

## DC Flow in a High Frequency Miniature Pulse Tube Cryocooler

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DC flow in the double-inlet pulse tube cryocooler is classified as intrinsic DC flow and artificial DC flow. The intrinsic DC flow is generated by the non-linear effect of the oscillating flow in the cooler. It has a fixed direction, which is from the pulse tube to regenerator through the cold end. The artificial DC flow is caused by the asymmetry of the secondary bypass, whose direction can be controlled. In the experiments, the asymmetry spray nozzle with reverse direction used as the secondary bypass can generate artificial DC flow with reverse direction to that of intrinsic DC flow, which can reduce the overall DC flow.

### INTRODUCTION

An important improvement in the history of the pulse tube cryocooler (PTC) is the introduction of the double-inlet configuration. The double-inlet PTC has two degrees of freedom in the impedance to allow the optimization of the phase difference between the mass flow rate and the dynamic pressure inside pulse tube, which leads to significant efficiency improvements over the single orifice PTC.

The double-inlet PTC, however, has a closed loop path, which may allow a DC circulating mass flow from ambient temperatures to cold temperatures, and result in a deterioration of the PTC performance [1]. As shown in Figure 1, DC flow means the non-zero time-averaged mass flow at any section of the closed loop path, it is on the order of only one percent of the AC mass flow rate. There are two main mechanisms to generate DC flow. The first one is due to the intrinsic characteristic of oscillating flow in the tube. Another is attributed to the asymmetry of flow impedances such as secondary bypass [1,4,5]. Thus DC flow can be classified as intrinsic DC flow and artificial DC flow which are generated by the first and the second mechanism, respectively.

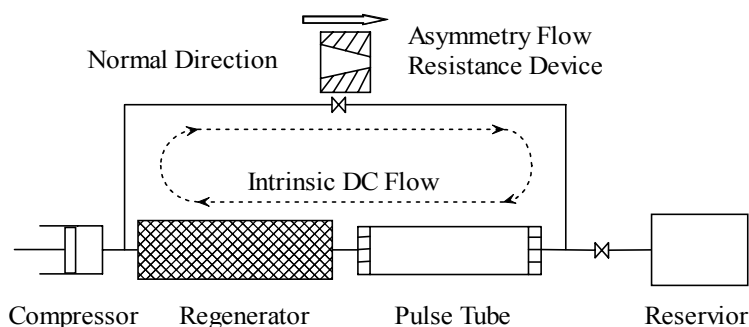


Figure 1 DC flow in the double inlet PTC and normal direction of asymmetric flow impedance

DC flow was firstly pointed out by Gedeon in 1996 [1]. Ju et al measured directly the DC flow in a multi-bypass PTC by hot-wire anemometry [2]. Charles and Kotsubo et al investigated the existence of DC flow by observing the temperature profile along the out wall of the regenerator and the pulse tube [3,4]. However, their experiments did not distinguish the intrinsic DC flow

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from the artificial DC flow.

## INTRINSIC DC FLOW

Supposed that fluid in the cooler is one-dimensional oscillating flow. To discuss the DC flow, the relevant variables in the PTC are extended as [5]:

$$\xi(x, t) = \xi_o(x) + \text{Re}(\xi_1(x)e^{j\omega t}) + \xi_{2,o}(x) + \text{Re}(\xi_{2,2}(x)e^{2j\omega t}) \quad (1)$$

where the subscript “o” refers to the average terms, subscripts “1” and “2” denote the first order term and second order term, respectively,  $\omega$  is the angular velocity.

In terms of density and volume flow rate, the time-average mass flow rate at any section can be expressed as [5]:

$$\dot{M}_2 = \rho_o U_{2,o} + \frac{1}{2} \text{Re}(\rho_1 U_1^*) \quad (2)$$

where  $\rho$  is density,  $U$  is volume flow rate, superscript “\*” denotes complex conjugate and “Re()” denotes the real part. The time-average mass flow rate means the DC flow in the PTC.

