Investigation on the Performances of the Gas Driven Vuilleumier Heat Pump

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ABSTRACT

Gas driven Vuilleumier heat pump is a closed cycle, where the working gas is kept inside the three cylinders and the heat of gas and surroundings are added to and removed from the cycle through heat exchanger. It has many advantages, such as fewer moving parts, low noise and long lifespan. Competitive to absorption cycle, It has the potential for higher Coefficient of Performance (COP). A prototype Vuilleumier heat pump is taken for an example to analyze the performances of gas driven VM heat pump. Results indicate that with higher mean working pressure, the performance of system is improved. As the cold cylinder temperature decrease, refrigerating capacity and COP are both decrease. The refrigerating capacity of gas driven VM heat pump is increased while the COP is decreased with an increase in the rotational speed. Selection of the working gases is also discussed.

1. INTRODUCTION

The Vuilleumier (VM) cycle is based on the same thermodynamic principles as the Stirling cycle. Like the Stirling cycle, the VM is a closed cycle, where the working gas is kept inside the cylinders and heat is added to and removed from the cycle trough heat exchangers (Carlsen, 1989). It has many advantages, such as fewer moving parts, low noise and long lifespan. Competitive to absorption cycle, It has the potential for higher Coefficient of Performance (COP).

Gas driven VM heat pump has all the advantages of the VM cycle, and it also can use gas high-effectively. It could avoid the summer short-term electric peak load and solve the problem of environmental pollution. It may reduce the redundance and the cost of the system, and without the problem of working gases substitution. It has very strong application prospect in our country. Much effort has been made to improve the system performance of VM refrigerator. Now, analyzing the performance of gas driven VM heat pump is significant.

2. WORKING PRINCIPLE

A schematic gas driven VM refrigerator is showed in figure 1. As it shows in the figure, using the heat obtained from the city gas to driven the hot cylinder of VM refrigerator directly, realizes the refrigeration cycle. It consists of a hot and a cold cylinder with a displacer piston in each cylinder. The cylinders are connected with a channel. The cylinder volumes over and under the displacer are connected through two heat exchangers separated by a regenerator. The regenerator works as a heat store when the working gas flows between the hot and cold cylinder volume.

In the gas driven VM heat pump, heat enters the cycle at a high temperature T_H (600℃ to 700℃) in the hot expansion volume by means of a burner. Heat enters the cycle at a low temperature T_C (-10℃ to 10℃) in the cold expansion volume. Heat is delivered to the radiator system from the intermediate compression volume at a medium temperature T_I (50℃ to 70℃) (Carlsen, 1990).

The displacers move the working gas between 4 cylinder volumes over and under the two displacers as shown in figure 2. From 1) to 2) the displacer in the hot cylinder is moved so that the working gas flowers from the volume with the temperature T_I to the hot volume with the temperature T_H. The pressure in all cylinder volumes will then increase. From 3) to 4) the displacer in the hot cylinder is moved back and the pressure will then decrease.
The piston rod in the cold cylinder acts as a small power piston like in a stirling engine. By proper dimensioning of the piston rod diameter it is possible to produce adequate power at the desired rotational speed to compensate for the power losses.

