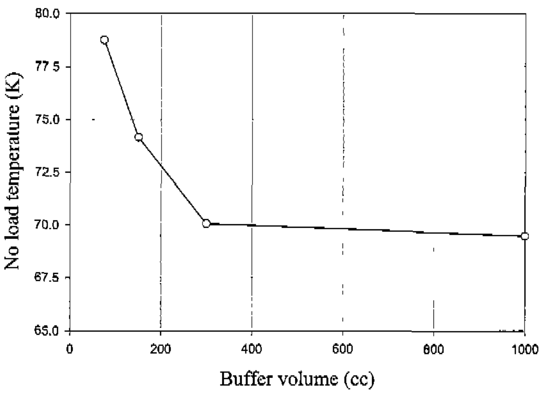

Fig. 2. Variation of no load temperature with buffer volume for fixed inertance tube

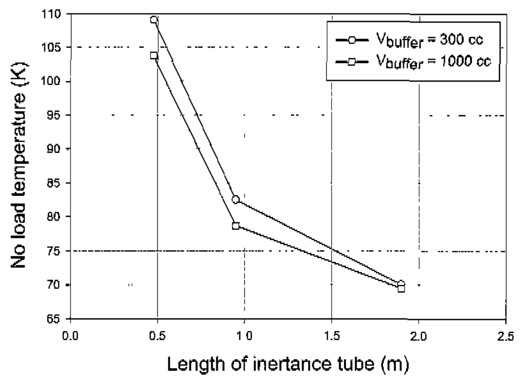

Fig. 3. Variation of no load temperature with the length for fixed diameter of inertance tube

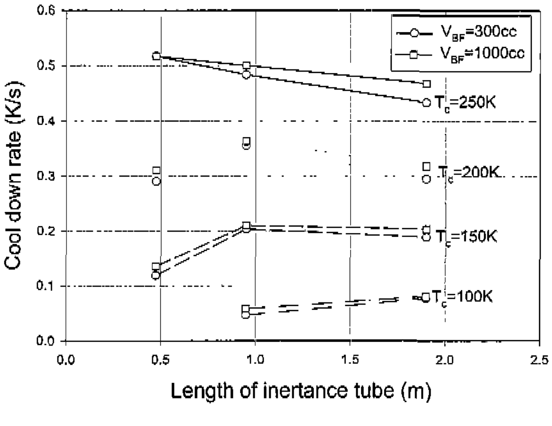

Fig. 4. Cool down rate as a function of length of inertance tube

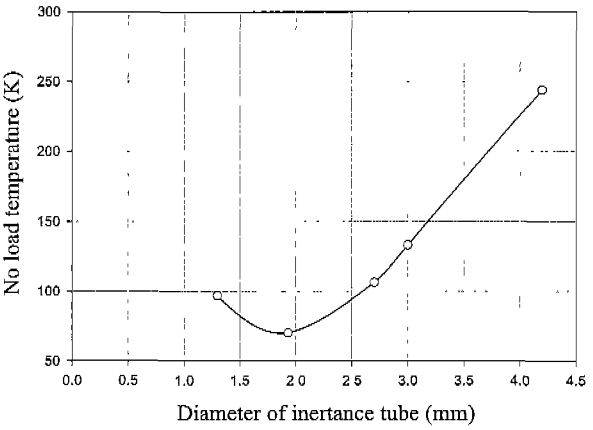

Fig. 5. Variation of no load temperature with diameter for fixed length of inertance tube

Fig. 3 shows influence of the length of inertance tubes on the no load temperature of IPTR. The lowest no load temperature is obtained at the length of 1.9 m. And no significant change in no load temperature is found when the volume of buffer are 300 cc and 1000 cc with different length and fixed diameter (1.9 mm) of inertance tube. Kanao et al. [7] showed the optimum length for the performance is exists, but in this study, there exists no optimal length because only the narrow range of the length was tested.

Fig. 4 shows the cool down rate at different cold end temperature with two different reservoir. The results show the effects of length of inertance tube on the maximum performance (high cool down rate) of IPTR is changed with cold end temperature. And the larger length is favorable when the cold end temperature is lower.

For the fixed length (1.9 m) of inertance tube and reservoir (300 cc), the influence of the inner diameter on the no load temperature of IPTR is shown in Fig. 5. The results shows there exits optimum diameter for IPTR, the inner diameter of inertance tube has significant effects on the performance of IPTR, and inertance tube with larger inner diameter are improper for IPTR.

The lowest temperature obtained in the present study is 69.4K at initial input power 220W using the diameter 1.9 mm, length 1.9 m of inertance tube with 1000 cc reservoir.

3.2. Pressure and phase relations

As shown in Fig. 6, the pressure oscillations in the IPTR are simultaneously measured with the same cold end temperature. The pressures in the IPTR shows that some phase lag exists between transfer line and pulse tube.

Fig. 7 shows the non-dimensional amplitudes of pressure oscillation at the pulse tube and buffer volume as defined in eqn. (4), (5). The results show the amplitude of pressure of the pulse tube increases as length increases, but pressure in the buffer volume decreases.

The decreases of amplitude of pressure in buffer volume mean the mass flow rate through the inertance tube decreases because the longer tube has larger flow resistance. And in the lower cold end temperature, the amplitude of pressure oscillation is small.

Fig. 8 shows cosine of phase angle as a function of the length of inertance tube and cold end temperature. The results shows the cosine of phase angle decrease as the length increase.

