Displacer Diameter Effect in Displacer Pulse Tube Refrigerator

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Abstract. Gas driving displacer pulse tube refrigerators are one of the work recovery type of pulse tube refrigerators whose theoretical efficiency is the same as Stirling refrigerators'. Its cooling power is from the displacement of the displacer. Displacer diameter, rod diameter and pressure drop of the regenerator influence the displacement, which are investigated by numerical simulation. It is shown that the displacement ratio of the displacer over the piston is almost not affected by the displacer diameter at the same rod diameter ratio, or displacer with different diameters almost has the same performance.

1. Introduction
Pulse tube refrigerators can be divided into non-work recovery type [1-9] and work recovery type [10-15]. Inertance tube pulse tube refrigerators [5-9] are one of the non-work recovery types in which the expansion power of the pulse tube is transformed to heat due to the heat transfer and friction loss in the inertance tube, its theoretical efficiency is lower than that of Stirling refrigerators. Due to the inertance tube, the pressure ratio also cannot be as high as that in the Stirling refrigerator. Displacer type pulse tube refrigerators are one of the work recovery types in which a displacer is used to recover the expansion work so that the theoretical efficiency is the same as that of the Stirling refrigerator. Compared with a simple displacer [12], a displacer with a rod has an additional driving force to control the displacer displacement [13], therefore, it has a greater potential to achieve higher efficiency. A confirmation test refrigerator [14,15] has reached the temperature of 39K and 15% of Carnot efficiency, which is lower than that of a well-designed inertance tube pulse tube refrigerator [9]. For future improvement of the efficiency, parameters which control the displacement of the displacer should be studied. There are two forces on the displacer, one is the force at both ends of the displacer which is from the pressure drop of the regenerator, and the other is at both ends of the rod which is from the pressure difference between the pulse tube and displacer buffer. A numerical simulation is carried out to investigate what is the main parameter controlling the displacer motion. Our group’s previous publications on this topic have presented the foundational theory and demonstrated the influence of the rod diameter on performance [13]. The present report details the influence of the displacer diameter and the pressure drop in the regenerator.
2. Structure

Figure 1 is the schematic of the displacer pulse tube refrigerator. It includes a compressor, a cold head, and a displacer unit. The compressor includes a linear motor, a motor spring and a piston. The cold head includes an after cooler, a regenerator, a cold heat exchanger and a pulse tube. The displacer unit includes a displacer, a displacer rod, a displacer spring, a displacer buffer and a displacer cylinder. The displacer and displacer cylinder form the displacer front space and back space. The displacer front space is connected to the hot end of the pulse tube, and the displacer back space is connected to the compression space. The driving force of the displacer is from the pressure difference between the left ends and right ends of the displacer and rod. The linear motor reciprocates under AC input to drive the oscillating piston and to generate the pressure wave and gas flow. Heat is discharged from the after cooler and the cooling power is obtained from the cold heat exchanger.

In this refrigerator, the linear motor should be operated at a resonant point, which can be realized by changing the piston weight. The displacer weight should be optimized so that the phase angle difference between the displacer and piston is optimized to achieve the highest COP, and the swept volume ratio of the displacer over that of the piston should be optimized for a maximum COP by a suitable rod diameter ratio, which is the rod diameter over the displacer diameter.

![Figure 1: Displacer pulse tube refrigerator](image)

**Figure 1** Displacer pulse tube refrigerator

11. after cooler 12. regenerator 13. cold heat exchanger 14. pulse tube
21. displacer connecting tube 22. displacer front space 23. displacer
24. displacer back space 25. displacer rod 26. displacer spring 27. displacer buffer
31. compression space 32. compressor piston 33. linear motor 34. motor spring
35. motor house 36. compressor connecting tube

Table 1 shows the basic size of the pulse tube refrigerator. The after cooler and cold heat exchanger are slot type. Other significant parameters include the refrigeration temperature 77K, room temperature 300K, operation frequency 50Hz, working medium helium, and charge pressure 3MPa.

The numerical simulation method is the same as that in the reference. It is based on a one dimensional unsteady periodic flow mode. The relation between the linear motor force and the current is linear. The driving force of the displacer is the pressure difference between both ends of the rod and displacer.
### Table 1. Basic size of the refrigerator

| Parts                      | Basic size                                      |
|----------------------------|-------------------------------------------------|
| After cooler               | height 0.33 mm, length 80 mm, width 2618 mm     |
| Regenerator                | Φ100 × 50 mm                                     |
| Cold heat exchanger        | height 0.33 mm, length 40 mm, width 2618 mm     |
| Pulse tube                 | Φ50 mm × 150 mm                                  |
| Linear motor piston        | Φ 118 mm                                        |
| Displacer                  | Diameter 120 mm, rod diameter 60 mm, weight 3.1 kg, spring stiffness 150 kN/m |

