CFD simulation and optimize of a 10K VM refrigerator

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Background

The Vuilleumier(VM) refrigerator, known as heat driven refrigerator, is one kind of closed-cycle regenerative refrigerator. It was not developed until 1960s due to its low efficiency and low cooling load. Later F.F.Chellis et al. (1964) developed this kind of refrigerator, using liquid nitrogen as driven power, and reached a terminal temperature of 15 K, which is the beginning to low-temperature. After that, Y.zhou et al. (1984)optimized this type machine and obtain a terminal temperature of 10 K. Sherman et al. (1971)has analyzed VM refrigerator numerically including most of heat losses. In recent years, Y.zhou et al. (2012) proposed a novel refrigerator in theory arming to attain the temperature below 1.7 K, which shown great potential for development below 10 K.

Objectives

- Built the numerical model of VM cryocooler and analyzed its performance.
- optimization of this CFD model is also discussed.

Conclusion

- CFD analysis on VM cryocooler is performed using Fluent. The coldest temperature reaches 10.7 K.
- The pressure in three cavities, the temperature profile along the regenerator is analyzed. It is shown that the heat loss of regenerator is about 3.842 W.
- the regenerator between cold with middle cavity is optimize to obtain the coldest temperature. The result shows that the best cold regenerator is 46mm stainless steel screens and 66 mm lead and the coldest temperature is 10.4 K.

Problem geometry

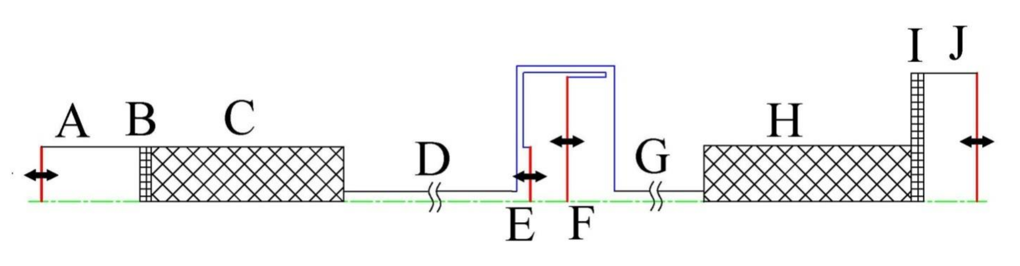

Fig. 1 Schematic of the VM refrigerator geometry simulated

Dimensions of the VM refrigerator according to Fig.1.

Components	Radius(mm)	Length(mm)
A (Cold end)	26	0~21
B (CHX)	26	1
C (Regenerator1)	26	108
D (IHX1)	5	100
E (Intermediate end1)	26	0~21
F (Intermediate end2)	47.5	0~21
G (IHX2)	5	900
H (Regenerator2)	26	100
I (HHX)	47.5	1
J (Hot end)	47.5	0~21

Mathematical model

$$v_{cold} = v_a \sin(\omega t)$$

$$v_{hot} = v_a \sin(\omega t + \pi/2)$$

Where va=0.12566 m/s is the amplitude, ω=2πf is the angular velocity, f is the operating frequency (in simulation, f=2Hz). The movement of pistons were tracked and guided by using the User Define Function (UDF).

Operational parameters of the porous media

Components	Material	Mesh	Porosity	Permeability	Inertial resistance factor
Regenerators	304SS	300	0.647	2.61×10^{-10}	1.591×10^{4}
Heat exchangers	Copper	100	0.697	5.15×10^{-10}	1.15×10^{4}

Boundary Conditions for the simulations

Components	Boundary Condition
IHX wall temperature(K)	77
HHX wall temperature(K)	300
Other wall	Adiabatic

