Study on the Surfactant Influence on the Heat Transfer Performance of Pulsating Heat Pipe

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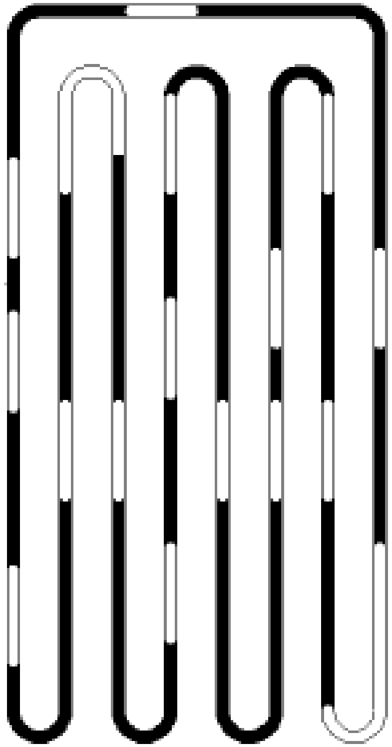
1. Introduction & Background



- **Working principle:**

Due to the influence of the surface tension, a train of vapor slugs and liquid plugs will be formed once charging a small channel by a fluid

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The input heat in EV section will cause the un-balance of the slugs

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The heat will be dissipated by the oscillation of the slugs

The surface tension, unbalanced oscillation motions define the PHP

1. Introduction & Background

- The heat transfer performance of the PHP is greatly influenced by many parameters, and they can be divided into three groups

Geometric Parameters → **Physical Properties** → **Operational parameters**

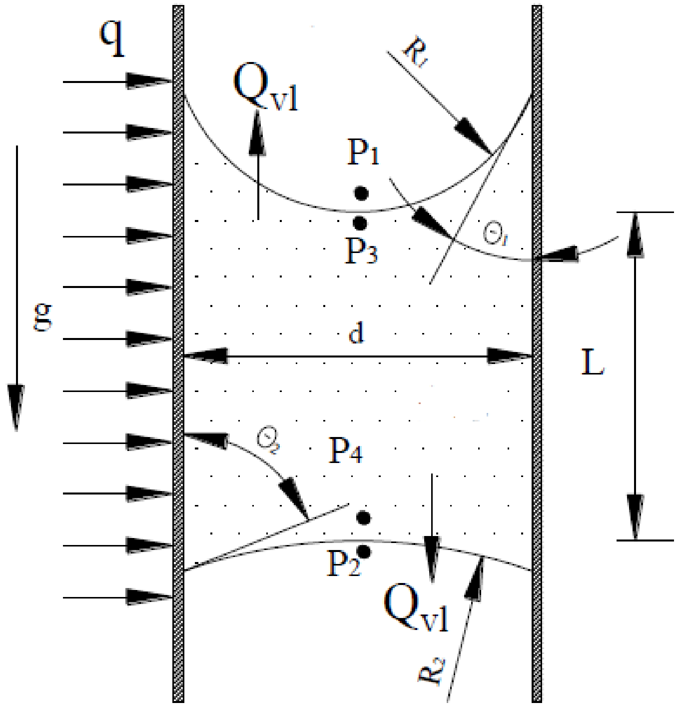
Geometric Parameters	Physical Properties	Operational parameters
Inner diameter; Cross-section shape; Channel configuration; Number of turns; Length of section; … ...	Surface tension; Thermal conductivity; Specific heat; Viscosity; … …	Charge ratio; Inclination angle; Gravity field; Heat flux; … …

- Few studies showed the influence of surface tension on the heat transfer performance of PHP

2. Simulation/Experiment

➢ Theoretical analysis on heat transfer

For the liquid slug with two adjacent vapor plugs



✓ Mass conservation

$$\frac{dm_{l_1}}{dt} = \frac{dm_{v_1l_2}}{dt} + \frac{dm_{v_1l_1}}{dt} + \frac{dm_{bw}}{dt} + \frac{dm_{bi}}{dt}$$

✓ Momentum conservation

$$\frac{d(m_l v_l)}{dt} = F_p + F_g \text{-} F_\sigma \text{-} F_f$$

$$F_g = (-1)^n m_1^{'} g \qquad F_\sigma = 2\sigma\left(\frac{1}{r_{\min}} - \frac{1}{r_{\max}}\right)$$

$$F_p = (p_{v1} - p_{v2})A \qquad F_f = \pi d L_{li} \tau$$

✓ Energy conservation

$$\frac{1}{\alpha_{li}} \frac{dT}{dt} = \frac{d^2 T_{li}}{dx^2} + Q_{wl} + Q_{v_1l} + Q_{v_2l} + Q_{el}$$

