Gas Spring Effect in a Displacer Pulse Tube Refrigerator

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ABSTRACT

Displacer type pulse tube refrigerator is a work recover type pulse tube refrigerator. It has high potential to achieve high efficiency. Gas spring in the displacer type pulse tube refrigerator is investigated with numerical simulation in this paper. It is found to be effective for increasing working frequency. With the increase of piston diameter and dead volume, the operation frequency can be increased without increasing the mechanical spring stiffness under the condition of the linear motor operating with current displacement ratio. The displacer rod diameter is not only a parameter to optimize the displacer stroke for the COP, but also is an effective parameter for decreasing the mechanical spring stiffness. Operation frequency increases with an increase in the piston diameter and the dead volume, without increasing mechanical spring stiffness when current displacement ratio is a constant.

INTRODUCTION

Pulse tube refrigerator can be with[1-6] or without[7-10] a warm displacer. The current trend is to develop a Stirling type pulse tube refrigerator with high frequency and high efficiency. High frequency means a high power density in the linear motor which can effectively decrease the weight and the linear motor size. The long development history of inertance tube and double inlet pulse tube refrigerator shows that high efficiency needs a work recover type phase shifter. Warm displacer type pulse tube refrigerator, whose theoretical efficiency is the same as the Stirling refrigerator, is the simplest type of work recover refrigerator. One of the development tendency is to increase the operation frequency[11,12]. Higher frequency means higher stiffness of the spring and lighter of the moving part of the linear motor. Weight of the moving part is limited by material and structure, which is difficult to loss. In brief, increasing stiffness of mechanical spring means to increase the number of flexible springs, which is a high cost method. Increasing gas spring stiffness without increase mechanical spring stiffness of the linear compressor is a realistic method. The gas spring effect of the displacer rod also should be considered for decreasing mechanical spring stiffness of the displacer. In this paper, a numerical simulation is used to study the gas spring effect of the linear motor and displacer.

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STRUCTURE

Figure 1 is the schematic of the warm displacer type pulse tube refrigerator. It includes a compressor, a cold head and a warm displacer. The compressor includes a linear motor, a piston and a dead volume. The cold head includes an after cooler, a regenerator, a cold heat exchanger and a pulse tube. The displacer has a rod which is connected to a spring in the displacer buffer. The displacer forms the displacer front space which is connected to the warm end of the pulse tube and the displacer back space which is connected to the compression space.

The linear compressor supplies power, generates pressure oscillation and oscillation gas flow in the refrigerator. The oscillation gas flow generates a pressure difference across both end of the displacer due to the pressure drop across the regenerator and heat exchangers. There is also a pressure difference across both ends of the rod due to the pressure difference between the displacer buffer and displacer back space, which causes the displacer to oscillate. Regardless of recovering the expansion power from the pulse tube, the displacer acts as a phase shifter to control the gas flow in the regenerator to let the regenerator reach a higher efficiency. The rod has two functions, one is to supply additional driving force for the displacer, another is to be a gas spring due to the pressure difference at both ends of the rod.

Basic data of the refrigerator is found in Table 1. During the numerical simulation, the piston weight and displacer weight is not changed. The resonant point of the linear motor is adjusted by the piston diameter and dead volume. The displacer natural frequency is adjusted by the displacer spring stiffness or rod diameter.

NUMERICAL METHOD

The numerical method found in S. W. Zhu, et. al.[9] is used for this simulation. The linear motor force current relation is assumed to be linear which is available for the moving coil and the moving magnet structure. This method is originally developed for the simulation of the double inlet pulse tube refrigerator[4], and improved for the simulation of the inertance tube pulse tube refrigerator[5], and some other types of pulse tube refrigerators. Past developments such as double inlet, inertance tube and active buffer pulse tube refrigerator, show that it is effective for the mechanism study of a new type of pulse tube refrigerator. The invention of the double inlet pulse tube refrigerator is partly due to the result of this numerical method.

