Numerical study on the influence of foamed copper on flow boiling characteristics

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Abstract. Traditional heat dissipation materials can no longer withstand the overheating phenomenon caused by excessive heat flux, metal foam materials provide new solutions for chip heat dissipation and air conditioning due to the superior structural characteristics. In this paper, the tetradecahedron model of the foamed copper was constructed to simulate the heat transfer characteristics of the filled foamed copper channel in the boiling flow process to explore the influence of the foamed copper structure parameters and filling length on the heat transfer characteristics. By changing the filling length of the foamed copper, the polynomial fitting function is solved to the optimum filling ratio of 0.6, and the gas phase rate and the working fluid outlet temperature are both at the optimum value. Introducing the heat transfer influence factor $i$, it is obtained that it increases with the increase of PPI and decreases with the increase of $\varepsilon$.

Key words: Foamed metal copper; Boiling flow; Numerical Simulation.

1. Introduction

Traditional electronic equipment uses convection heat transfer technology for heat dissipation, and overheating often occurs due to excessive heat flow density. Since the working fluid in the boiling heat transfer technology undergoes phase change behavior when it flows in boiling, compared to the single phase change heat transfer without phase change, the use of the latent heat of the phase change of the working fluid can greatly increase the heat transfer coefficient and obtain higher heat transfer effectiveness. Foam metal has excellent material properties such as low density, high porosity and ultra-high thermal conductivity. Researches have found that filling foam metal in heat exchange pipes can enhance flow heat transfer and greatly increase boiling heat transfer coefficient. Most of the existing research on foam metal flow boiling stays at the large-scale and experimental stage, and the research on its related mechanism is not thorough yet. In this paper, by means of numerical experiment and theoretical analysis, the flow boiling heat transfer characteristics in small channels filled with foamed metal are deeply studied to provided solutions for the heat dissipation and cooling of micro electronic chips.
2. Research status at home and abroad

Scholars at home and abroad have done a lot of researches on the boiling heat transfer phenomenon of filled foam copper. Yu Zhu\(^2\) analyzed the influence of foam metal structure and lubricant concentration on pool boiling heat transfer characteristics. The results show that the metal foam significantly improves the pool boiling of the refrigerant and oil mixture, and its heat transfer coefficient is increased by 1.7 times; while the lubricating oil deteriorates the heat transfer performance of the refrigerant, and the heat transfer coefficient is reduced by 17%. In order to optimize the performance of hydrophilic metal foam, Zhan\(^3\) et al. experimentally studied the effect of pore density on the heat transfer and pressure drop characteristics of the humid air in the hydrophilic metal foam. The results show that as the pore density increases from 5PPI to 40PPI, the total heat transfer coefficient of the humid air in the hydrophilic metal foam is always at a relative humidity of 30–70%, the hydrophilic metal foam is more hydrophilic than the uncoated metal foam. The finned tube heat exchanger has better overall performance, compared with the uncoated metal foam, the total heat transfer coefficient of the humid air in the hydrophilic metal foam is increased by 3%-21%. Yinghai Li\(^4\) used air as the medium to conduct a two-dimensional simulation of the convective heat transfer of a foamed metal tube. The simulation results are in good agreement with the relevant experimental results, which show that with the decrease of \(\varepsilon\) or the increase of PPI, the Nu number of the filled foam metal tube increases, and increases more when the thermal conductivity of the fluid and the solid are close with significant heat transfer enhancement. At the same time, the heat transfer resistance and pressure drop are greatly increased due to the complex porous structure.

3. Numerical simulation of boiling flow

3.1. Mathematical model

Continuity equation:

\[
\frac{\partial}{\partial t} \rho_h + \nabla \cdot \left( \rho_h \mathbf{v}_h \right) = 0
\]  

Momentum equation:

\[
\frac{\partial}{\partial t} \left( \rho_p \mathbf{v}_h \right) + \nabla \cdot \left( \rho_p \mathbf{v}_h \mathbf{v}_h \right) = -\nabla p + \nabla \cdot \left( \mu_h \mathbf{v}_p \right) + \rho_h g + S_M
\]  

The porous structure inside the foam metal will have a great influence on the fluid momentum transfer, and the momentum source term can be obtained by Brinkman-Forchheimer\(^5\):

\[
S_M = -\frac{\mu_h}{K} \mathbf{v}_p - \frac{\rho_h C}{\sqrt{K}} \mathbf{v}_p
\]  

The first term in the formula is viscosity loss, and the second term is internal loss. Energy equation:

\[
\frac{\partial}{\partial t} \sum \left( \rho_h H_h + (1-\varepsilon) \rho_s \right) + \nabla \cdot \left( \rho_p \mathbf{v}_p \mathbf{v}_p \right) = \nabla \cdot \left( k_{eff} \nabla T \right) + S_E
\]  

The boiling phase change is mainly accompanied by the mass transfer and energy transfer process between gas and liquid phases. The boiling model is set by a custom function in the Fluent software. The study of De Schepper gave the calculation expression of the mass source term in the mass transfer process.

