Pressure Ratio Effect to Warm Displacer Type Pulse Tube Refrigerator

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ABSTRACT

A two-stage pulse tube refrigerator with a warm step displacer is discussed with a numerical simulation model. It is shown that there is an optimum swept volume ratio of displacer over compressor or an optimum pressure ratio for a given refrigerator with a given compressor. There is an optimum compressor swept volume or an optimum pressure ratio for a given refrigerator.

INTRODUCTION

In an ordinary two-stage pulse tube refrigerator[1-4], the inertance tube is used as a phase shifter. The theoretical efficiency can increase by using a warm displacer as a phase shifter[5-7]. Changing the displacer as to a step displacer for both stages is a simple structure for a two-stage cooler[8]. The advantage of this type of refrigerator is the high theoretical efficiency. We can use any pressure ratio we want, and can also use a lower frequency for higher efficiency. High pressure ratios mean high temperature oscillation in the compression space, pulse tubes, and displacer spaces which generate high irreversible losses in the heat exchangers. The pressure ratio effect for a precooling type two stage pulse tube refrigerator and a numerical simulation is discussed in this paper.

STRUCTURE

Figure 1 is the schematic of the step-displacer type two stage pulse tube refrigerator. The first stage includes a first stage consisting of an after-cooler, a regenerator, a cold head, a pulse tube and a pulse tube gas distributor. The second stage includes an after cooler, a first regenerator, a precooler, a second regenerator, a cold head, a pulse tube and a pulse tube gas distributor. There is a step-displacer as a phase shifter for the first stage and the second stage. A compressor supplies gas to the first stage and the second stage, and the cold head of the first stage and the precooler is connected by a heat bridge.

The displacer has two expansion spaces. One is for the first stage pulse tube and the other is for the second stage pulse tube. The displacer spaces get the expansion work. The back space of the displacer transfers the expansion work to the compressor side, and is reused as input work.

ADVANTAGE

Compared to the inertance tube or the double inlet two-stage pulse tube refrigerator, one moving part is added and this is the disadvantage. Until now, it has been difficult for pulse tube refrig-

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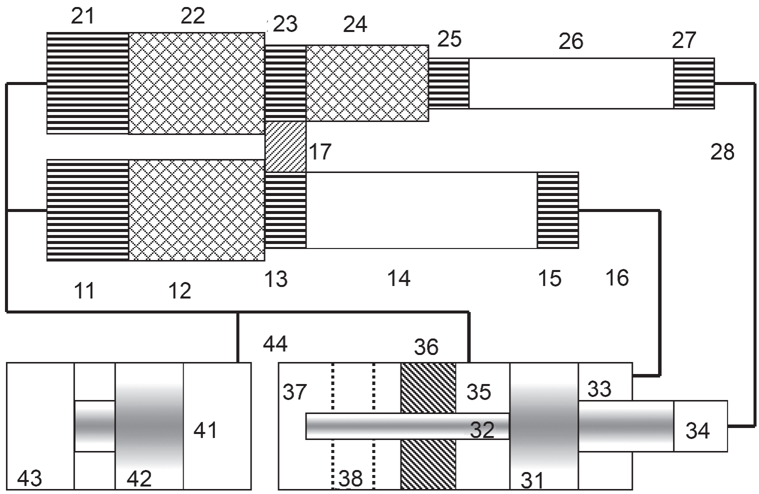

Figure 1. Schematic of the two-stage pulse tube refrigerator with step-displacer

11. first stage after cooler	12. first stage regenerator	13. first stage cold head
14. first stage pulse tube	15. first stage gas distributor	16. first stage connecting tube
17. heat bridge	21. second stage after cooler	22. second stage first regenerator
23. pre-cooler	24. second stage regenerator	25. second stage cold head
26. second stage pulse tube	27. second stage gas distributor	28. second stage connecting tube
31. step-displacer	32. displacer rod	33. displacer first space
34. displacer second space	35. displacer back space	36. stopper
37. displacer buffer	38. suspension spring	41. compressor space
42. piston	43. linear motor	44. compressor connecting tube

erator with an inertance tube or a double inlet to reach the same efficiency as a Stirling refrigerator. There are possible three reasons: (1) expansion work is not recovered, (2) the phase shift effect is not sufficient, and (3) the pressure ratio is not high enough. A step displacer at room temperature can solve the above three problems and does not add any moving part at low temperature.