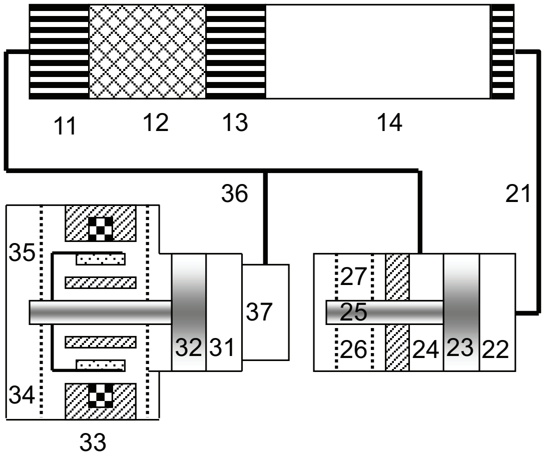

Figure 1. Displacer pulse tube refrigerator with rod: 11. warm heat exchanger 12. regenerator 13. cold heat exchanger 14. pulse tube 21. displacer connecting tube 22. displacer front space 23. displacer 24. displacer back space 25. displacer rod 26. displacer spring 27. displacer buffer 31. compression space 32. compressor piston 33. linear motor 34. motor spring 35. motor house 36. compressor connecting tube 37. dead volume

Table 1. Basic data of the refrigerator

Regenerator	Φ80mm×50mm, wire diameter 0.025mm, porosity 0.7
Pulse tube	Φ30mm×150mm
Motor	Spring stiffness 160N/mm, piston weight 2.9kg, motor force factor 100N/A, voltage 500V
Displacer	Displacer diameter 70mm, rod diameter 35mm, weight 0.4kg, spring stiffness 150N/mm
Operation condition	Room temperature 300K, refrigeration temperature 77K, charge pressure 2MPa, operation frequency 100Hz

PISTON DIAMETER EFFECT

In order to let a pulse tube refrigerator whose natural frequency is lower than operation frequency to match the resonant point without increasing the mechanical spring, the piston diameter should be enlarged to increase the gas spring stiffness. With the increase in the piston diameter, the compressor will supply extra gas to the cold head. In order to balance the extra gas, a dead volume is needed. Figure 2a shows the piston diameter effect to the dead volume(Vd) of the compressor. Figure 2b shows the piston diameter effect to the current displacement ratio of the linear motor(I/Xp), and the current (I). Figure 2c shows the piston diameter effect to the displacement of the piston(Xp), the displacer(Xd), and the phase angle difference (ϕ) between the piston and displacer. Figure 2d shows the piston diameter effect to the input power(W), and the cooling power(Q). Figure 2e shows the piston diameter effect to the COP and motor efficiency(Em). With the piston diameter expanding, the dead volume and piston displacement increase; and the current, current displacement ratio, phase angle difference between the piston and displacer decrease for the same performance. There is a peak for the displacer displacement, the motor input power, the cooling power, and the COP when the piston diameter increasing. Motor efficiency increases with piston diameter increasing as well.

For a given linear motor, there is an optimal current and displacement. There is a ratio of the optimum current divided by the optimum piston displacement which is named optimum current displacement ratio. Finding the best match of the linear motor becomes a search to find the relation between the optimum displacement ratio and the piston diameter. Figure 2 shows that the optimum displacement ratio decreases with an increasing piston diameter. Hence, there is a piston diameter with which the optimum current displacement ratio can be reached.

ROD DIAMETER EFFECT

The linear motor can reach high frequency with increasing piston diameter. The displacer also can operate at a high frequency with a larger rod diameter, which is demonstrated in Figure 3. As shown in Figure 3, piston diameter is 152mm, when rod diameter is increased from 5mm to 45mm, though there is a peak of COP, the difference is rather small in a wide range, the spring stiffness of the displacer(Kd) almost decreases about 100 N/mm when the rod diameter increases from 5mm to 45mm. Due to the increasing rod diameter, the dead volume of the compressor has to be increased a little in order to adjust the resonant point of the linear motor (Figure 3a). The current displacement ratio and current increase slightly (Figure 3b). The piston displacement basically has no variation, the displacer displacement has few increasing (Figure 3c). The phase angle difference between the piston and displacer, input power and cooling power increase (Figure 3d). The motor efficiency almost remains unchanged (Figure 3e).

Rod diameter has a strong effect of decreasing mechanical spring stiffness, and has a slight influence on the others, thereby, we may design the displacer with a slightly larger rod diameter for decreasing the mechanical spring.