$$Q_{wli} = h_{li} \pi d (T_{li} - T_w) / \lambda_{li} A$$

$$Q_{vl} = \dot{m}_{v_1l} h_{fg}(T_{1l}) + \dot{m}_{v_2l} h_{fg}(T_{2l})$$

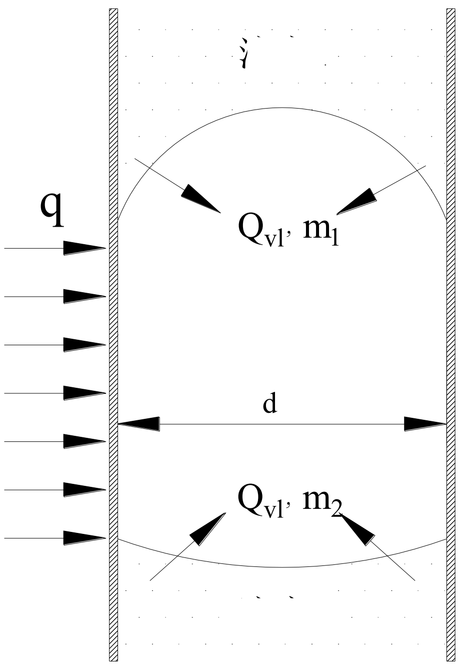
$$Q_{el} = \dot{m}_{bl} h_{fg}(T_{lb})$$

✓ Mass balance

$$\frac{dm_{v_i}}{dt} = \frac{dm_{tf}}{dt} + \sum_{j=1}^{2} \frac{Q_{v_i l_j}}{h_{fg}}$$

2. Simulation/Experiment

For the vapor plug with two adjacent liquid slugs



✓ Mass conservation

$$\frac{dm_{v_i}}{dt} = \frac{dm_{tf}}{dt} + \sum_{j=1}^{2} \frac{Q_{v_i l_j}}{h_{fg}}$$

✓ Energy conservation

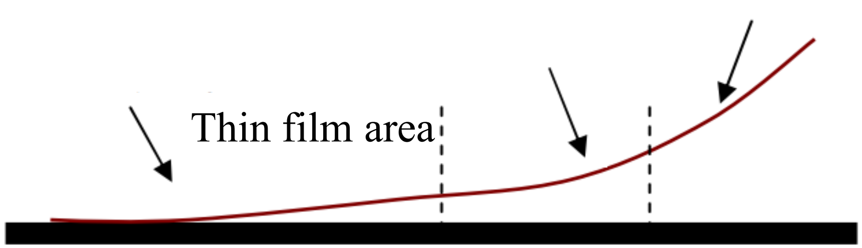
$$Q_{v_i} = dm_{v_i} h_{fg} + Q_{v_i w}$$

$$m'' h_{fg} = \frac{k_l (T_w - T_{lv})}{\delta}$$

$$Q_{v_i w} = 2\pi (R - \delta_{tf}) L_v \lambda_l \frac{T_{wi} - T_{vi}}{\delta_{tf}}$$

$$\frac{\delta}{r} = \frac{1.34 Ca^{2/3}}{1 + 3.35 Ca^{2/3}}$$

$$Ca = \frac{\mu u}{\sigma}$$



$$m'' = \frac{2\hat{\sigma}}{2 - \hat{\sigma}} \left(\frac{M}{2\pi R}\right)^{0.5} \left(\frac{p_{v\_equ}(T_{lv})}{T_{lv}^{0.5}} - \frac{p_v}{T_v^{0.5}}\right)$$

2. Simulation/Experiment

- **The heat transfer of the liquid plug and vapor plug are analyzed based on the model presented**