NUMERICAL METHOD

Assuming a one dimensional periodic unsteady flow without pressure drop, the numerical method without momentum equation[9] is used for the numerical simulation. This method is developed for the numerical simulation of the double inlet pulse tube refrigerator. It is used for the development of the active buffer pulse tube refrigerator, and improves the simulation of the thermal acoustic engine and inertance tube pulse tube refrigerator. The development of some of the refrigerators in industry and basic research shows that this method is suitable for the basic study of pulse tube refrigerators.

In this paper, we choose a no pressure drop model to focus on the analysis of the compression ratio effect.

DISPLACER EFFECT

Table 1 shows the basic data of the two-stage pulse tube refrigerator. The working medium is helium gas. It is assumed that room temperature, the first stage refrigeration temperature and second stage refrigeration temperature is 300K, 80K, 20K, respectively. The charge pressure is 2 MPa. and the working frequency is 20 Hz. The displacer swept volume ratio is the ratio of the displacer swept volume over the compressor swept volume. The step ratio is the swept volume of the displacer for the first stage over that for the second stage. The phase angle difference is the difference between the phase angle for the compressor and displacer.

Table 1. Main parameters of the refrigerator

First stage after cooler	Gap width 982mm, height 0.33mm, length 60mm
First stage regenerator	Φ50mm×50mm, mesh wire diameter 0.035mm, porosity 0.7
First stage cold heat exchanger	Gap width 1257mm, height 0.33mm, length 30mm
First stage pulse tube	Φ40mm×150mm
Second stage after cooler	Gap width 982mm, height 0.33mm, length 60mm
Second stage first regenerator	Φ50mm×50mm, mesh wire diameter 0.035mm, porosity 0.7
Pre-cooler	Gap width 628mm, height 0.33mm, length 20mm
Second stage second regenerator	Φ40mm×30mm, mesh wire diameter 0.025mm, porosity 0.62
Second stage cold heat exchanger	Gap width 314mm, height 0.33mm, length 30mm
Second stage pulse tube	Φ20mm×195mm
Compressor swept volume	200cm^3
Phase angle difference	60 degrees
Displacer swept volume ratio	0.375
Displacer dead volume ratio	0.1
Displacer step ratio	3

For a given pulse tube refrigerator with a given compressor swept volume, the displacer swept volume ratio and the phase angle difference between the compression space and displacer space should be optimized.

Figure 2 shows the mass flow rate and pressure at the cold ends of pulse tubes for the first stage and second stage. There is phase angle difference between the pressure and mass flow rate at the cold end of the pulse tube, which indicates good working condition for regenerators.

Figure 3 shows the equivalent PV diagrams in the pulse tube. There is a sufficient distance between the PV diagrams at the cold ends and the warm ends of pulse tubes, which indicate low shuttle loss.

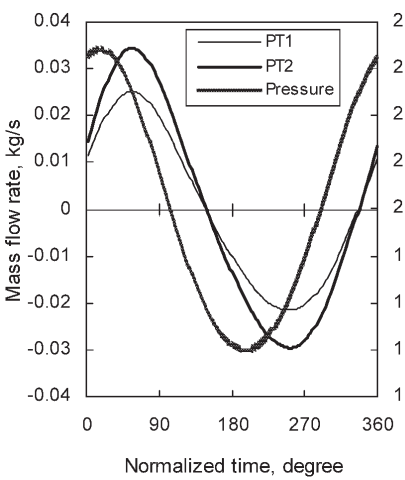

Figure 2. Mass flow rate and pressure at the cold end of pulse tubes

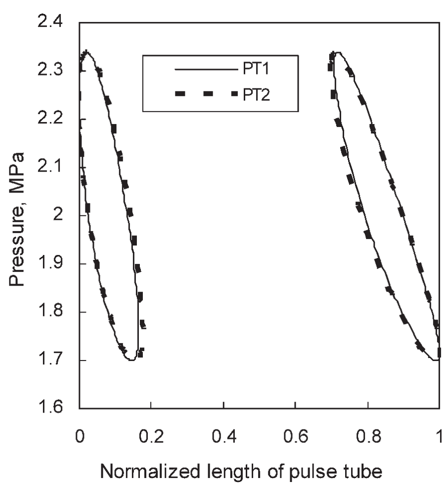

Figure 3. Equivalent PV diagrams

Figure 4 shows the exergy flow at the left end of each component. Exergy flow decreases at the left end of each component, except the precooler. In Figure 4a, 1-6 represent the first stage after cooler, the first stage regenerator, the first stage cold head, the first stage pulse tube and the first stage pulse tube gas distributor. In Figure 4b, 1-8 present the second stage after cooler, the second stage first regenerator, the precooler, the second stage second regenerator, the second stage cold head, the second stage pulse tube and the second stage pulse tube gas distributor.

