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Dynamic experimental investigation of a multi-bypass pulse tube refrigerator

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We designed and constructed a dynamic experimental apparatus to measure the instantaneous velocity and pressure in the multi-bypass pulse tube refrigerator (MPTR). Some experimental results of the instantaneous measurements of velocity and pressure in an MPTR with two-bypass tubes during actual operation are presented. D.c. flow phenomena are observed in this MPTR. Reasons are given for the multi-bypass version improving the performance of the pulse tube refrigerator. © 1997 Elsevier Science Ltd.

Keywords: multi-bypass; pulse tube refrigerator; experiment

Since the basic pulse tube refrigerator was first discovered by Gifford and Longsworth[1], the orifice pulse tube refrigerator has been introduced by Mikulin *et al.*[2] and the double inlet pulse tube refrigerator reported by Zhu *et al.*[3]. Still other modifications were presented by Ishizaki and Ishizaki[4] and Matsubara *et al.*[5]. Interest in the applications of pulse tube refrigerators has been growing rapidly due to their lack of moving parts at the cold head, so they have considerable system advantages over most other types of refrigerators in reliability, lifetime, vibration and cost[6,7]. To make further improvements, the multi-bypass pulse tube was first suggested by Zhou and Han[8]. A bypass tube and a valve connect the middle of the pulse tube and the regenerator; they have a part of the gas flow in or out of the pulse tube. The improvement of adding the middle bypass to the pulse tube refrigerator was initially verified experimentally by Cai *et al.*[9] and Wang *et al.*[10]. However, for lack of experimental results on instantaneous measurements of mass flow rate and temperature in MPTR during actual operation, there has been little experimental and theoretical analysis concerning the effects of the multi-bypass on the refrigeration performance of the pulse tube refrigerator.

A better understanding of the pulse tube refrigerators requires measurements of the velocity, temperature and pressure waves at different locations in the pulse tube. The difficulty here lies in obtaining velocity measurements independent of temperature and with minimal disturbance. David *et al.*[11] reported a method of measuring instantaneous velocity in an orifice pulse tube (OPTR), a hybrid pulse tube (HPT) and a double inlet pulse tube (DPT) using hot wire anemometry. Rawlins *et al.*[12] adapted constant temperature anemometers (CTA) and resistance temperature detectors (RTD) to measure instantaneous mass flow rates and temperature during actual operation of an OPTR. They presented the values of enthalpy, entropy, and work flow at the cold end of the pulse tube evaluated from their measurements. Cai *et al.*[13] measured the amplitudes and phase difference of the pressure wave and mass flow by using CTA.

In this paper, we construct a dynamic experimental apparatus to present some experimental results for the amplitudes and phase difference of the pressure wave and mass flow at the cold head of an MPTR with two bypass tubes. The effects of the middle-bypass version on the pressure and mass flow rate at the cold head of the pulse tube were evaluated from experimental measurements. Reasons are given as to why the multi-bypass improved the performance of the pulse tube refrigerator.

Multi-bypass principle

Figure 1 shows the energy flows in the multi-bypass pulse tube refrigerator, where H_r is the enthalpy flow in the regenerator, H_p the enthalpy flow through the middle-bypass valve, Q_c the heat flow in the cold head, H_c the enthalpy flow in the pulse tube, H_d the enthalpy flow through the double-inlet valve, etc. There is an enthalpy flow H_p from

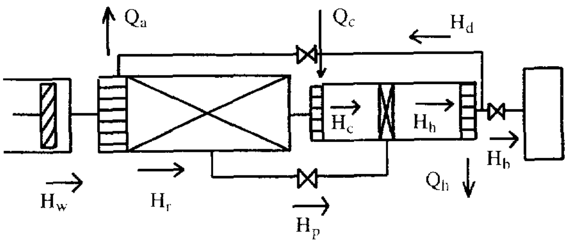

Figure 1 Energy flows in the multi-bypass pulse tube refrigerator

the regenerator to the pulse tube through the middle-bypass tube. That means that the refrigerative capacity is generated at the connected part of the multi-bypass tube and pulse tube.