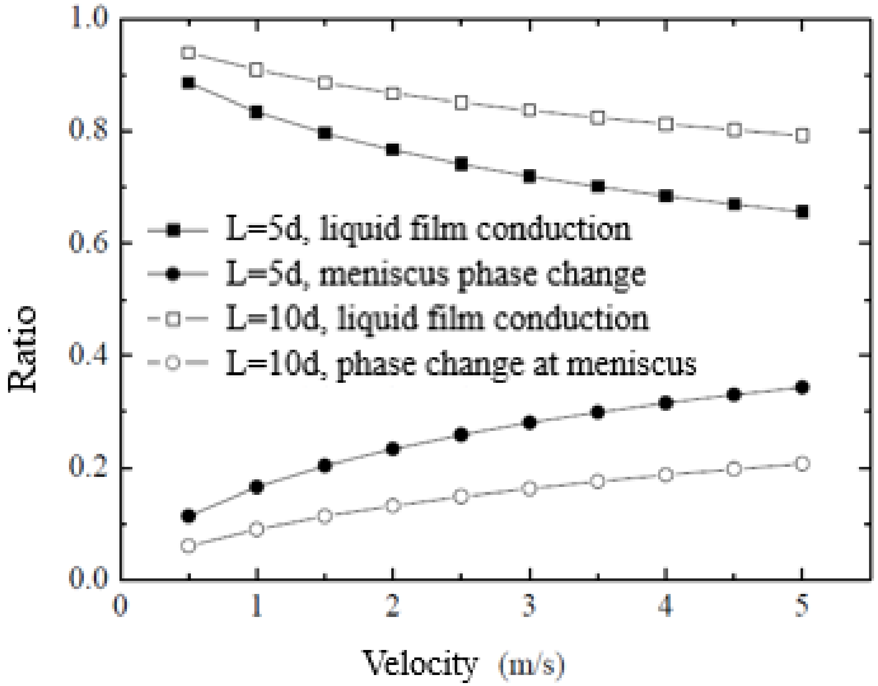


Fig. 1 For a vapor plug

$T_w - T_l = 10, T_l = T_{lv}, T_{lv} - T_v = 10; p_d + p_c = 100Pa$

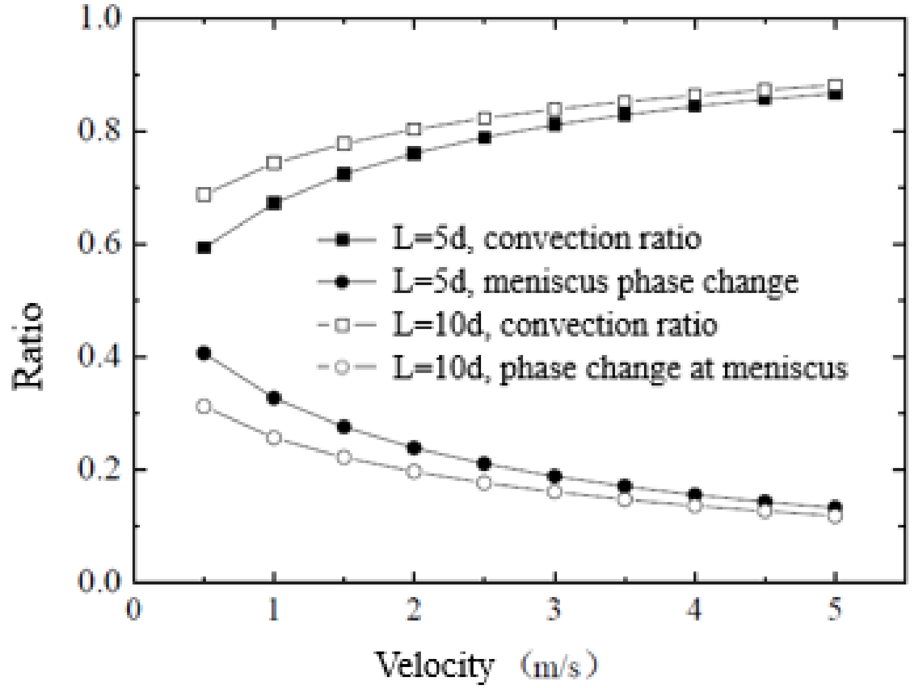


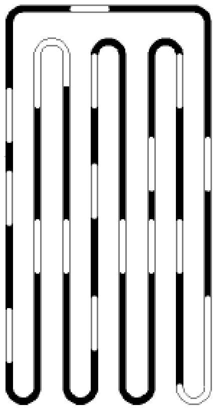
Fig. 2 For a liquid slug

$T_w - T_l = 10, T_l = T_{lv}, T_{lv} - T_v = 10; p_d + p_c = 100Pa$

For a typical long vapor plug, the heat transfer in the liquid conduction contributes a lot. For a liquid slug, the convection heat transfer ratio is great. However, the **contribution of heat transfer in meniscus also play an important role, which is greatly influenced by surface tension of the working fluid**.

2. Simulation/Experiment

✓ Theoretical analysis on the force



The length of slug/plugs are randomly and small compared with the length of pipe. **So it is assumed the length distribution functions of the slugs in every single channel are the same**

- Force/Pressure drop caused by U-turn

$$\frac{\sum_{k=1}^{x} L_{li,b}}{\sum_{i=1}^{N} L_{li}} = \frac{1}{2}\frac{L_b}{L_{tot}} \qquad F_{lb} = \sum_{k=1}^{x} \pi d^2 \Delta p_{bi}$$

- Force/pressure drop by the gravity

$$G_{li} = -\pi d^2 \rho_l L_{li} g \cos\phi$$

- Force/pressure drop by the flow resistance

$$F_{fli} = \pi d L_{li} \tau_i$$

- Force/pressure drop by the capillary force

$$F_{cli} = \pi d \sigma_i (\cos\theta_{ai}' - \cos\theta_{ri}')$$

$$\begin{aligned} F_{tot} &= F_{lb} + F_{ld} + F_{lu} \\ &= \sum_{i=1}^{N/2} (\pi d \sigma_i (\cos\theta_{ai}' - \cos\theta_{ri}') + \pi d L_{li} \tau_i - \pi d^2 \rho_l L_{li} g \cos\phi) \\ &+ \sum_{i=1}^{N/2} (\pi d \sigma_i (\cos\theta_{ai}' - \cos\theta_{ri}') + \pi d L_{li} \tau_i + \pi d^2 \rho_l L_{li} g \cos\phi) \\ &+ \sum_{k=1}^{x} \pi d^2 \Delta p_{bi} \end{aligned}$$