In the after cooler, part of the exergy flow is lost. We call this loss a compressor loss. It includes the non-isothermal compression loss and heat exchanger loss. In the regenerators, part of the exergy flow is lost. We call it a regenerator loss. The remain exergy flows through cold head where part of it is transferred out as cooling power, part of it flows to the pulse tube, decreases a little due to shuttle loss, and the last part is received by the displacer expansion spaces. Pulse tube loss is defined as the exergy flow at the cold end of the regenerator minus the exergy of the cooling power and the expansion works of the displacer spaces. It includes non-isothermal expansion loss, shuttle loss and heat exchanger loss. The precooling is also a loss, which includes the cooling power loss and exergy loss due to heat transfer in the precooling heat exchanger. If the regenerator of the second stage is very good, precooling is not necessary.

Figure 5 shows input power, pressure ratio, first stage cooling power, second stage cooling power, and efficiency, vs. the swept volume ratio and phase angle difference with compressor swept

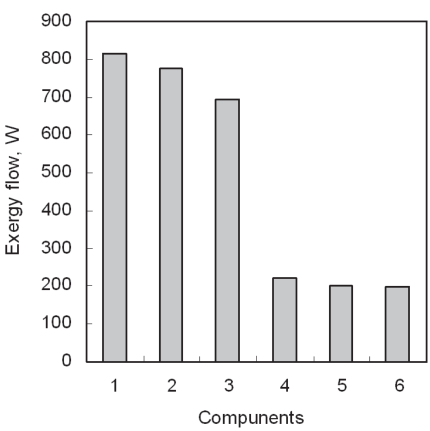

Figure 4a. First stage exergy flow

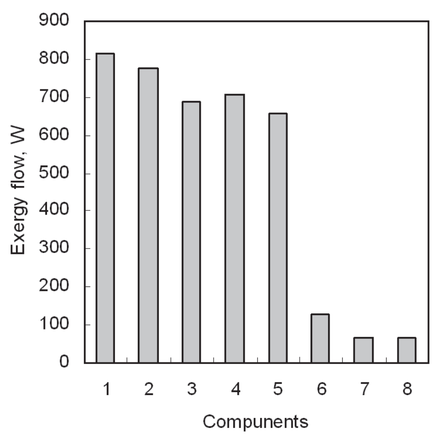

Figure 4b. First stage exergy flow

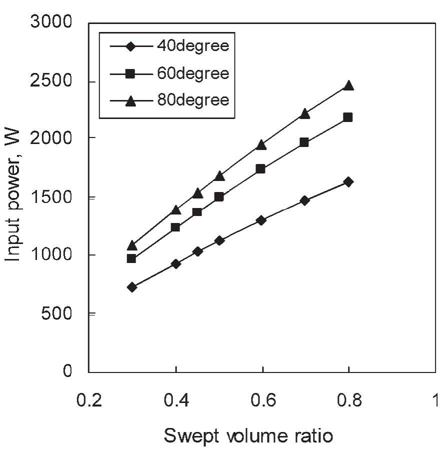

Figure 5a. Input power

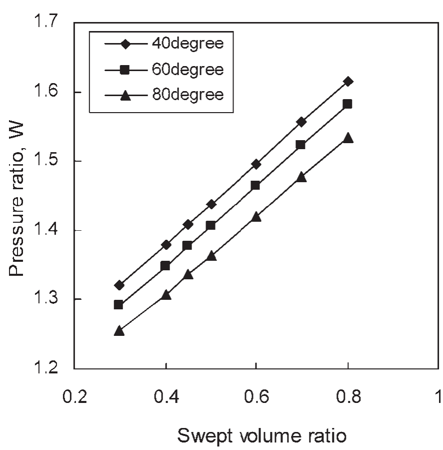

Figure 5b. Pressure ratio

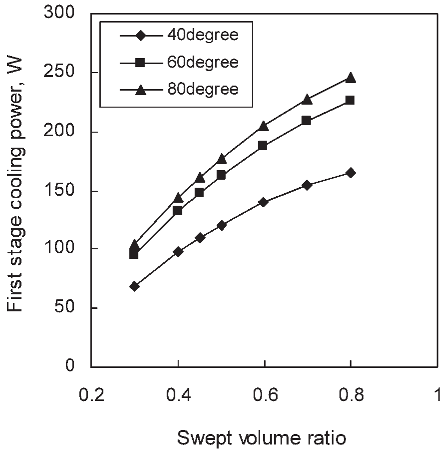

Figure 5c. Cooling power of the first stage

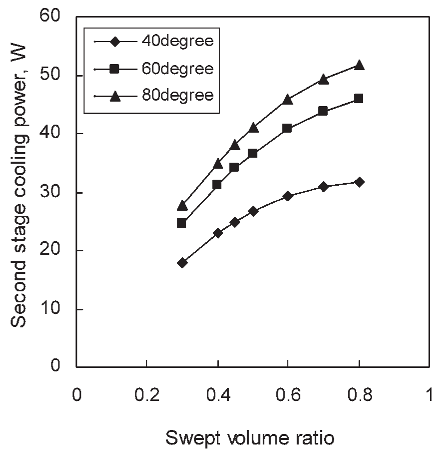

Figure 5d. Cooling power of the second stage

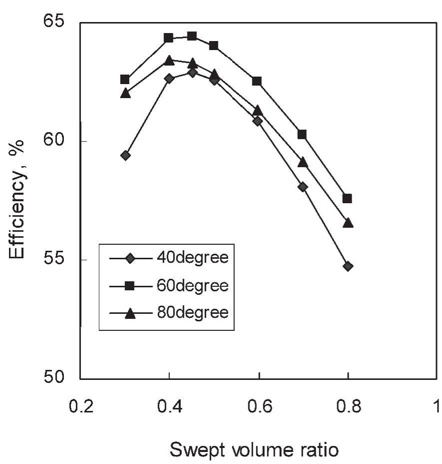

Figure 5e. Efficiency

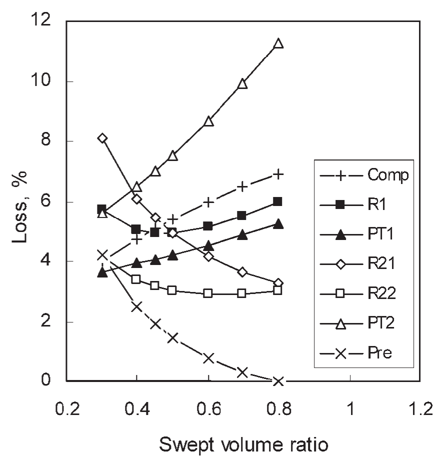

Figure 6. Loss

volume 200 cm^3. In the calculation range, cooling power of the first stage and second stage, input power, increase with the increasing of the swept volume ratio and phase angle difference. Pressure ratio increases with swept volume ratio and decreases with the increasing of the phase angle difference. There is an optimum swept volume ratio and phase angle difference with which the efficiency is the maximum. We can say that there is an optimum pressure ratio for efficiency because the pressure ratio is proportional to the swept volume ratio.