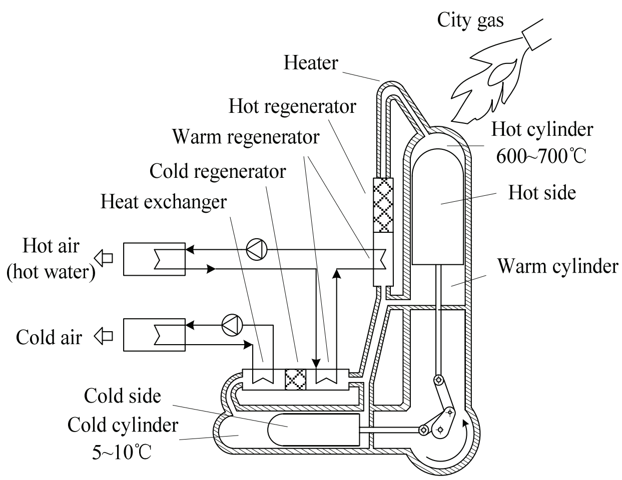

Figure 1: The configuration of gas driven VM heat pump

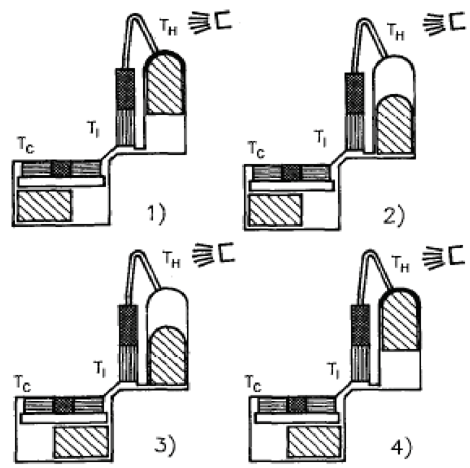

Figure 2: The VM cycle

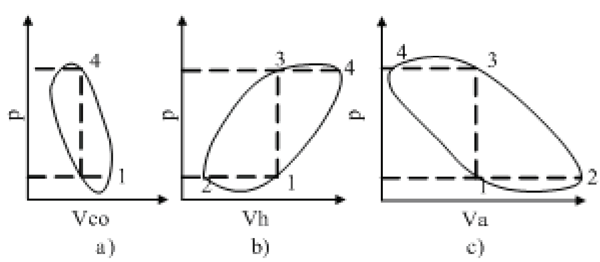

Figure 3: p-V diagram of three cylinder volumes
a) cold cylinder b) hot cylinder c) warm cylinder

Figure 3 shows the p, V-diagram of three cylinder volumes. Apparently, the area closed by the p, V-diagram of the warm cylinder is the largest. This is because the warm cylinder is the total changing volume of the two cylinders at warm cylinder temperature, and the pressure of each cylinder doesn't change much. The p, V-diagrams of the cold and hot cylinder is clockwise, which accounts for the gas in these two cylinders absorbs heat; while the p, V-diagram of the warm cylinder is counter-clockwise, which means the gas in this cylinder gives up of heat.

3. COP OF GAS DRIVEN VM HEAT PUMP

The refrigerating capacity of gas driven VM heat pump is the heat which the cold cylinder absorbs Q_{co}

$$Q_{co} = \frac{n}{60}\oint p dV_{co} = \frac{n}{60}\oint p_{av} \frac{\sqrt{1-\delta^2}}{1+\delta\cos(\alpha-\theta)} \times d\left[\frac{1}{2}V_o(1+\cos\alpha)\right] = \frac{\pi n}{60} p_{av} V \frac{\delta}{1+\sqrt{1-\delta^2}} \sin\theta \qquad (1)$$

where n is the rotational speed, p_{av} is the average pressure, V_0 is the max volume of the cold cylinder, δ is the pressure parameter.

The heat gas driven VM heat pump consumed is the liberated heat of the gas, using the net calorific power of the gas to denote the quantity of liberated heat of the nature gas Q_{ng}

$$Q_{ng} = m q_{dw} \qquad (2)$$

where m is the mass of the consumed nature gas, q_{dw} is the net calorific power of the nature gas per unit mass.
So COP of the gas driven VM heat pump is

$$COP = \frac{Q_{co}}{Q_{ng}} = \left(\frac{\pi n}{60} p_{av} V_0 \frac{\delta}{1+\sqrt{1-\delta^2}} \sin\theta\right) \Big/ m q_{dw} \qquad (3)$$

4. THE FACTORS AFFECTING THE PERFORMANCE OF GAS DRIVEN VM HEAT PUMP

The performance of gas driven VM heat pump is not only associated with the geometric configuration and working gas, but also with the working condition. Because the changing process of working gas and energy transformation of the regenerative heat pump is complex, accurate theoretical analysis is complicated. We can obtain the factors effecting on the heat pump by computer and experiment.

Here, taking the prototype VM heat pump for example, analyze the factors effecting on the performance of gas driven VM heat pump.