It is believed that the pulse tube refrigerator is a variation of the Stirling refrigerator, where the moving displacer is substituted by a 'gas connecting reservoir'. That is, a gas piston takes the place of a solid displacer. As shown in *Figure 1*, the refrigeration substance in a pulse tube refrigerator includes three parts: hot gas, cold gas and medium gas. The medium gas acts as a gas piston. The same refrigerating cycle exists in the pulse tube refrigerator as in the Stirling machine.

The double-inlet tube acts as an expander in the refrigeration process. To raise the efficiency of the pulse tube refrigerator, we tried to increase the pressure ratio in the pulse tube refrigerator and decrease the proportion of the gas quantity in the gas piston; which is the principle of the double-inlet method. Actually, the double-inlet version let some room-temperature gas enter the pulse tube directly without passing through the regenerator. The main contribution of the double-inlet pulse tube is to adjust the phase shift between the pressure wave and the mass flow at the hot head of the pulse tube refrigerator, and to increase their amplitudes[13]. Unfortunately, we do not know whether the phase differences between the pressure wave and the mass flow at the cold head are changeable with the various double-inlet valves.

To further improve the performance of the pulse tube refrigerator, we adopted a multi-bypass version based on the double-inlet principle. Besides the double-inlet valve in the system, a multi-bypass tube is added between the middle part of the pulse tube and the regenerator. That means a part of the gas stream is allowed to flow into the pulse tube refrigerator directly from the regenerator. This method can increase the pressure ratio and gas piston stroke in the cold part of the pulse tube refrigerator. Thus, the pulse tube refrigerator can achieve a low refrigerator temperature.

Also, a numerical model of an MPTR with single bypass tube has been developed and equations of continuity, momentum and energy (for both gas and solid) have been solved numerically. The detailed numerical method can be seen elsewhere[14,15]. *Figure 2* shows the numerical results of the gas temperature distributions in the MPTR with single bypass tube[16], where Θ is the crank angle. The authors found that two expansion processes occurred in the pulse tube. It can be concluded that two refrigeration processes occur in an MPTR. Thus, the pulse tube refrigerator may obtain more refrigeration power and lower refrigeration temperature. However, the refrigeration processes of the MPTR have distinctions from the two-stage pulse tube refrigerators, since the expansion process at the middle-bypass part is restricted by the multi-bypass valve. Performance comparisons of the MPTR with a two-stage pulse tube refrigerator are being carried on in our laboratory.

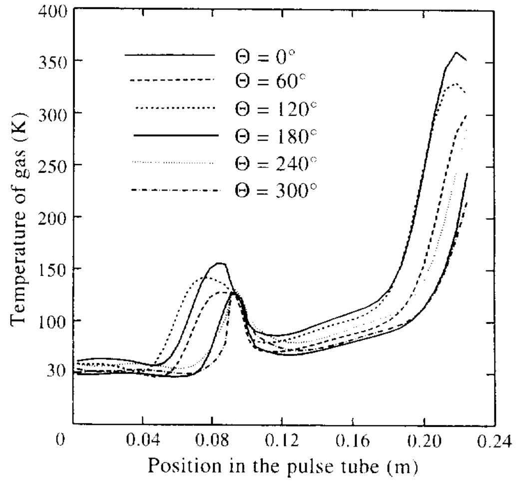

Figure 2 Calculated gas temperature distributions in the MPTR[16]

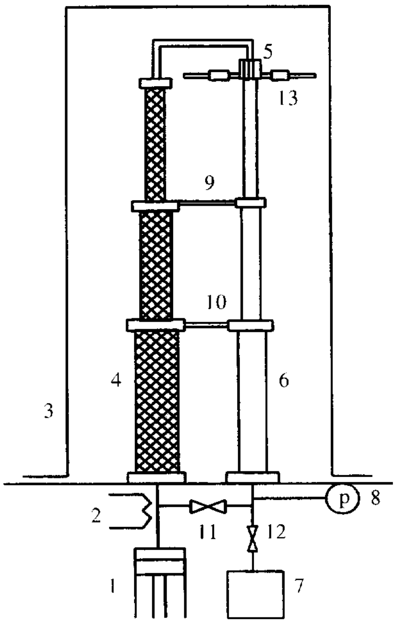

Figure 3 Experimental apparatus: 1, compressor; 2, after-cooler; 3, vacuum chamber; 4, regenerator; 5, cold head; 6, pulse tube; 7, reservoir; 8, pressure transducer; 9, middle-bypass valve (K2); 10, middle-bypass valve (K1); 11, double-inlet valve; 12, orifice