The second-order time-average momentum equation can be written as [5]:

$$\frac{1}{2} \text{Re} \left[ -j\omega \rho_1 U_1 + \rho_o U_1 \frac{\partial U_1}{\partial x} \right] = -\frac{dp_{2,o}}{dx} + \lambda_v U_{2,o} \quad (3)$$

where  $p_{2,o}$  is the second-order average pressure.

For the orifice PTC, there exists a second-order pressure gradient resulting in  $\dot{M}_2 = 0$  automatically. However, for the system with a closed loop path such as double inlet PTC,  $\dot{M}_2 \neq 0$ , which means DC flow occurring in the system. For any oscillating flow in tubes, the DC flow generated by Equation (2) is called intrinsic DC flow. One question is how to determine the direction of the intrinsic DC flow in the high frequency PTC.

A one-dimensional numerical method is used to determine the direction of the intrinsic DC flow. The one-dimension model treats the secondary bypass as a symmetry flow impedance [6], the DC flow calculated by the numerical method may be regarded as the intrinsic DC flow. The positive direction in the simulation is from the compressor to the reservoir. Table 1 is the simulative result for a miniature PTC.

Table 1 The intrinsic DC flow in a miniature PTC

Opening of the secondary bypass (mm)	0.2	0.25	0.3	0.35	0.4	0.45
DC Flow (g/s)	-0.119E-04	-0.167E-04	-0.194E-04	-0.211E-04	-0.232E-04	-0.227E-04

The negative DC flows in Table 1 show that the direction of the intrinsic DC flow is from the pulse tube

to the regenerator through the cold end, across secondary bypass, and then to the pulse tube (as shown in Fig. 1).

## EXPERIMENTAL RESULT AND DISCUSSION

Experiments are carried out to investigate the DC flow phenomenon in a miniature double inlet PTC using the method described by Charles and Kotsubo et al [3,4].

### Experimental setup

The experimental setup is shown in Figure 2, which consists of a pulse tube cryocooler, a vacuum system and a measuring system.

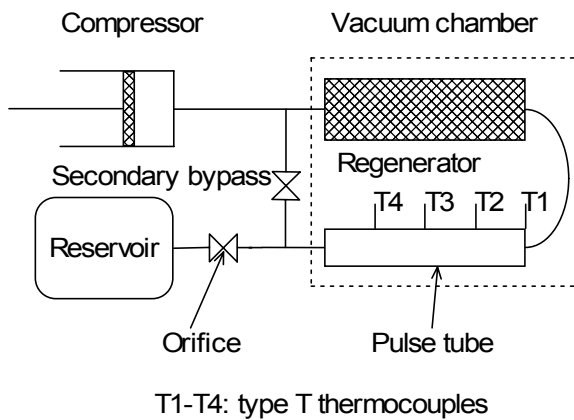


Figure 2 Experimental setup

The pulse tube cryocooler is arranged in the “U” shape. The compressor is of a rotary type with a constant swept volume of  $1.66\text{cm}^3$ . The regenerator has an outer diameter of 8mm and the pulse tube has an outer diameter of 5mm. A symmetric and an asymmetric nozzle spray are adopted as the secondary bypass. A fine needle valve and inertance tube are acted as orifice. The vacuum environment is maintained by a vacuum pump, and the lowest vacuum of 1.0Pa can be reached. Temperature profile along the outer wall of the pulse tube is measured by using four copper-constantan thermocouples (Type T).

The symmetric and asymmetric spray nozzles are shown in Figure 3. For the asymmetric nozzle spray, mass flow along the normal direction is larger than that of the reverse direction. Therefore, the asymmetric nozzle spray can be used to induce the artificial DC flow.