4.1 Rotational speed

The refrigerating capacity of gas driven VM heat pump is increased while the COP is decreased with an increase in the rotational speed. The refrigerating capacity is enhanced due to the increase in mass flow rate of the working gas during a given time. However, COP is decrease due to the increase in the several losses, such as shuttle loss, pumping loss and reheat loss of regenerator when the rotational speed is increased (figure 4) (Geon *et al*. 1996).

4.2 Working pressure

Taking no account of the refrigerating loss, we can see from the equation (1) that the refrigerating capacity and the working pressure are at direct ratio, and so is the result of actual experiment. Table 1 shows the effect of working pressure on the refrigerating performance. Obviously, the refrigerating capacity and COP both increase when the working pressure increases.

Table 1: The refrigerating capacity *Qc* and COP at different *P*

***P*(MPa)**	***Qc* (W)**	**COP**
2.0	54	0.24
2.5	57	0.25
3.0	96	0.33

4.3 The heater tuber temperature

The heat tube temperature is an important parameter for the heat input to the gas driven VM heat pump. More heat input is needed to increase the heater tube temperature for a given system. Figure 5 shows the effect of the heater tuber temperature on the refrigerating performance. As the heater tuber temperature is increased, the refrigerating capacity is increased while the COP is decreased. The conduction heat loss becomes substantial with higher heater tube temperature.

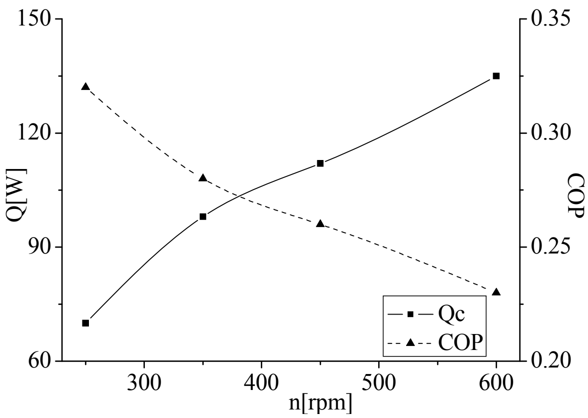

Figure 4: Effect of the speed of rotation on the refrigerating performance

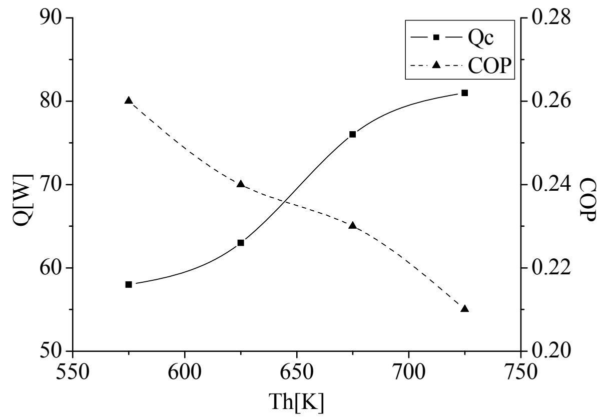

Figure 5: Effect of the heat tube temperature on the refrigerating performance

4.4 Cold cylinder temperature

Cold cylinder temperature influences the heat pump sharply. Figure6 gives the refrigerating capacity Q_c and the COP at different T_c. We can see that when the cold cylinder temperature decreases, the refrigerating capacity and COP both decrease.

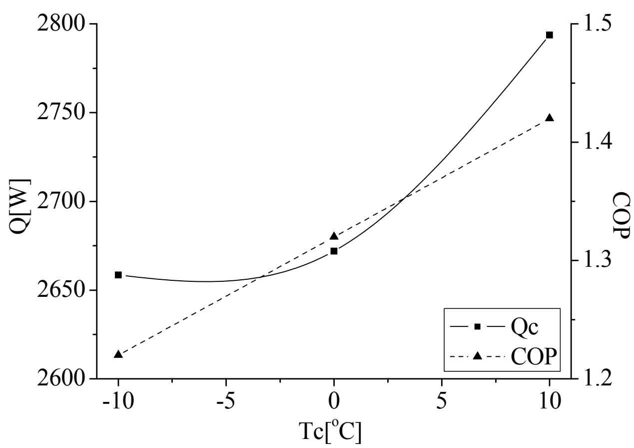

Figure 6: Effect of the cold cylinder temperature on the refrigerating performance