Experimental apparatus

Figure 3 shows the configuration of the experimental apparatus of the multi-bypass pulse tube refrigerator with two bypass tubes. The swept volume of the valveless compressor was 55.6 cm^3; the compressor rotating speed was 960 rpm, so the frequency was 16 Hz; the reservoir volume was 300 cm^3. The pulse tube and the refrigerator were made of stainless steel with a thickness of 0.25 mm. Considering that the gas density and viscosity vary greatly with temperature in the refrigerator, the pulse tube and the regenerator were separated into three parts, respectively. The dimensions of each part of the pulse tube and refrigerator are given in *Table 1*. The regenerators were packed with phosphor bronze screens and stainless steel screens. In the con-

Table 1 The dimensions of each part of the pulse tube and refrigerator

Component	Pulse tube	Regenerator
First part	12 mm × 85 mm	17 mm × 80 mm
Second part	10 mm × 60 mm	14 mm × 58 mm
Third part	7.5 mm × 50 mm	10 mm × 55 mm

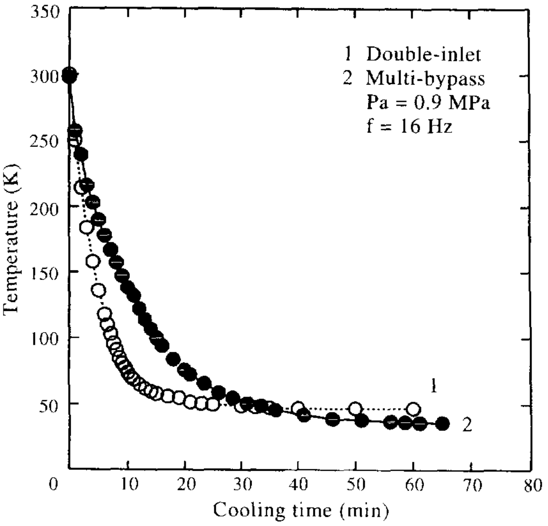

Figure 4 Comparison of the cooling rate of the MPTR with that of the DPTR

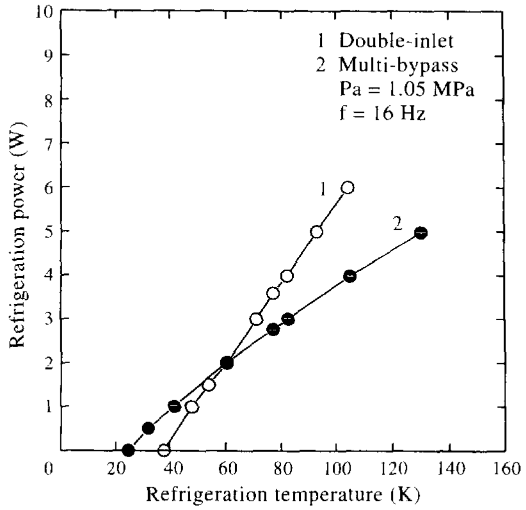

Figure 5 Comparison of the refrigeration capacities of the MPTR with those of the DPTR

necting parts of the pulse tube, we added 20 sheets of 100 mesh copper screens as a gas flow straightener to reduce the gas flow disturbance caused by gas flow in or out of the pulse tube[10]. The multi-bypass valves 9 and 10 were capillary tubes whose flow area can be adjusted, the length of the capillary tubes was 25 mm. A pressure transducer to measure the transient gas pressure wave was placed at the hot end of the pulse tube. Although the gas flow straightener may produce some pressure drop and phase difference, a comparison of the experimental results with screens and with no screens in the pulse tube showed that the effects of the screens on the amplitudes of pressure could be neglected. Therefore, the amplitude and phase of pressure wave at this location were assumed to be the same as those measured at the cold head of the pulse tube, as in Rawlins *et al.*[12]. The hot ends of the pulse tube and the regenerator were mounted on an aluminium base.