#### 3. Displacer diameter effect

Figure 2 shows the influence of the displacer diameter and weight at a rod diameter ratio of 0.5, which is the rod diameter over the displacer diameter. With the same rod diameter ratio, a larger displacer implies a larger rod diameter and a greater gas spring stiffness, which in turn requires a larger displacer weight. Figure 2a displays the influence of the displacer size on the resulting phase angle difference between the compressor piston and displacer. As shown in Figure 2b, a larger displacer has a shorter displacement amplitude. For each displacer diameter, the phase angle differences between the displacer and piston change with the displacer weight. Figures 2c-2h re-arrange the same data with the phase angle difference as the x-coordinate. From these one may observe that when the displacer diameter increases, the swept volume of the piston decreases slightly, while the swept volume of the displacer increases slightly, so the swept volume ratio (displacer volume over piston volume) increases slightly. The COP, the current displacement ratio (current amplitude over the piston displacement amplitude of the linear compressor), and the cooling power are essentially unaffected by the displacer diameter. The optimum phase angle difference for the COP also remains essentially unchanged when the displacer diameter is changed. So for a rod diameter ratio of 0.5, changing the displacer diameters has almost no effect on other parameters including performance, except for a small change of the swept volume ratio.

![Figure 2a Phase angle difference at rod diameter ratio 0.5](image)

![Figure 2b displacer displacement at diameter ratio 0.5](image)
Figure 2c Swept volume of piston at rod diameter ratio 0.5

Figure 2d Swept volume of displacer at rod diameter ratio 0.5

Figure 2e Swept volume ratio at rod diameter ratio 0.5

Figure 2f COP at rod diameter ratio 0.5

Figure 2g Current displacement ratio at rod diameter ratio 0.5

Figure 2h Cooling power at rod diameter ratio 0.5
Figures 3-4 show the swept volume ratio, COP, current displacement ratio, and cooling power versus phase angle difference and displacer diameter for rod diameter ratios of 0.6 and 0.4 respectively. With a rod diameter of 0.4, the COP almost does not change with displacer diameter, while the swept volume ratio increases a little as the displacer diameter increases. With a rod diameter of 0.6, the influence is larger than that with a rod diameter of 0.4, but still can be considered as almost having no influence. Similar to Figure 2, the current displacement ratio and cooling power are almost on the same line, which means that the displacer diameter has almost no influence.

Comparing Figure 2e, Figure 3a, and Figure 4a, one may observe that the rod diameter ratio and the displacer diameter exert a strong and relatively weak but noticeable influence, respectively, on the phase angle dependence of the swept volume ratio. Comparing Figure 2f, Figure 3b, and Figure 4b reveals that the optimum COP is obtained at a rod diameter ratio of 0.5. A larger rod diameter ratio results in a larger swept volume ratio and visa-versa. Notice that for the rod diameter ratio of 0.5, the optimum swept volume ratio and optimum COP occur at that same phase angle difference.
It is especially significant to note the weak dependence of the swept volume ratio and the COP, on the displacer diameter for a given rod diameter ratio. Although one should be careful to pick an optimum rod diameter ratio, since it has a strong influence on the swept volume ratio, the displacer diameter can be varied without effect. This is very convenient for the design of the displacer, since in many cases one would prefer the displacer diameter to be the same as that of the piston so that they can share the same cylinder within the compressor as shown in Figure 1.

4. Regenerator length effect
Because the pressure drop across the regenerator directly influences the pressure differential available to drive the displacer, it is not surprising that related performance parameters are also influenced by this factor. Indeed, Figure 5 shows the influence of the regenerator length on the swept volume ratio and the COP when the regenerator volume and matrix are held constant. The pressure drop of the regenerator increases with the regenerator length when the volume of the regenerator and the matrix remain constant. The results shown here are for a rod diameter ratio of 0.5 and a displacer diameter of 120mm. Figure 5 shows that the swept volume ratio increases significantly as the regenerator length decreases. The optimum COP value also changes although the optimum phase angle difference...
remains the same. Interestingly, the regenerator length that produces the optimum COP also produces the same dependence of the swept volume ratio on the phase angle difference as the COP.

**Figure 5a** Swept volume ratio versus regenerator length

**Figure 5b** COP versus regenerator length

5. **Voltage effect**
Figures 6a and 6b show the effect of the driving voltage on the COP, cooling power, swept volume ratio, and current displacement ratio with a rod diameter ratio of 0.5 and a displacer diameter of 120mm. Within a wide range, the swept volume ratio and current displacement ratio are essentially constant. The cooling power increases with the voltage. The optimum COP is a very broad function of the voltage above a certain voltage, here 200 V. To obtain a high power density, a high voltage, or high pressure ratio, could be used for the displacer type pulse tube refrigerator without a significant decrease in the COP.

**Figure 6a** Cooling power and COP versus voltage

**Figure 6b** Swept volume ratio and displacement ratio versus voltage
6. Conclusion
Although an optimum rod diameter ratio exists that maximizes the COP of a warm displacer type pulse tube, the performance is only weakly dependent on the displacer diameter. The displacer diameter can therefore be conveniently sized with the piston so that both can be housed in the same compressor cylinder. Increasing rod diameter ratio effectively increases the swept volume ratio. For a fixed refrigerator, the regenerator length, and therefore its pressure drop, also significantly influences the swept volume ratio and COP. Both at the optimum rod diameter ratio and at the optimum regenerator length, the swept volume displays the same dependence on the phase angle difference as does the COP.

7. References
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