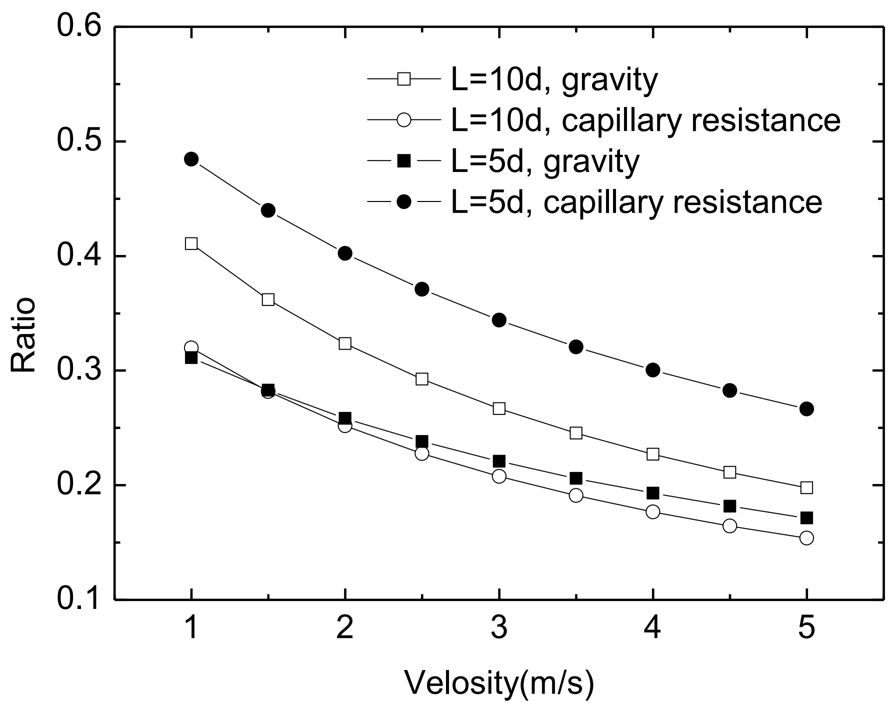
⇓

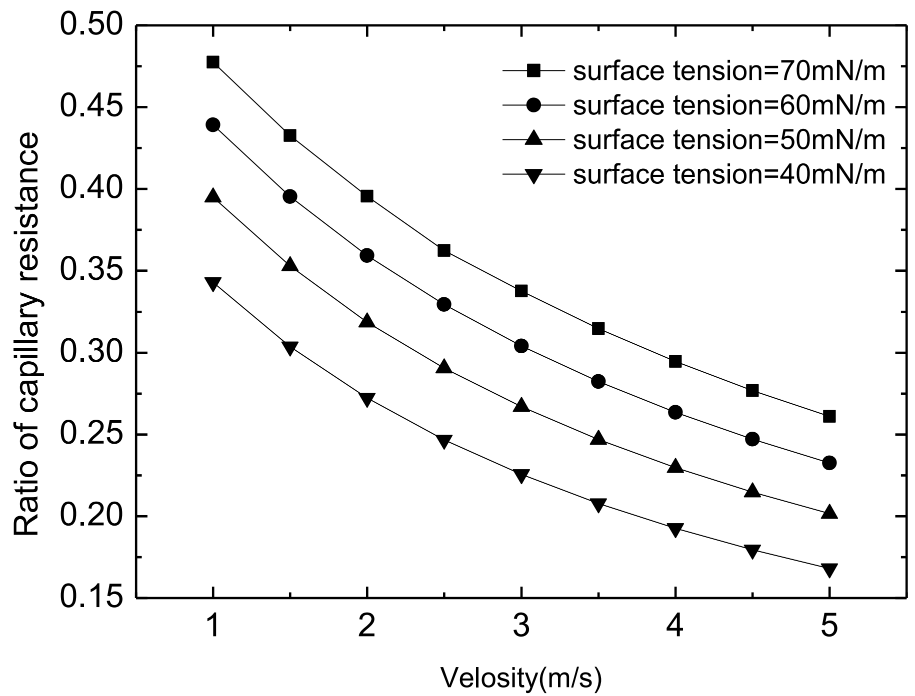
$$F_{tot} = \underbrace{\pi d \sum_{i=1}^{N} \sigma_i (\cos\theta_{ai}' - \cos\theta_{ri}')}_{F_C} + \underbrace{\pi d \sum_{i=1}^{N} L_{li} \tau_i}_{F_f} + \underbrace{\sum_{k=1}^{x} \pi d^2 \Delta p_{bi}}_{F_{pf}}$$

2. Simulation/Experiment

✓ **Theoretical analysis on the force**

$$F' = F_g + F_\sigma + F_f \qquad \chi_2 = \frac{F_\sigma}{F'} \qquad \chi_1 = \frac{F_g}{F'}$$

