The influence of pressure ratio on the regenerator performance

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Abstract. For a multi-stage pulse tube refrigerator with displacer, improving the regenerator efficiency is important. A displacer can get higher operating pressure ratio compared with inertance tube. The pressure ratio and porosity influence on the regenerator performance with is discussed, and CFD simulation is done on a two-stage pulse tube refrigerator with displacer to show that mass flow rate and pressure wave relation in the regenerator can be realized by a step-displacer.

1. Introduction

Stirling type pulse tube refrigerators have already been developed as a commercial product. Moreover, it plays an important role in cooling infrared sensors on satellites. The high reliability, simple structure and long lifetime are the advantages that drive us to extend its application range. However, after many attempts, the efficiency at 20 K is still not good. The primary reason is that the regenerator has poor performance at low temperature. Many studies have been done on the regenerator [1-7]. One of the problems is that the specific heat capacity of stainless steel or copper screen becomes very low. Lead shot is not qualified in high frequency, though, its specific heat capacity and packing factor can be much higher than stainless steel or copper screen. To solve this problem, the compressed mesh is considered a solution, which can realize a high packing factor with stainless steel screen. Another problem is that the traditional phase shifter, such as inertance tube, is not strong enough to get high-pressure ratio and suitable phase angle difference. To solve this problem, the concept of step-piston pulse tube refrigerator has been put forward [8]. In this way, the phase shifter changes into solid piston, which is confirmed to be a more effective second stage [9].

This article focuses on the performance the second stage regenerator. With the software REGEN3.3 [10], the regenerator performance with compressed stainless screen and high pressure ratio is discussed. Furthermore, based on the result from REGEN3.3, Ansys Fluent [11] is used to simulate the two-stage pulse tube refrigerator with step displacer with 2D model.

2. Model description

The numerical simulation tool is REGEN 3.3 developed by NIST. It is a powerful tool to investigate the influence of geometry, material, frequency, temperature, pressure ratio, charge pressure and the phase angle difference between flow and pressure on regenerator performance.
In REGEN 3.3, a discretization of the differential equations for conservation of mass, momentum and energy in the gas and regenerator matrix is used. Newton iteration is used for solving the equations of the temperature, pressure and mass flux at all the mesh points simultaneously.

In the numerical simulation, the pressure is assumed as sinusoidal as

\[ P = P_0 (1 + \frac{r-1}{r+1} \sin(\omega t)) \]  

(1)

Where \( P \) is the momentary pressure; \( P_0 \) is the charge pressure; \( r \) is the pressure ratio.

We defined the mass flow rate of the cold end as described in \[2\]

\[ \dot{m}_c = m_{c0} \sin(\omega t) - \alpha \frac{V_R}{RT_R} P_0 \frac{r-1}{r+1} \omega \cos(\omega t) \]  

(2)

Where \( \dot{m}_c \) is the mass flow rate at the cold end; \( m_{c0} \) is the mass flow rate in phase with the pressure wave; \( \omega \) is the angular frequency; \( t \) is the time; \( \alpha \) is a constant; \( V_R \) is the void volume of the regenerator; \( R \) is the gas constant.

By this definition, the mass flow rate at cold end of the regenerator consists two terms. One is the first term of right side of the Eq. (2), which is in-phase with the pressure wave to generate cooling power and in the following description of REGEN model, the mentioned mass flow rate is \( m_{c0} \); the second term represents the mass flow generated by the void volume of the regenerator. Figure 1 shows the equivalent phasor diagram of the Eq. (2). In Figure 1, \( \theta \) represents the phase angle difference between the mass flow rate and pressure wave at the cold end of the regenerator. For a given regenerator, there is an optimum \( \alpha \) to optimize regenerator efficiency. In this way, the function of the phase shifter in the pulse tube refrigerator is adjusting the value of \( \alpha \). The displacer type phase shifter can achieve any \( \alpha \).

In this calculation, we change \( \alpha \) instead of the phase angle difference between mass flow rate and pressure wave. However, in the REGEN 3.3, only the phase angle difference can be defined. Therefore, a transform between \( \alpha \) and phase angle difference is performed.

