Numerical simulation of 4-turns nitrogen pulsating heat pipe

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Abstract. In the present study, an investigation of temperature and pressure behavior in a two-dimensional closed-loop pulsating heat pipe (PHP) in vertical bottom heating mode has been carried out numerically. Nitrogen was used as working fluid in this 4-turns PHP. Structured meshing configuration has been used and Volume of Fluid (VOF) method has been employed for the two-phase flow simulation. Constant heat flux and constant temperature boundary conditions have been applied for the evaporator and the condenser sections, respectively. The initial condition was set as 0.5 liquid volume fraction and 77 K in every cell. Under the combined function of gravity and surface tension, pure liquid and vapor phase were produced, and the random liquid slugs and vapor bubbles distribution was formed. The temperature oscillation of every channel in evaporator and condenser sections was obtained and analysed.

1. Introduction
The cryocoolers have been widely used in the conduction cooled cryogenic systems, which can simplify the cooling system, reduce the operating cost and release the users from bothersome handling. But the cryocoolers can only provide cooling power at the cold heads. Therefore, efficient thermal links are essential to transfer the cooling power from the cold head to the working assembly. Copper or sliver bars are usually used as thermal links, but the thermal conductivity is not as high as we need, which easily leads to significant temperature gradients and high mass and space costs. To alleviate this constraint on the heat transport, a novel heat transport means which can transfer much more heat within relatively small temperature difference is needed. Pulsating heat pipe [1] is a highly effective two phase heat transfer device whose thermal conductivity is several orders of magnitude larger than that of copper. It usually consists in a capillary tube bended into meandering tube, partially filled with a working fluid which disperses itself into vapor and liquid volumes within the internal structure via capillary action. The PHP essentially utilizes changes of the pressure and the temperature in volume expansion and
contraction during phase changes to excite the pulsation motion of liquid plugs and vapor bubbles in capillary tube between the evaporator and the condenser.

For cryogenic PHP, many factors influence the thermal performance, but the experimental costs to change the factors are relatively high compared with room temperature PHP experiments. It is also difficult to conduct a visual experiment. While the numerical simulation gives a method to change the working factors easily and observe the motions of working fluid. Zirong Lin et al. [1] built a comprehensive mathematical and physical model of water-based PHP to simulate the two-phase flow behavior in vertical bottom heating mode. The volume of fluid (VOF) and mixture model in FLUENT were used for comparison in their simulations.

In the present study, investigation of temperature and pressure behavior in a two dimensional closed-loop pulsating heat pipe (PHP) in vertical bottom heating mode has been carried out numerically. The settings of this simulation are elaborated for readers to refer to.

2. Physical model
A 2D physical model was developed to simulate the internal flow and heat transfer in a PHP, because of the rotational symmetry structure. According to the experimental condition, a PHP was divided into six sections shown in Fig. 1, including h-wall, h-wall-1, a-wall, c-wall and c-wall-1. Among them, h-wall and c-wall represent the evaporation section and condensation section. Both their lengths are 40 mm. The a-wall represents the adiabatic section. Its length is 60 mm. The curving sections are also set as adiabatic sections. The operational orientation of the PHP is vertical bottom heating mode. Eight temperature monitors are set at the eight points in every channel of the PHP shown in Fig.1.

![Fig.1. Schematic of the 4-turn PHP.](image)

The uniform, rectangular cells of dimension about 0.25 mm* 0.05 mm for meshing h-wall and c-wall. This resulted in 10 cells through the channel of 0.5 mm inner diameter containing the working fluid. To reduce the amount of mesh, the mesh size in adiabatic section was 1 mm* 0.05 mm. The total number of notes was 26829.