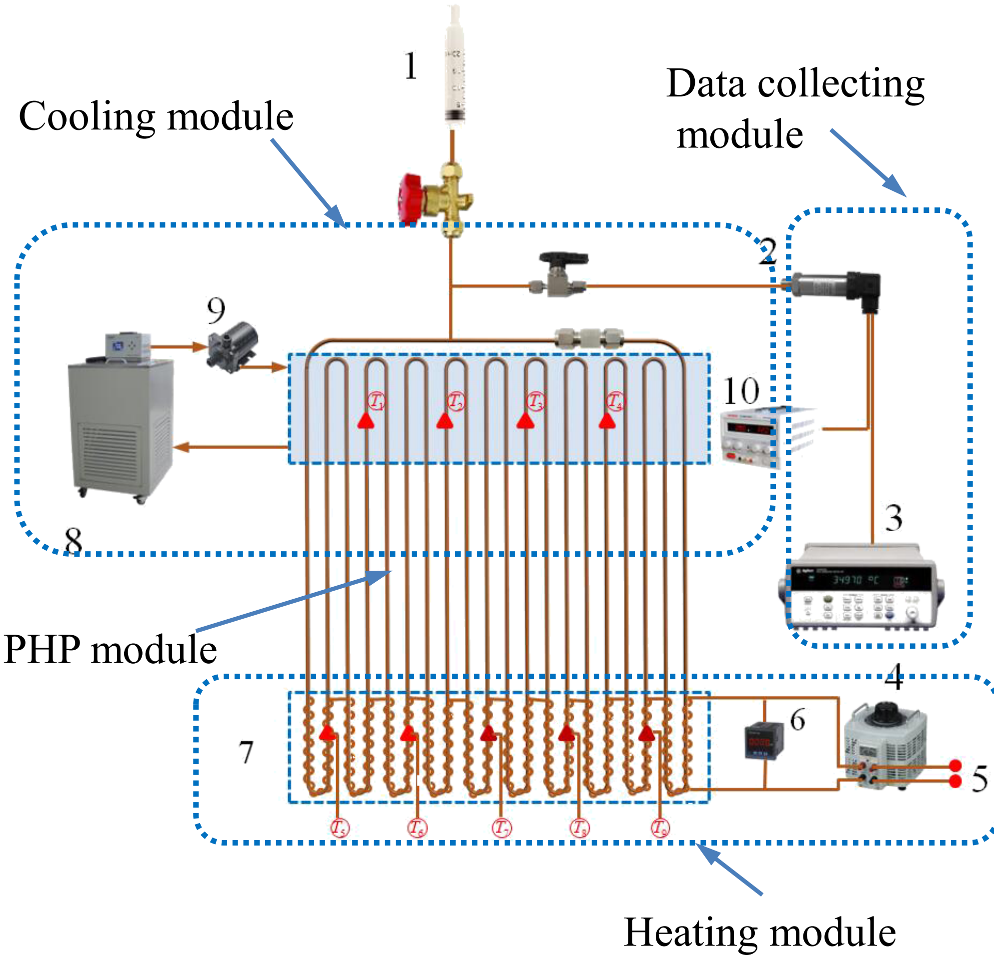


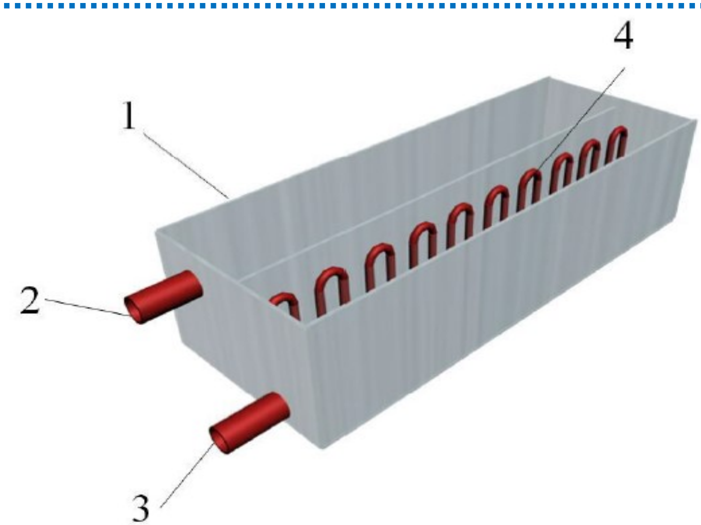


For typical liquid slug, the capillary resistance could be the same level of the gravity of the it. Meanwhile, with the decrease of the surface tension of the working fluid the ratio of the capillary tension sufficiently decrease.