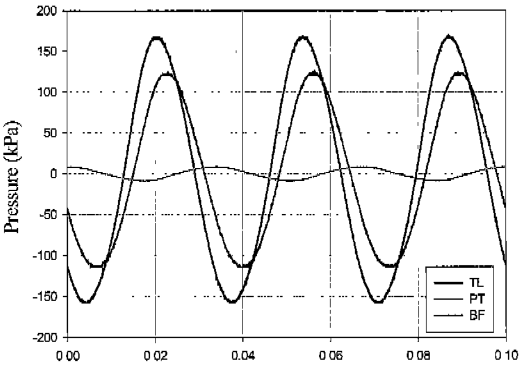

Fig. 6. Measured pressure oscillation in IPTR

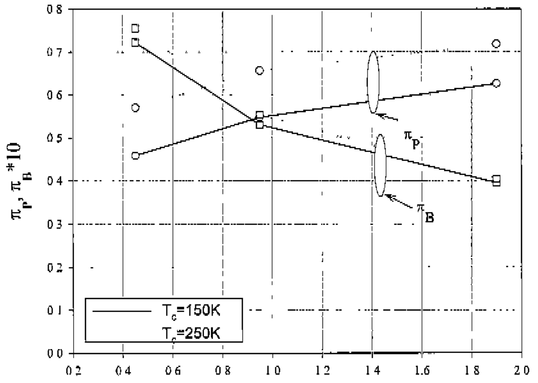

Fig. 7. Pressure as a function of length of inertance tube and cold end temperature

In present study, the pressures in the basic pulse tube refrigeraor (BPTR) [1] were measured for comparison with these results.

The results of measurements for BPTR, which is operated at operating frequency of 30 Hz with the same regenerator, pulse tube and charging pressure, shows the phase angle between pressure in pulse tube and mass flow rate through regenerator is about 90 degree.

Fig. 8 shows the decrease of the length result in shift of phase angle to the similar values of BPTR. The pressure drop through regenerator does not change with the length of inertance tube. Therefore, the gross refrigeration power (product of amplitude of pressure, mass flow rate, and cosine of phase angle) at length 0.475 m would be larger than case of length 1.9 m at 250 K, These results could results in cool-down rate as shown in Fig. 4.

For the fixed length (1.9 m) of inertance tube and reservoir (300 cc), the influence of the inner diameter on the amplitude of the pressures at cold end temperature 250 K is shown in Fig. 9. The results shows the pressure in the pulse tube decreases as diameter increase, but pressure in reservoir increase due to decreasing flow resistance through inertance tube.

Fig. 10 shows cosine of phase angle as a function of diameter of inertance tube. The results shows the decrease in the diameter of inertance tube result in the shift of phase angle to the similar that of BPTR. Hence the pressure drop through regenerator increase as the diameter of inertance tube decrease, so the mass flow rate through regenerator would increase.

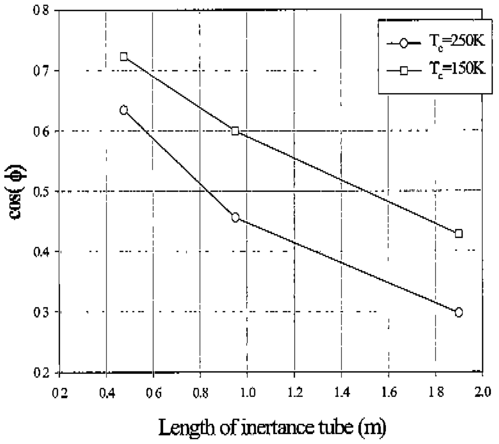

Fig. 8. cosine of phase angle as a function of length of inertance tube and cold end temperature

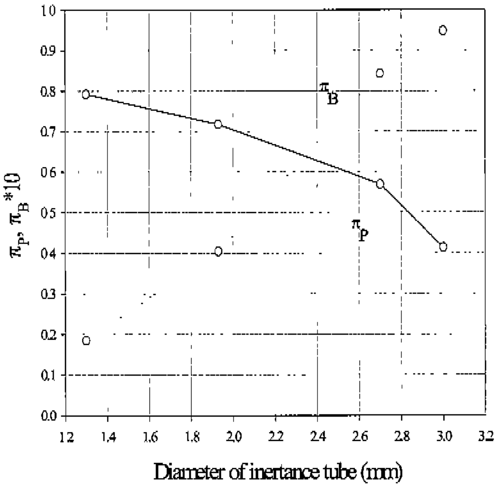

Fig. 9. Pressure as a function of diameter of inertance tube

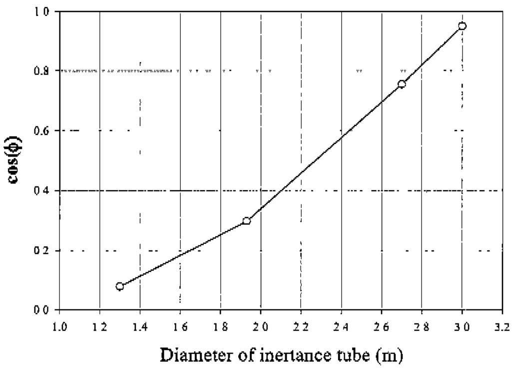

Fig. 10. cosine of phase angle as a function of diameter of inertance tube

4. CONCLUSION

The thermal performance of the in-line type IPTR with a linear compressor was experimentally investigated. The lowest temperature obtained in the present study is 69.4K at initial input power 220 W using the diameter 1.9 mm, length 1.9 m of inertance tube with 1000 cc reservoir. And the inner diameter of inertance tube has significant effects than length on the performance of IPTR, and inertance tube with larger inner diameter are improper for IPTR.

The pressure in pulse tube and phase angle of mass flow are measured to investigate the effects of the phase shifter in the IPTR and BPTR. The results show the dependency of the gross refrigeration power on the phase angle between pressure in pulse tube and mass flow rate through regenerator.

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