Figure 6 shows the loss vs. swept volume ratio at 60 degree phase angle difference. The compressor loss and pulse tube losses increase with the increasing of the displacer swept volume ratio, or increase with the increasing of the pressure ratio. There is a lowest loss point for the first stage regenerator and second stage second regenerator in the calculation range. The second stage first regenerator loss and precooling loss decrease with the increasing of the swept volume ratio. The lowest point of the first stage regenerator loss and second stage second regenerator loss is near the maximum efficiency point. At this point, precooling is important for getting cooling power for the second stage. It is a first stage load.

COMPRESSOR SWEPT VOLUME EFFECT

Figure 7 shows the compression swept volume effect. The compressor swept volume is 100 cm^3, 200 cm^3, 300 cm^3, and 400 cm^3. For each compression swept volume, there is an optimum swept volume ratio for peak efficiency, and the optimum swept volume ratio decrease with the increasing of the compressor swept volume. The phase angle is kept as 60 degree which is optimum. The pressure ratio increases with the increasing of the compressor swept volume.

In Figure 8, the cooling power, input power, efficiency, and pressure ratio is from the optimum point for each compressor swept volume in Figure 7. The input power, cooling powers and pressure ratio increase with the increasing of the swept volume of the compressor, there is an optimum swept volume with which the efficiency gets peak. In another words, there is an optimum pressure ratio with which efficiency is maximum.

Figure 9 shows the loss and efficiency vs. swept volume ratio with compressor swept volume 400 cm^3. The lowest point of the regenerator is not the high efficiency point. This may be caused by the compressor loss and the pulse tube loss increases rapidly with the increasing of the swept volume ratio. Other losses do not make a big difference with the 200 cm^3 swept volume compressor.