2. Experimental rig

➢ **The rig for the experimental rig is shown below**

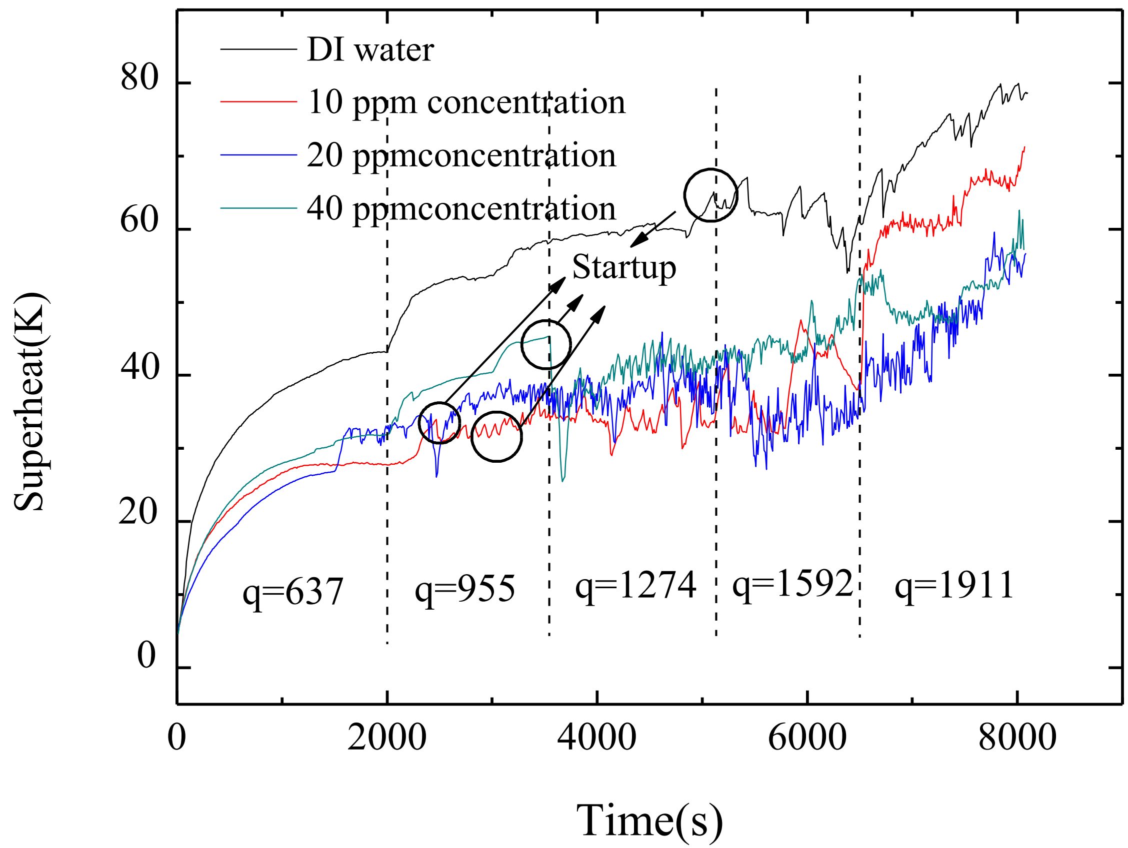


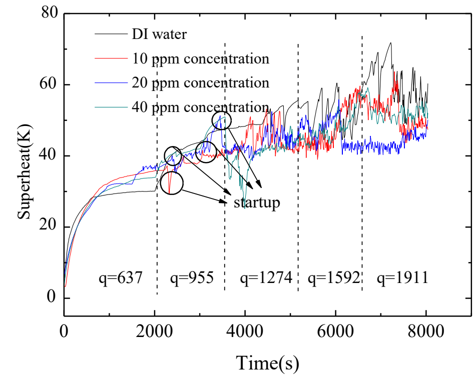


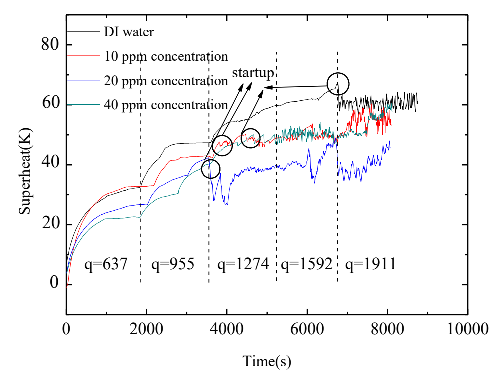
➢ **Criteria for the performance** $R = \frac{\overline{T}_e - \overline{T}_c}{Q}$ (thermal resistance) $\Delta T = \overline{T}_e - \overline{T}_c$ (superheat)