Results

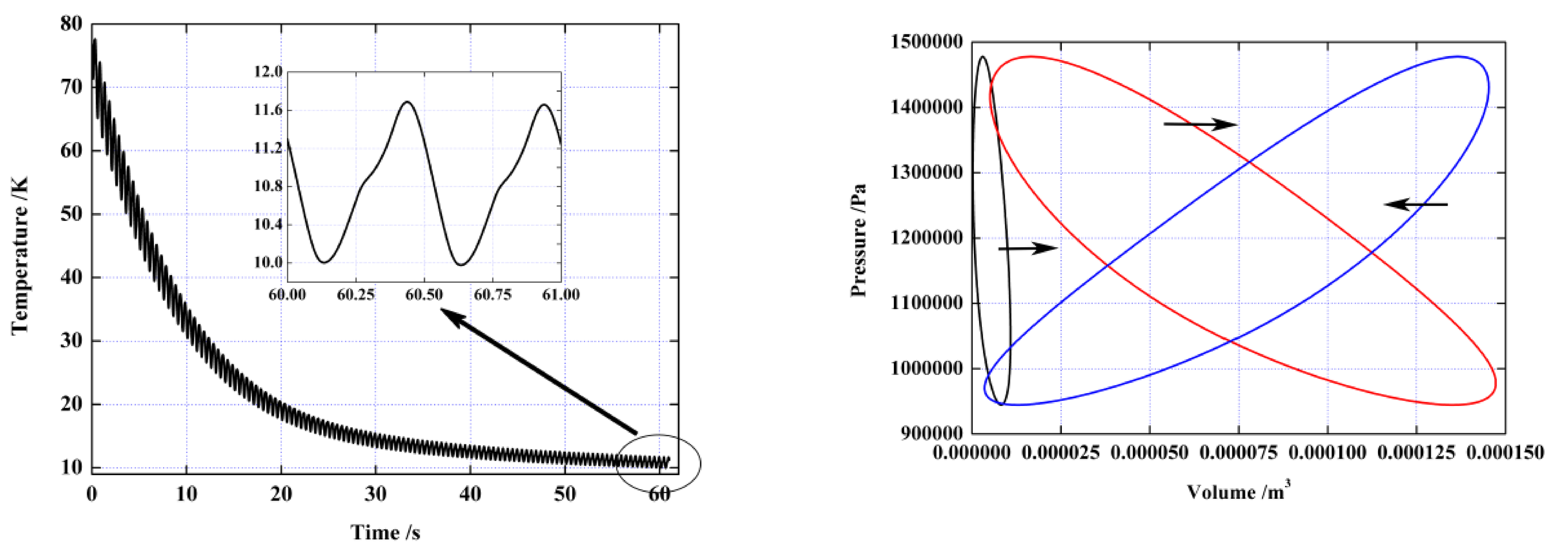

Fig. 2. The cooling curving and the PV diagram

The coldest temperature of simulation is about 10.7 K that shows good agreement with Y.zhou's experimental result. The temperature fluctuation of cold end is as large as 1.7 K, which is a characteristic of the low frequency refrigerator. The right side of figure 1 is the PV diagram in three cavities, which shows that the heat is absorbed in cold and hot cavity and rejected in the middle cavity. The cooling power in the cold cavity is equilibrium with the heat loss in regenerator, so the heat loss of regenerator is about 3.842 W.

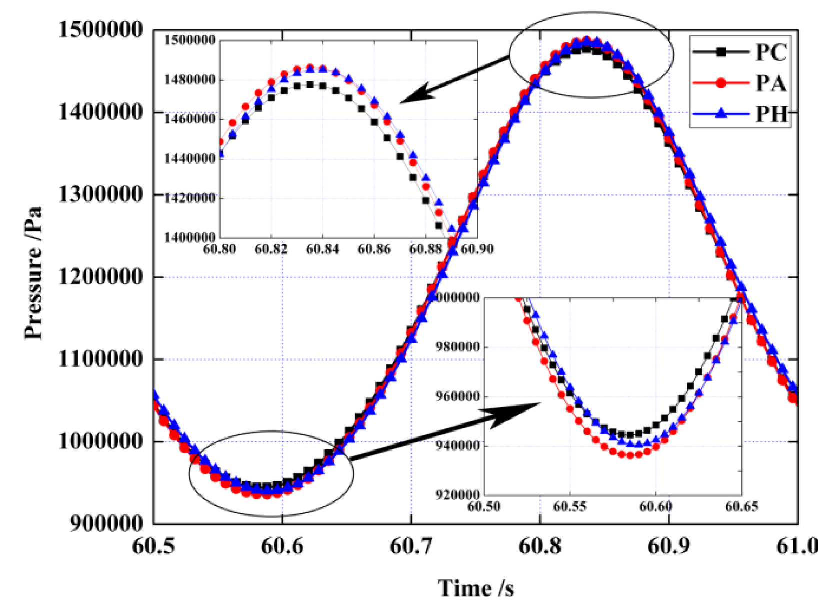

Fig. 3. The instantaneous pressure in three cavities

It is interesting that the pressure ratio in the middle cavity is the largest but not the hot cavity, which manifested in the pressure of middle cavity smaller. And what's more, the phase difference exists between the hot cavity with the middle and the cold cavity. The pressure drop of cold regenerator is about 20Kpa.