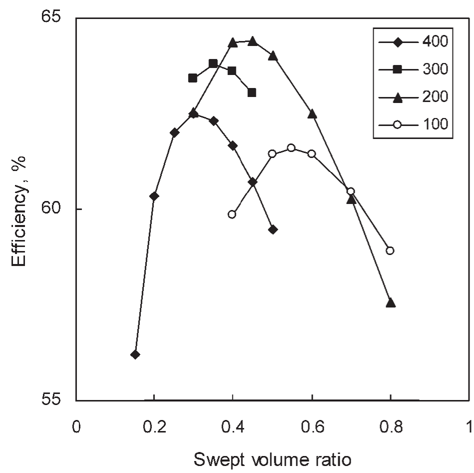

Figure 7a. Efficency vs. compressor

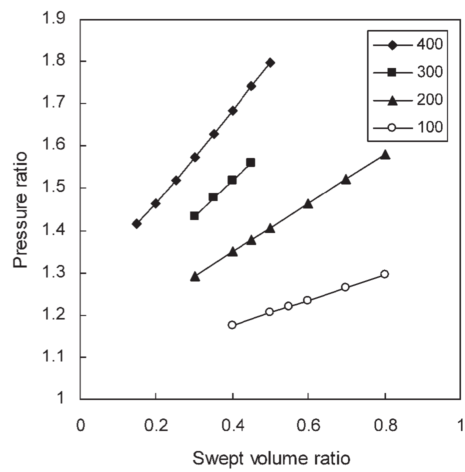

Figure 7b. Pressure ratio vs. compressor

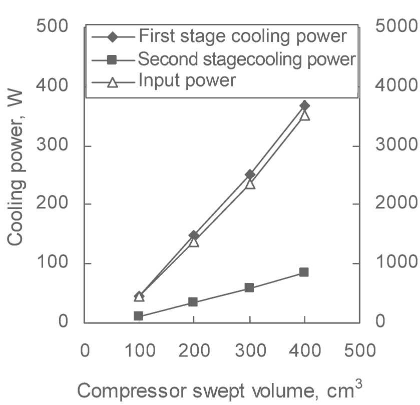

Figure 8a. Cooling power and input power vs. compressor swept volume

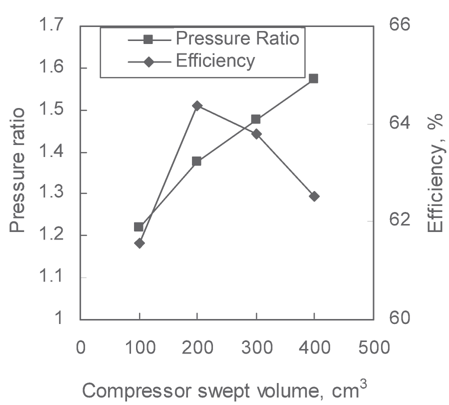

Figure 8b. Efficiency and pressure ratio vs. compressor swept

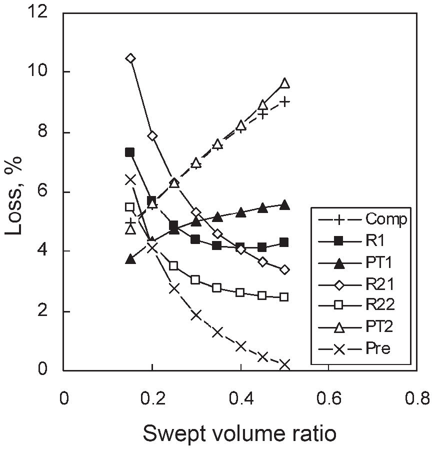

Figure 9. Loss with 400cm^3 compressor

CONCLUSION

For a fixed compressor swept volume with a given refrigerator, it is found that the optimum swept volume ratio of the displacer over the compressor can be predicted by the computing method used in this paper. The pressure ratio is almost proportional to the swept volume ratio, therefore there is an optimum pressure ratio. The loss of the first stage regenerator and the second stage second regenerator have a minimum point within the calculated range, however the loss of second stage first regenerator and precooling heat exchanger decrease within the calculated range. The loss of compressor and pulse tubes increase with the increasing of the swept volume ratio or the pressure ratio.

For a given refrigerator, there is an optimum compressor swept volume where the efficiency is maximized. The cooing powers, input power, and the pressure ratio are proportional to the compressor swept volume. Stated in a different manner, there is an optimum pressure ratio where the efficiency is maximized.

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