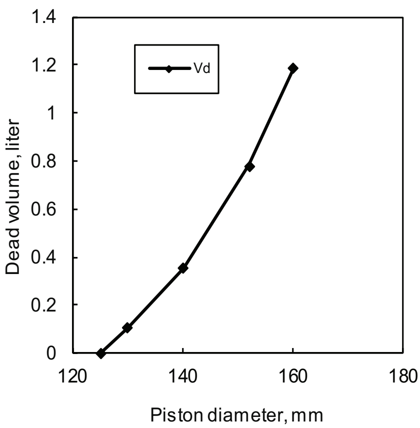

Figure 2a. Dead volume vs. piston diameter

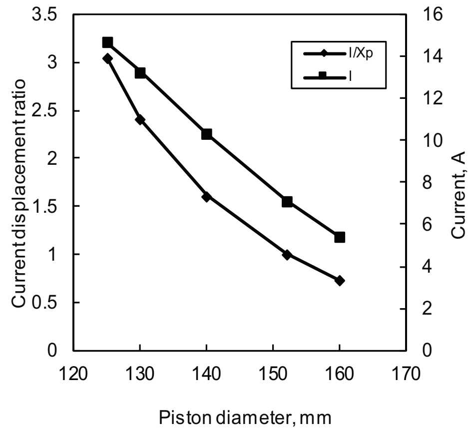

Figure 2b. Current diplacement ratio and current vs. piston diameter

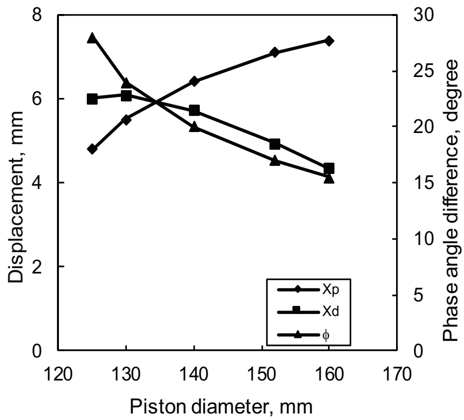

Figure 2c. Phase angle diffference and displacement of piston and displacer vs. piston diameter