Nitrogen was chosen as the working fluid with all the physical properties set as constant values. Liquid nitrogen was the primary phase, and nitrogen vapor the secondary phase. The continuum surface force (CSF) model was used to consider the effect of surface tension. The surface tension coefficient was set as 0.009133n/ m.
3. Definite conditions

In the FLUENT, two dimensional version with double precision and segregated solver were started. The unsteady time condition was selected due to the oscillation characteristics of PHPs. Implicit body force and gravity were turned on under gravitational acceleration; enable heat transfer by activating the energy equation. Because the inner diameter of the PHP tube is small (0.5 mm), the viscous model was laminar by selecting the viscous heating. The operating temperature was 77 K. The phase change process in a PHP was deal with by evaporation-condensation model. The evaporation frequency and condensation frequency were set as 10 and 100, respectively.

In the model solution, the pressure–velocity coupling was simple. The relaxation factors of pressure and momentum were set to 0.3 and 0.7, respectively. Under discretization, pressure interpolation scheme was set to body force weighted; momentum and volume fraction were changed to QUICK; the energy retained first order upwind. The time step was $10^{-4}$ s.

4. Results and discussion

4.1. Initial state

In order to get the initial distribution of liquid slugs and vapor plugs. The boundary condition of all sections was set as a constant temperature 77 K. The volume fraction of vapor in every cell was 0.5 and the temperature was 77K in the beginning. After 1000 time steps, the contour of volume fraction of liquid was shown in Fig.2 (a). The liquid slugs and vapor plugs were formed under the combined effect of gravity and surface tension. The distribution situations in the evaporation section and condensation section are similar, which indicates the surface tension dominate in the system.

Fig. 2. Volume fraction of liquid phase: (a) initial state; (b) 1s; (c) 2s; (d) 3s.
4.2. Working state

The upper state was used as the initial state. The heat flux in the evaporation section (h-wall) used in this simulation was 200W/m², which means the total heat added to the evaporation section was 0.05 W. The boundary condition of the condensation section (c-wall) was set as a constant temperature 74 K, to ensure the temperature differences. The adiabatic section (a-wall) and other sections (h-wall-1, c-wall-1) were set as insulation boundary condition.

After 1 s, the contour of volume fraction of liquid is shown in Fig.2 (b). Due to the evaporation and condensation process, there are more vapor in the evaporation section and more liquid helium in the condensation section. The contour of static pressure is shown in Fig.3. The reference pressure was set as the default value 1 bar. The pressure imbalances between adjacent channels and between the evaporator and condenser provide the driving forces for the working fluid circulation. After 2s and 3s, the contour of volume fraction of liquid is shown in Fig.2 (c) and (d).

The temperature oscillations at the points in every channel were recorded, shown in Fig.4. In the evaporation section, when the temperature is higher than 77 K, the phase at this point is vapor. Otherwise, the phase is liquid. The phase of every point changes with time. The amplitude of the temperature oscillation at every point is random. While the frequencies of the temperature oscillation of the evaporation section and the condensation section are uniform, which indicates a pressure-driven holistic flow is in progress in the PHP. This phenomenon fits with our understandings about the PHPs.

5. Conclusions

1) The simulation presented in this paper simulated the process of forming liquid slugs and vapor plugs randomly under surface tension. The surface tension dominates in the capillary tube.
2) Under a fixed heat flux added to the evaporation section (h-wall) and a constant temperature of the condensation section (c-wall), the case run successfully. The contours of liquid volume fraction and
temperature at 1s, 2s and 3s were obtained. In the evaporator zone, the volume fraction of vapor is larger than that of liquid, because of the heat input. In the condenser zone, the volume fraction of liquid is larger.

3) During the simulation, the temperatures at 4 points in the evaporator zone and 4 points in the condenser zone were monitored. The temperature fluctuations are clearly presented, which indicate the phase change and fluid flow in the PHP.

4) This model has some places to be improved. ① All physical properties were set as constant values, while they did change with temperature. ② Although no heat exchange happens in the adiabatic section, the mesh size in this zone should be uniform to the size in other sections. ③ The values of the simulation results have not been compared with the experimental results.

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