We used hot wire anemometry to measure the gas velocity and temperature. The anemometer works according to the constant temperature anemometer (CTA) principle where the sensor probe forms a Wheatstone bridge. It is kept in balance by the error signal across the bridge diagonal so that the probe resistance, and hence its temperature, is kept constant independent of the cooling from the flowing medium. The bridge output voltage is thus always a function of the effective cooling velocity acting on the probe.

The solution for fast varying temperature is to operate two identical probes placed simultaneously close to each other with different overheat ratios; the power drop for double sensors method. That is, we can obtain the velocity independent of temperature according to power drops of two identical probes operated with different overheat ratio.

Two hot wire probes which were verified to be precisely identical to each other were located at the centre in the cold head of the pulse tube. We assume that the velocity is homogeneous in a cross-sectional area. The wires of 5 μm diameter between the probe supports of 2 mm diameter and 30 mm length were made of tungsten. The wires were suspended in the gas stream by probe supports which were electrical conductors and also served as the electrical connections for the sensor. The CTA was operated at approximately 200 K warmer than the environmental fluid, both hot wires were placed inside the cold head of the pulse tube. The response times of the CTA in this system were 20 μs.

Results and discussion

Comparing performances of the multi-bypass and double-inlet versions

To compare the effects of the multi-bypass version with the double-inlet version on the performance of the pulse tube refrigerator, we studied experimentally the refrigeration performance of the MPTR and the DPTR without the hot wire anemometry. *Figure 4* shows the cooling rate. *Figure 5* shows the refrigeration capacities of the pulse tube refrigerator with multi-bypass version and double-inlet version. A lowest temperature of 24 K and a cooling capacity of 3.5 W at 77 K were obtained with optimum values of the two middle-bypass tubes. When the middle-bypass tube was closed, the lowest temperature of 38 K was obtained with the optimum value of the double-inlet valve. The multi-bypass version improved the performance of the pulse tube refrigerator in a very low temperature range.

Figure 6 shows the comparisons of the cold head tem-

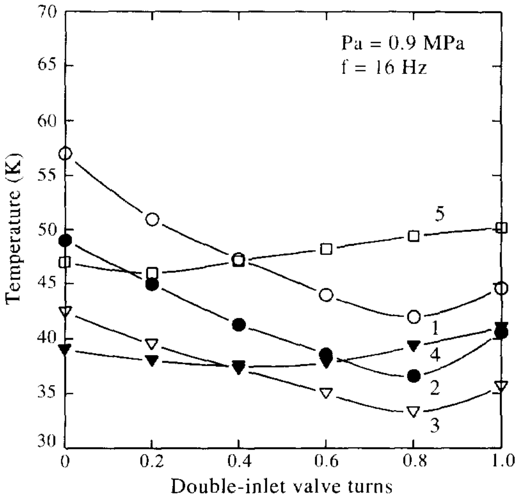

Figure 6 Comparisons of the cold head temperature for different flow areas of the multi-bypass valve (mm^2): 1, 0; 2, 0.51; 3, 0.75; 4, 1.05; 5, 1.30

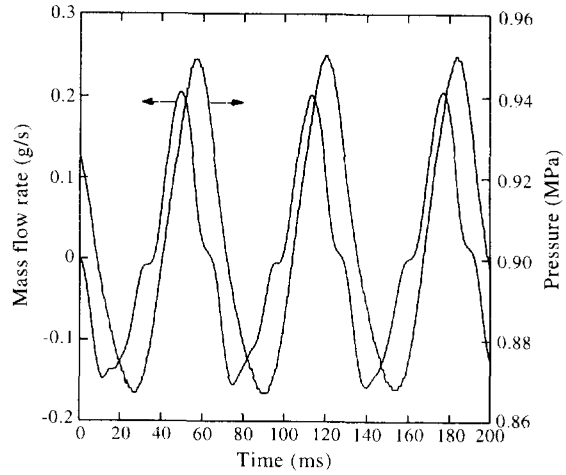

Figure 7 Mass flow rate and pressure as functions of time at the cold head of the pulse tube refrigerator