The dimension of the regenerator is \( \Phi \ 25 \ mm \times 50 \ mm \). The mass flow rate, pressure ratio, mesh porosity, frequency and charge pressure are discussed. Helium gas is working medium. High temperature is 80 K, while low temperature is 20 K.

![Figure 1. Phasor diagram of the mass flow rate at the cold end of regenerator](image)

3. Regen simulation results

3.1. Mass flow effect

Figure 2a, Figure 2b and Figure 2c show the efficiency, cooling power and input power with different mass flow rate and \( \alpha \), when porosity is 0.5. Here, the frequency is 30 Hz, charge pressure is 1.5 MPa, and pressure ratio is 1.3. With the changing of \( \alpha \), there is an optimum efficiency for different mass flow rate. Figure 2b and Figure 2c show the cooling power and input power change with \( \alpha \) and mass flow rate. For equivalent mass flow rate, the cooling power is nearly constant. The input power is getting smaller gradually with the increase of \( \alpha \). When \( \alpha \) is greater than 0.8, the input power is constant, which is in accordance with the efficiency in Figure 2a.

Figure 3a and Figure 3b show the efficiency with different porosity. Compared with Figure 2a, the efficiency decreases with the increase of porosity. When achieving the optimum efficiency, the value of
α is about 0.8 with porosity 0.5 and 0.6, while it is about 0.6 with porosity 0.7. From these Figures, we find the mass flow rate at optimum efficiency is unchanged with different porosities.

3.2. Pressure ratio effect
Figure 4a, Figure 4b and Figure 4c show the efficiency changing with pressure ratio of different porosities. When the pressure ratio changes, the α to get the optimum efficiency is almost same. The optimum pressure ratios are different with different porosities. With a lower porosity, a high pressure ratio leads to better performance. When the pressure ratio is higher than the optimum pressure ratio, the efficiency does not decrease much. However, as can be seen from Figure 4d and Figure 4e, a high pressure ratio can achieve a high input power and cooling power.
Figure 4a. Efficiency vs. Pressure ratio
Figure 4b. Efficiency vs. Pressure ratio
Figure 4c. Efficiency vs. Pressure ratio
Figure 4d. Cooling power vs. pressure ratio
Figure 4e. Input power vs. pressure ratio
3.3. Mixing mesh effect

The thermal capacity of stainless steel sharply decreases at low temperature. Therefore, the porosity of the regenerator should be decreased to improve the volume of filling material. The compressed mesh is an efficient way to get a much lower porosity, which is cost-effective and gained easily. Figure 2a, Figure 3a and Figure 3b show the efficiency improvement with a lower porosity mesh. The result shown in Figure 5a is much more intuitive. The low porosity can improve the efficiency significantly, and with a mixing mesh, the efficiency can be improved further. The mixing mesh means half of the regenerator, which is near the hot end of the regenerator, is filled with high porosity mesh, while the rest part is filled with low porosity mesh. In Figure 5a, we can also find that the low porosity mesh can achieve good performance at high pressure ratio. Over a certain value, the pressure ratio does not benefit the efficiency.

Figure 5b shows the performance of the regenerator with mixing mesh. When any other parameters are fixed, there is an optimum pressure ratio with different mass flow rates. The efficiency of a generator is the balance of generated cooling power and losses. If the mass flow is getting larger, the losses, both pressure drop and thermal loss, are getting bigger. We need to increase the pressure ratio to get a higher cooling power. Therefore, for a large mass flow rate, the big pressure ratio is much suitable.

3.4. Charge pressure and frequency effect

Figure 6 shows low operating frequency and low charge pressure lead to high efficiency, with pressure ratio of 1.3, mass flow rate of 0.004kg/s and $\alpha$ of 0.8. The efficiency is improved significantly with a low charge pressure. However, in a real refrigerator, with the same input power, the lower charge pressure means larger swept volume of the compression space. Moreover, from the aspect of the efficiency of the linear compressor, the operating frequency should not be too low. Therefore, the charge pressure and frequency should be determined based on the operating condition of the compressor.