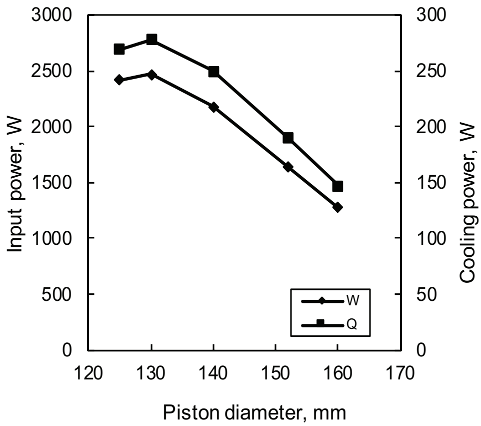

Figure 2d. Input power and cooling power vs. piston diameter

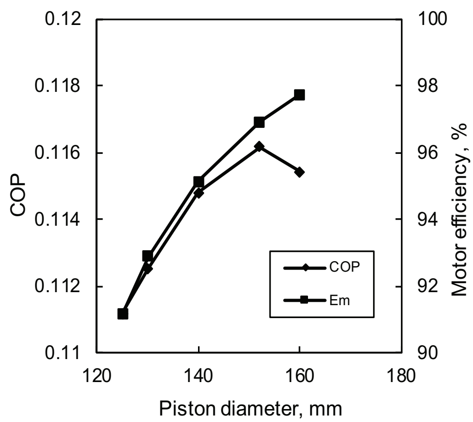

Figure 2e. COP and motor efficiency vs. pistion diameter

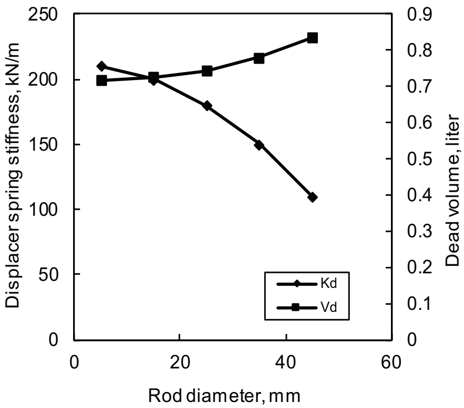

Figure 3a. Dead volume and displacr stiffness vs. rod diameter

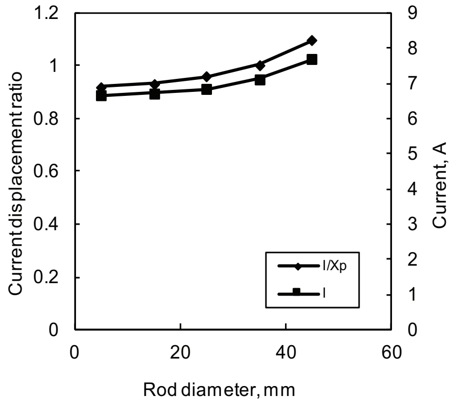

Figure 3b. Current displacement ratio and current vs. rod diameter

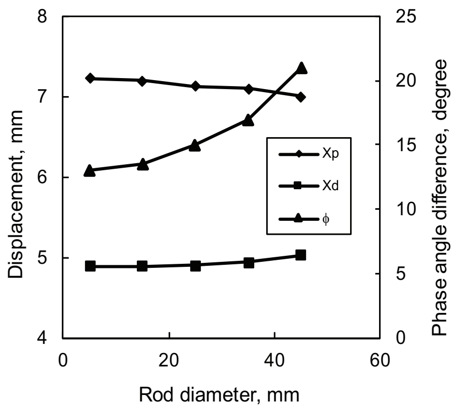

Figure 3c. Phase angle diffference and displacement of piston and displacer vs. rod diameter