perature for different flow areas of the multi-bypass valves. In our experiments, both valves 9 and 10 were changed simultaneously. The double-inlet version can improve the refrigeration performance of the pulse tube. These experimental results are in good agreement with the results of Cai *et al.*[13]. From *Figure 6*, we find that the multi-bypass version can improve the refrigeration performance of the pulse tube. The optimum values of the two middle-bypass valves were 0.75 mm^2. The temperature of the MPTR was 10–15 K lower than that of the DPTR. However, the refrigeration temperature increased with increasing flow area of the multi-bypass valve. We will explain the reasons through the dynamic experimental results.

The dynamic experiment of the multi-bypass pulse tube refrigerator

Figure 7 shows an example of the mass flow rate and pressure as a function of time at the cold head of this multi-bypass pulse tube operating at 16 Hz. It demonstrates the amplitudes and phase relationship between the mass flow rate and dynamic pressure. We calculated the actual average mass flow rate from the experimental data and found that the total mass flow rate which flows past the sensor in the positive direction was not equal to that in the negative direction. The results are different from the experimental results for OPTR of Rawlins *et al.*[12]. Some reasons may be the effects of the multi-bypass version. From the experimental results, we found that the phase relationship between the mass flow rate and pressure wave at the cold head of the pulse tube is independent of the multi-bypass flow area and the double-inlet opening values. It is different from the phase shift at the hot head of the pulse tube[13]. In this pulse tube refrigerator system, the phase differences are about 40–45°.

Figure 8 shows the velocity values from the CTA at the cold head of the pulse tube refrigerator for different flow