3. Results &Discussions

- **The influence of the surfactant on the startup characteristics of the PHP**



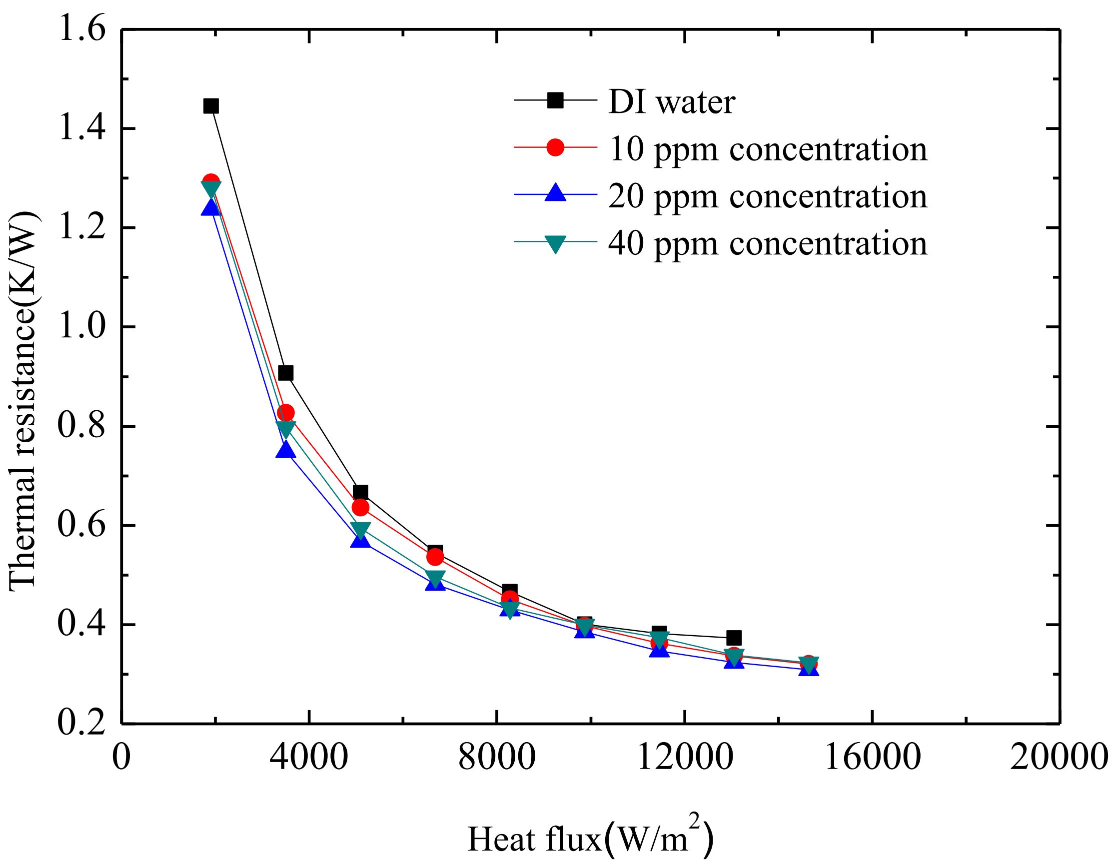


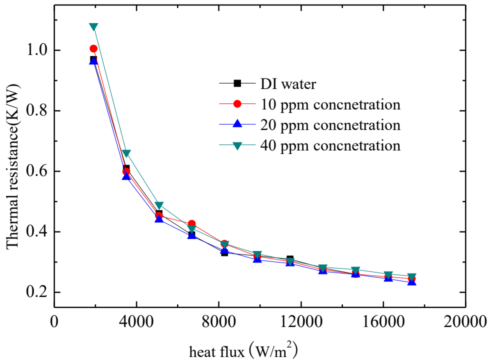


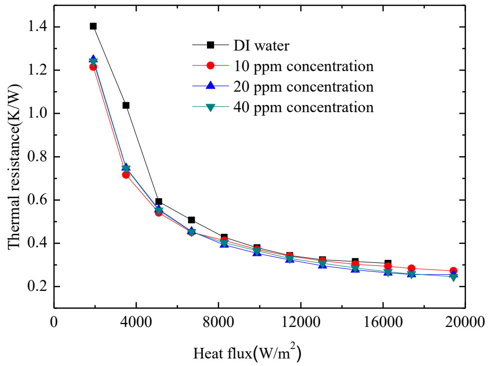
The surfactant solution decreases the start up power of the pulsating heat pipe

3. Experimental results

➢ **The influence of the surfactant on the heat transfer performance of the PHP**