![Figure 5a: Mixing mesh effect](image1)

![Figure 5b: Performance with mixing mesh](image2)

![Figure 6: Charge pressure and frequency effect](image3)
4. The CFD model of the two-stage pulse tube refrigerator

To check if we can get the desired pressure ratio and \( \alpha \), we build a two-dimensional model of step piston type two-stage pulse tube refrigerator with ANSYS Fluent [11], shown in Figure 7. ANSYS Fluent has already been successfully used in simulating the pulse tube in many studies [12-16]. In this model, the filling material in the regenerator is stainless steel while in the heat exchanger is copper. The specific heat capacity and heat conductivity of the both materials and working medium, here is helium, are changing with temperature based on the database of NIST [17]. The dynamic mesh method is used for simulating the movement of the piston of compressor and expanders. The non-equilibrium thermal model is used in regenerators. In this simulation, the unsteady second order model, the pressure based coupled algorithm, PRESTO! Pressure based solver, PISO scheme for pressure-velocity coupling, second order upwind for the density, momentum, turbulence model parameters and energy are used. Viscous models of k-omega is used. The parameters used in the CFD model is listed in Table 1.

![Figure 7. Temperature distribution at the beginning](image)

| Components                        | Parameters       | size     | porosity |
|-----------------------------------|------------------|----------|----------|
| Compressor (c)                    |                  | 60cc     | -        |
| First stage displacer(dis1)       |                  | 40cc     | -        |
| Second stage displacer(dis2)      |                  | 8cc      | -        |
| First stage hot heat exchanger(ex1)|                  | Φ43mm*30mm | 0.7    |
| First stage regenerator(rg1)      |                  | Φ43mm*50mm | 0.7    |
| First stage cold heat exchanger(ex2)|                  | ~Φ43mm*15mm | 0.7    |
| First stage pulse tube(pt1)       |                  | Φ24mm*110mm | -    |
| Second stage regenerator(rg2)     |                  | Φ22mm*50mm | 0.7+0.5 |
| Second stage heat exchanger(ex3)  |                  | ~Φ24mm*10mm | 0.7    |
| Second stage pulse tube(pt2)      |                  | Φ10mm*155mm | -    |

The phase angle difference of compressor piston and displacer piston is 25° Charge pressure is 1.5MPa, Frequency is 30Hz.
In Figure 8a, the pressure wave in compression space and two expansion spaces are presented, the pressure ratio is over 1.4. Figure 8b shows the mass flow rate at different places of the second stage, the phase angle of the mass flow rate is changing along the regenerator. In the point $x=0.4$ ($x=1$ means the hot end of rg2, $x=0$ means the cold end of rg2), the mass flow rate and the pressure wave are in-phase, which is near the middle of the regenerator. Figure 8c shows the mass flow rate at different places of the first stage. There is also a point that the mass flow rate and pressure wave are in-phase. But the value of $x$ has a different meaning from $\alpha$. According to Figure 8b, we can know that the phase angle difference between the pressure wave and mass flow rate at the out of regenerator is about $-60^\circ$ ($-$ means mass flow rate lagging pressure wave). With the information from Figure 8b and the parameters in Table 1, we are able to calculate that, in this case, $\alpha$ is around 0.7–0.8. This is consistent with the previous calculation. The mean purpose of simulating this model with CFD is to show that the required phase angle can be got by the step displacer. So it is feasible to get a high performance with such an experimental setup.

5. Conclusion
To improve the performance of the regenerator at low temperature, the compressed mesh and mixing compressed mesh are discussed. The results show that the lower porosity can improve the efficiency significantly, while the mixing compressed mesh can improve the efficiency further. With a low porosity mesh, a high pressure ratio should be selected to get a good performance. A CFD model is built with
ANSYS Fluent. The results show that the suitable phase angle difference and pressure ratio can be achieved. An experimental setup will be fabricated based on the simulation results.

6. References

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