\[
m_i = -0.1 \alpha_i \rho_i \frac{T_i - T_{sat}}{T_{sat}}
\]

\[
m_v = 0.1 \alpha_v \rho_v \frac{T_v - T_{sat}}{T_{sat}}
\]
3.2. Geometric model

In recent years, some scholars have discovered that foam metal can be seen as a periodic arrangement of metal micro-element structures. Among them, the tetradecahedron is currently a more accurate structural model. Its characteristics are: by slicing the body-centered cube into a sphere, the cross-section of each vertex is triangular and symmetrical about the vertex of the tetrahedron; the distribution of metal along the length of the skeleton shows the characteristics of more vertices and less in the middle. This is very close to the actual metal foam structure, so it can well reflect the actual structural characteristics. This article adopts the tetradecahedron geometric model.

![Figure 1. Tetrahedron spatial structure model](image)

3.3. Simulation process

Meshing: ICEM CFD quadrilateral unstructured grid.

- Boundary conditions: the inlet is set to the "velocity inlet" boundary condition, the outlet is set to the "outflow" boundary condition, the pipe wall boundary condition adopts "fixed temperature" uniform heating, the lower wall is set to the "pipe wall" boundary condition, and the upper wall is adiabatic.
- Model and calculation solution: Choose the RNG k-ε turbulence model, use a two-dimensional double-precision solver, import the grid into fluent and check the grid, use the separation solution solver to simulate, initialize the flow field and discretize the control equation.
- Material selection: liquid R141b and gas R141b-v are selected as the fluid working medium, copper foam is selected as the foam metal material, and copper pipe is also selected for the pipe wall, and the pipe diameter is 13.8mm.

4. Analysis of simulation results

4.1. Influence of foam copper filling ratio on heat transfer characteristics

![Figure 2. Variation of vapor phase rate and pipe outlet temperature with foam copper filling ratio](image)
It can be seen from the figure 2 that the gas phase rate firstly rises and then falls. This is because when the filling ratio is relatively small, it has a dominant effect on the boiling heat transfer, and as the filling ratio increases, the bubble escape resistance increases, causing the gas phase rate to decrease. The temperature of the working fluid at the outlet of the pipeline has an opposite trend with the filling ratio, the reason is that when the filling is relatively small, the enhancement of boiling heat transfer is not obvious. At this time, the liquid phase is still dominant, while the gaseous R141b is less, so the outlet temperature is higher; when the filling ratio increases, the foamed copper strengthens the phase change of the working fluid significantly, and the gas phase increases, so the outlet temperature decreases; when the filling ratio is too large, the porous structure prevents the escape of bubbles, so the heat transfer deteriorates, so the outlet temperature gradually rises. By fitting the curve with a polynomial and solving the polynomial maximum value, a dual optimal solution of the gas phase rate and the outlet temperature can be obtained when the filling ratio is 0.6, which is the optimal filling length.

4.2. Influence of flow velocity on heat transfer characteristics

![Figure 3. The change of heat transfer coefficient with speed and gas phase rate under 10PPI](image)

It can be found that as the speed $v$ increase, the heat exchange is strengthened, but as the flow rate becomes larger and larger, the strengthening effect becomes less and less obvious. This is because the disturbance between the pores and the heat transfer becomes stronger between the tube wall and the solid framework as $v$ grows; on the other hand, the increase in $v$ makes forced convection heat transfer dominate, while nucleate boiling is affected inhibition.

Foam metal can enhance boiling flow heat transfer. In order to measure the ability of foam metal to enhance heat transfer, the heat transfer influence factor and Reynolds number $Re_k$ are defined as follows:

$$i = \frac{h}{\rho h c_p \nu v^2 (Pr)^{2/3}} \quad Re_k = \frac{\rho v d \sqrt{K}}{\mu}$$

(7)

![Figure 4. The variation of the heat transfer factor $i$ with PPI and $\epsilon$.](image)

![Figure 5. shows the porosity=0.9](image)

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Figure 4, 5 shows the porosity=0.9, which changes with PPI at a certain time. It can be found that $i$ increases with the increasing of PPI, This is because when $\varepsilon$ is constant, As the PPI increases, the diameter of the internal framework of the foamed metal decreases, which increases the specific surface area and increases the heat exchange area, thereby enhancing heat exchange. Figure 4-7 shows the relationship between PPI being 10 and changing with $\varepsilon$ at a certain time. It can be found that $i$ decreases as $\varepsilon$ increases. The reason is that the proportion of the foamed metal in the same volume becomes smaller as the increase of the $\varepsilon$, which reduces the specific surface area between the fluid and the solid, resulting a reduction in the heat exchange between R141b and the foamed metal and weaken the heat exchange capacity.

5. Conclusion
In this paper, a tetradecahedral model of foamed metal is constructed to simulate the flow and boiling process of a small pipe filled with foamed copper. The focus is on the influence of factors such as PPI and filling degree on heat transfer characteristics. The results indicates that the optimal filling ratio is 0.6; Introducing the heat transfer influencing factor $i$, which increases with the increase of PPI and decreases with the increase of $\varepsilon$.

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