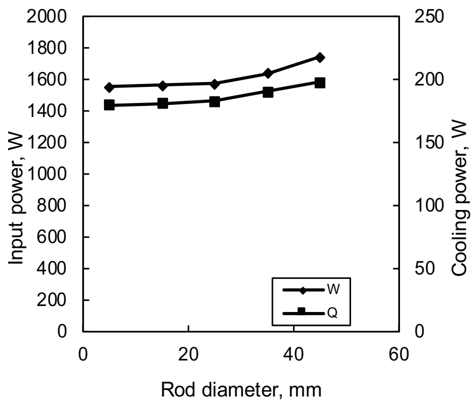

Figure 3d. Input power and cooling power vs. rod diameter

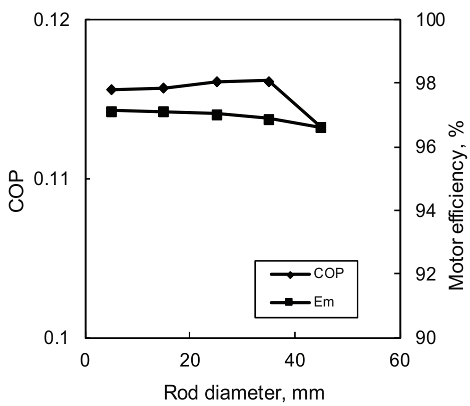

Figure 3e. COP and motor efficiency vs. rod diameter

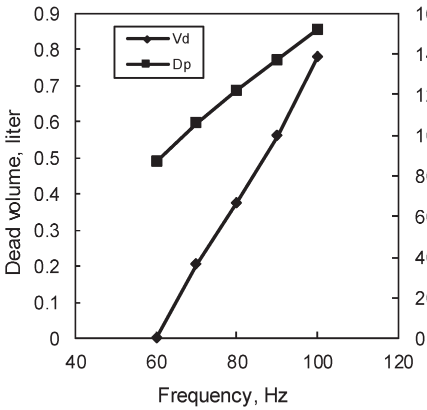

Figure 4a. Dead volume and piston diameter vs. frequency

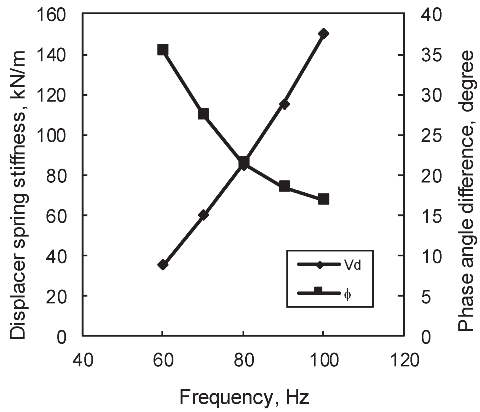

Figure 4b. Displacer spring stiffness and phase angle difference vs. frequency

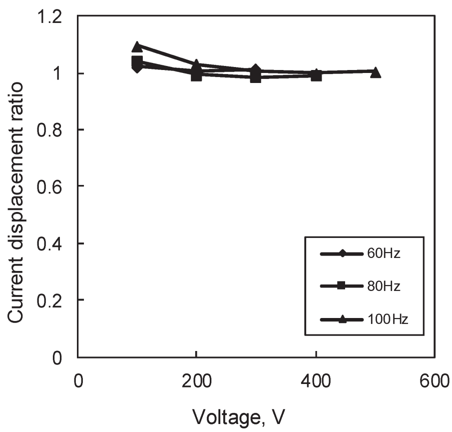

Figure 5a. Current displacement ratio vs. frequency and voltage

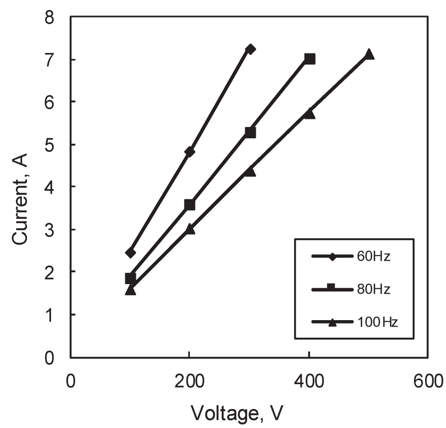

Figure 5b. Current vs. frequency and voltage

FREQUENCY EFFECT

Assuming the rated current displacement ratio is 1A/mm, displacer spring stiffness can be changed to fit the frequency change, the piston diameter and compressor dead volume can be adjusted to let linear motor operate at resonant point. The frequency effect is shown in Figure 4. Figure 4 shows that the piston diameter, compressor dead volume (4a), displacer spring stiffness (4b) increases with an increase in frequency. The phase angle difference between the piston and displacer decrease. Figure 5 shows the current displacement ratio (5a), current (5b), input power (5c), cooling power (5d) and COP change (5e) with the voltage. There is a peak COP for each frequency. At higher frequency, the COP is lower. Current is almost increases linearly with the an increase of voltage. However, the current displacement ratio almost does not change when the voltage increases.

Figure 5e shows that the cold head should be redesigned for a higher operation frequency. Otherwise, the efficiency decreases with an increase of operation frequency. Figure 5a shows that the current displacement ratio is a weak function of voltage for a rather wide range. So, in Figure 2, we can use constant voltage to find the relation between the current displacement ratio and the piston diameter.

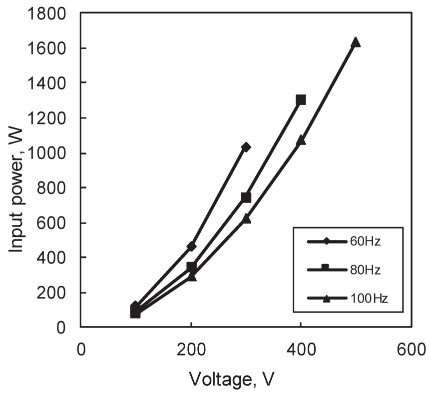

Figure 5c. Input power vs. frequency and voltage

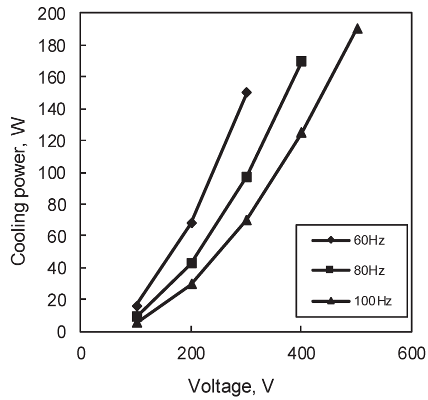

Figure 5d. Cooling power vs. frequency and voltage

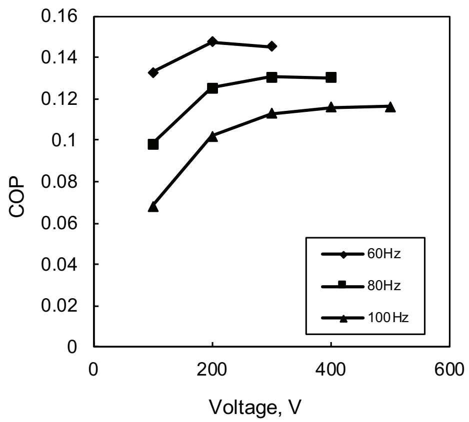

Figure 5e. COP vs. frequency and voltage

CONCLUSION

For a displacer type pulse tube refrigerator, operating at some frequency, the dead volume should be increased to keep the linear motor at its resonant point. When the piston diameter is increased, the current displacement ratio decreases with the piston diameter increasing, which means that there is a piston diameter that the linear motor can be operated at resonant point with the optimum current displacement ratio. An increase in the rod diameter can decrease the mechanical spring stiffness at same operation frequency. The rod diameter influences the motor matching slightly with the cold head. Operation frequency increases with an increase in the piston diameter and the dead volume without increasing mechanical spring stiffness at the optimum current displacement ratio.

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