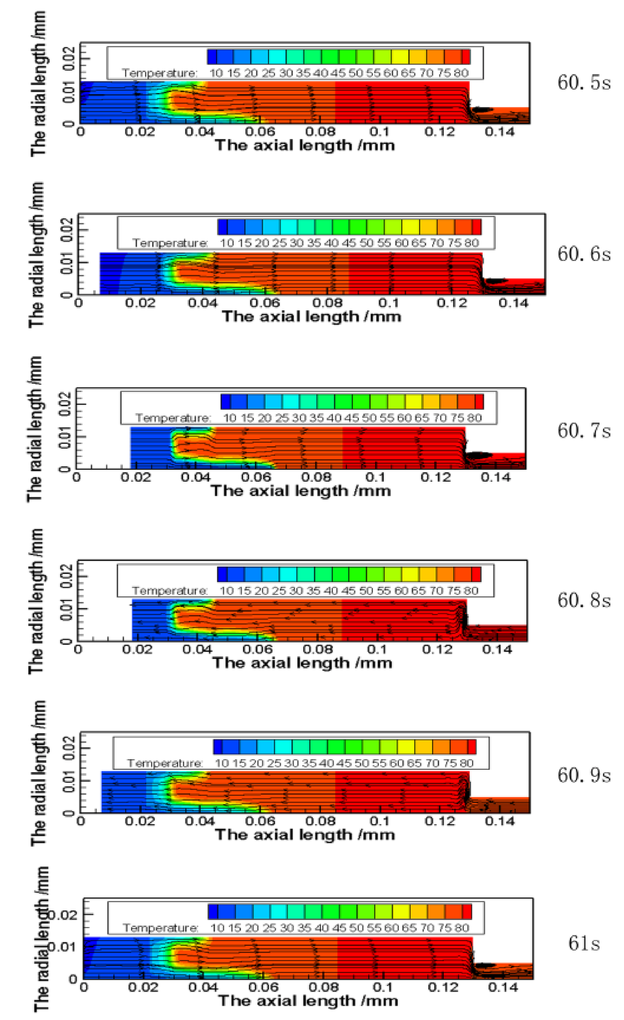

Fig. 4. The temperature distribution in one cycle

The temperature distribution of regenerator in y-axis shows inhomogeneous. Because the heat exchanger tube and the cold displacer land in the same axis, the pressure drop in the tube's direction is smaller. So the center of regenerator shows the colder temperature. This inhomogeneous temperature distribution is disadvantageous, because the material of regenerator is not used effectively. It should be avoided in the structural design.

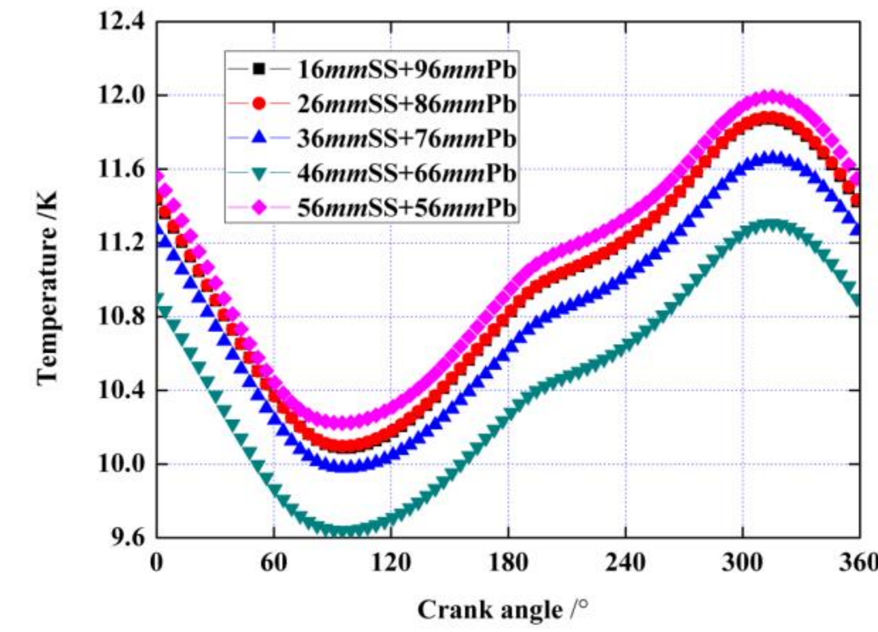

Fig.5. The coldest temperature for different ratio of stainless steel screens and lead

The ratio of stainless steel screens and lead will decide the no-load temperature, because it will have influence on pressure drop and the incomplete heat transfer. The result shows that the best combination of stainless steel screens and Pb lead is 46 mm+66 mm. The coldest temperature will reaches 10.4 K by optimizing the length of SS and lead.

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