### Experimental result and discussion

All experiments are performed at the frequency of 50Hz and the charge pressure of 2.2MPa. The results are shown in Figure 4. Curve A represents the temperature profile of the pulse tube wall for the PTC using the inertance tube (with inner diameter of 1.5mm and length of 2.0m) as the phase shifter. Curve A is approximately linear, which indicates no DC flow in the cooler [1,3,4], since the inertance PTC has no closed loop path for the DC flow.



Figure 3 The symmetric (right) and the asymmetric spray nozzle (the arrow indicates the normal direction of the spray)

Curve D is the wall temperature profile of the PTC using the needle valve as orifice and symmetric spray nozzle as the secondary bypass. Curve D is upcurved, which means that there exists the DC flow from the pulse tube through the cold end to the regenerator [1,3,4]. This DC flow is considered as the intrinsic DC flow in the PTC because the symmetric spray nozzle does not induce artificial DC flow.

Curve B is the wall temperature profile of the PTC using the needle valve as orifice and asymmetric spray nozzle with reverse direction as the secondary bypass. Curve B is downcurved, which means the DC flow is from the regenerator to the pulse tube through the cold end [1,3,4]. The asymmetric spray nozzle with reverse direction induces DC flow with the direction opposite of the intrinsic DC flow.

Curve C is the wall temperature profile of the PTC using the needle valve as orifice and asymmetric spray nozzle with normal direction as the secondary bypass. Curve C is also upcurved, which means the

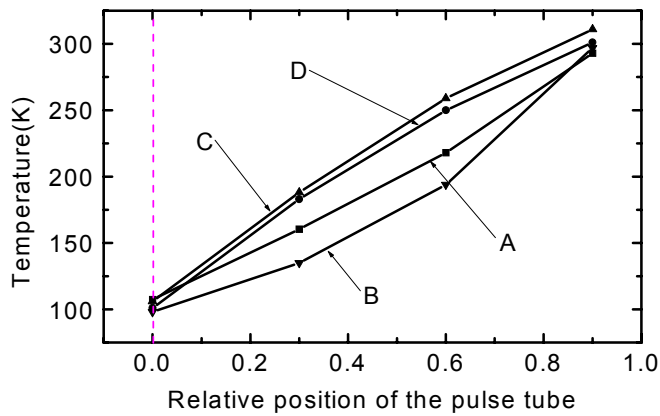


Figure 4 Temperature profiles of the pulse tube at different condition

Curve A: Inertance tube

Curve B: Asymmetric spray nozzle with reverse direction

Curve C: Asymmetric spray nozzle with normal direction

Curve D: Symmetric spray nozzle.

and then to pulse tube. The artificial DC flow is caused by the asymmetry of the secondary bypass, whose direction can be controlled. In the experiments, the symmetry spray nozzle is acted as the secondary bypass in a high frequency miniature PTC to indicate the intrinsic DC flow, and the asymmetry spray nozzle with normal direction and reverse direction are used as secondary bypass to induce the artificial DC flows with different direction. The different temperature profiles along the pulse tube are measured. The experimental results verified the existence of the intrinsic DC flow, and the use of asymmetry spray nozzle with reverse direction as the secondary bypass can reduce the overall DC flow.

## ACKNOWLEDGMENT

This work is supported by the National Nature Science Foundation of China (Grant No. 50176052)

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DC flow is from the pulse tube to the regenerator through the cold end [1,3,4]. The asymmetric spray nozzle with normal direction induces DC flow with the same direction of the intrinsic DC flow. Therefore, the artificial DC flow is imposed on the intrinsic DC flow, which makes curve C is more upcurved.

## CONCLUSIONS

DC flow in the double-inlet pulse tube cryocooler is classified as intrinsic DC flow and artificial DC flow. The intrinsic DC flow is generated by the non-linear effect of the oscillating flow in the cooler. It has a fixed direction, numerical simulations show that the direction of the intrinsic DC flow is from the pulse tube to regenerator through the cold end, across the secondary bypass