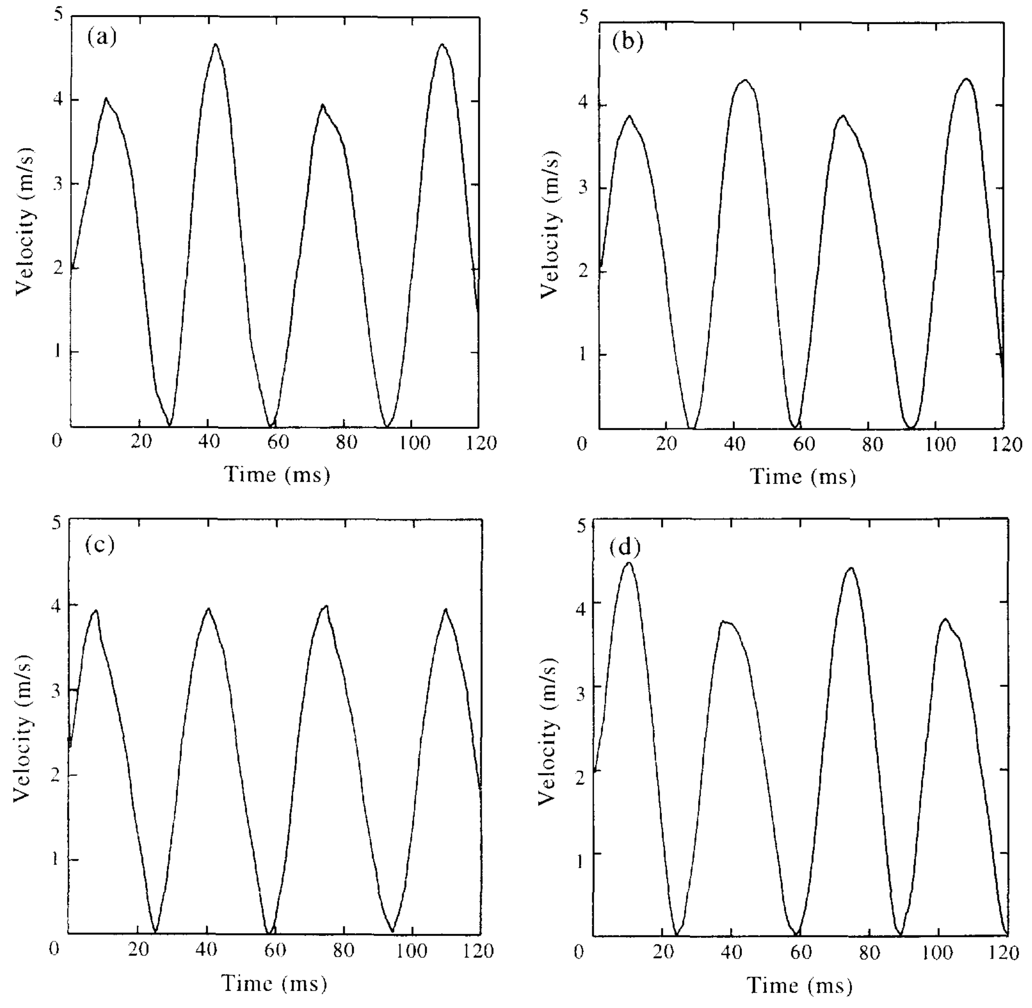

Figure 8 Velocity distribution for different flow areas of the multi-bypass valve (mm^2): (a) 0; (b) 0.51; (c) 0.75; (d) 1.05

areas of the multi-bypass valves. Note that the frequency of the CTA signal is twice the operating frequency of the pressure oscillation. We also calculated the actual average mass flow rate and found that the mass flow rate in the positive direction is not equal to that in the negative direction. Therefore, there is a net mass flow rate which flows in one direction for a fixed flow area of the multi-bypass valves. This is a kind of d.c. flow phenomenon which is not analogous to that with the a.c. electrical system described previously[6]. It is natural to guess that the d.c. flow is some kind of circulating flow. However, there are two multi-bypass valves in our MPTR apparatus, so we think there are two paths of circulating flow between the cold head and the two multi-bypass tubes.

From experimental results, as can be seen in *Figure 8*, the d.c. flow rate changed with the flow area of the multi-bypass valves. When the flow area of the multi-bypass valves was adjusted to optimum value, the d.c. flow rate is zero. The lowest temperature at the cold head of the multi-bypass pulse tube corresponds to the zero of the d.c. flow rate. The optimum values of the two middle-bypass valves in the pulse tube refrigerator were both 0.75 mm^2. By further increasing the flow area of the multi-bypass valve, the d.c. flow appeared and resulted in decreasing the refrigeration performance of the MPTR. The temperature at the cold head was increasing and might be higher than that at the multi-bypass region. Some reasons might be the distribution ratio of the mass flow rate at the cold head to that at the multi-bypass region.

Therefore, the d.c. flow is a kind of loss. It is one of the reasons why the refrigeration performance of the multi-bypass pulse tube refrigerator is worse than that of the multi-stage pulse tube refrigerator. From the analysis and experimental results that multi-stage refrigeration processes and d.c. flow occurred in the MPTR, we conclude that the multi-bypass pulse tube refrigerator is actually a kind of multi-stage pulse tube refrigerator, and produces multi-stage expansion processes: one is at the cold head and the others at the multi-bypass part. The upper stage cooling power can be used to compensate for the losses occurring in the lower stage pulse tube, resulting in achieving a lower temperature and increasing the refrigeration performance.

Conclusions

The effects of the multi-bypass version on the refrigeration performance of the pulse tube refrigerator were studied experimentally. Results revealed that there were d.c. flow and multi-stage refrigeration expanding processes occurring in the MPTR. The d.c. flow is a kind of loss which could be decreased to zero by adjusting the flow area of the multi-bypass tube to an optimum value. Comparison of experiments verifies that the multi-bypass version can improve the performance of the pulse tube refrigerator. An analytical study of the effects of the multi-bypass version on the mass flow rate and enthalpy and work fluxes at the cold head of the pulse tube refrigerator will be published soon.

Acknowledgements

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