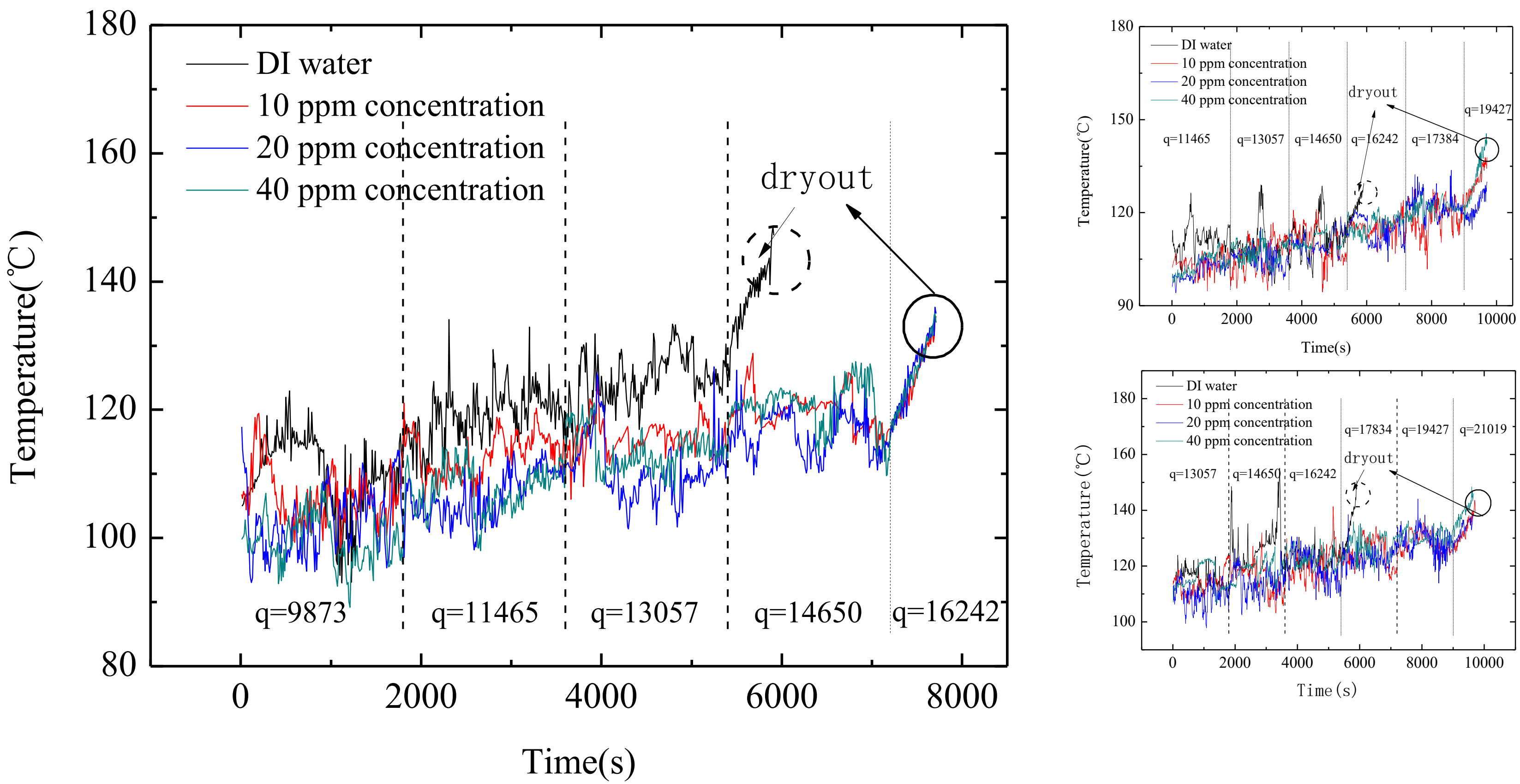




The existence of the surfactant greatly enhances the heat transfer of the PHP

2. Simulation/Experiment

➢ **The influence of the surfactant on the dry-out characteristics of the PHP**



The existing of surfactant increases the dry-out heat flux of the pulsating heat pipe

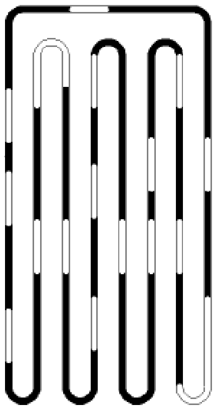
3. Conclusions

- For the PHP with surfactant solutions, they start at a lower heat flux. Furthermore, the temperature fluctuates at a lower level.
- The heat transfer performance of the PHP significantly improves by using surfactant solutions as the working fluid
- The experimental results indicated that the dry-out heat fluxes are higher when the working fluids are surfactant solutions

- ❑ Decrease the superheat of the bubble
- ❑ Better wetting of the wall
- ❑ Decrease the capillary resistance

4. Discussions

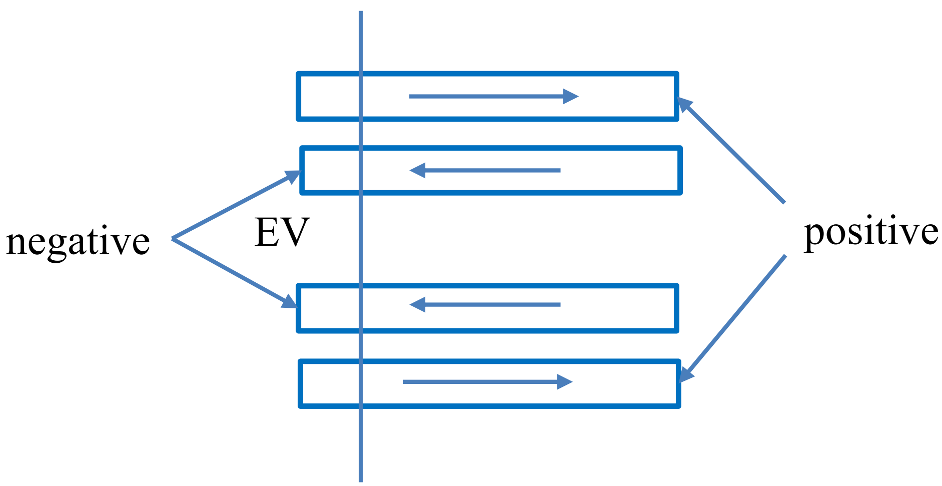
1. Is there a 'best condition' or 'dead condition' for the PHP?



Best: making best use of the heat;
Dead: the unbalanced flow is balanced

Input heat

Charging a pipe → Plugs and slugs → Oscillation motions → Heat dissipated



4. Discussions

2. Whether the initial distribution of the vapor plug and liquid slug affect the performance of the PHP? If so, how to build the analytical model?