4.5 Working gas

The refrigerating capacity and coefficient of VM refrigerator are different when using different working gas. Some scholars did experiments on the performance of the VM refrigerator using different working gas. Figure 7 (Jin, 1990) shows the relation between the refrigerating capacity difference of different working gas and the ideal gas and refrigerating temperature. It is obvious that, if the refrigerating temperature is above 60K, hydrogen is the best working gas. Generally, the refrigerating capacity of helium is less. Using neon as working gas, when refrigerating temperature is below 60K, it is better than hydrogen; when refrigerating temperature is 60~153K, it is better than helium.

Figure 8 (Jin, 1990) is the relation between the refrigerating coefficient and refrigerating temperature while using different working gas. We can see from the figure, helium is close to ideal gas, refrigerating coefficient and temperature is nearly linearity. But, using neon as working gas, the refrigerating coefficient is the highest. Obviously, if operating a VM refrigerator, considering the refrigerating coefficient, choosing neon is the best.

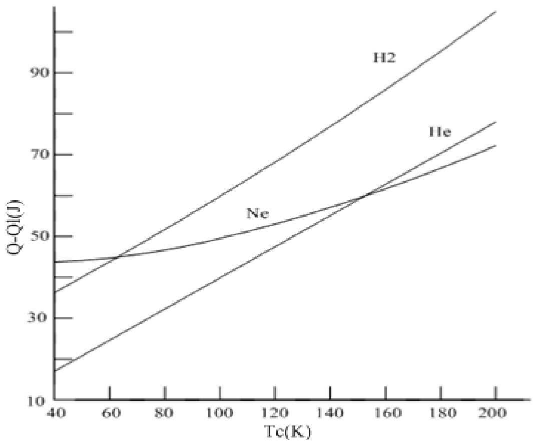

Figure 7: The relation between the refrigerating capacity difference of different working gas and the ideal gas and refrigerating temperature

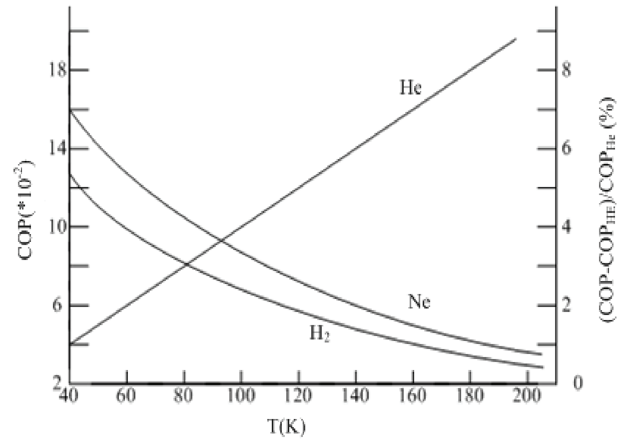

Figure 8: The relation between the refrigerating coefficient and refrigerating temperature

5. CONCLUSIONS

This paper analyzed gas driven VM heat pump, and obtained the equation of the refrigerating capacity and coefficient. Taking the prototype VM heat pump for example, the factors effecting on the performance are analyzed. The performance of gas driven VM heat pump is not only associated with the geometric configuration and working gas, but also with the working condition. The refrigerating capacity of gas driven VM heat pump is increased while the COP is decreased with an increase in the rotational speed. With higher mean working pressure, the performance of system is improved. As the heater tuber temperature is increased, the refrigerating capacity is increased while the COP is decreased. When cold temperature decreases, refrigerating capacity and COP both decrease. Considering the refrigerating capacity, hydrogen is the best working gas; considering COP, neon is the best working gas. But, whatever gas you choose, the refrigerating capacity and coefficient decrease when the refrigerating temperature decreases.

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