

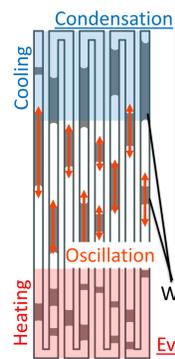


Thermal Performance Evaluation of a Meander-Shaped Low-Fill Heat Pipe Using Water and Ethanol

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Background Miniaturized aerospace systems demand thermal control technologies that are compact, lightweight, and passive

Pulsating Heat Pipe: PHP^[1]



- ✓ Meandering sealed channels
- ✓ Filled with working fluid (about **50 vol.%**)
- ✓ Phase change between heating and cooling sections
- ✓ Drives oscillatory flow
- ⇒ Latent and sensible heat transport
- ⚠ Low filling ratio leads to instability, dry-out

Fig. Schematic diagram of PHP.

Meander-Shaped Low-Fill Heat Pipe: MLFHP^[2]

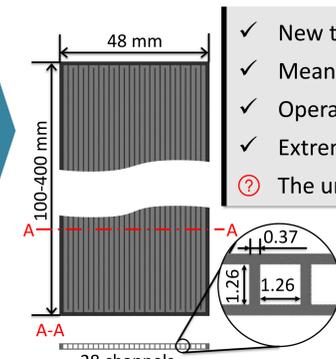


Fig. Schematic diagram of MLFHP.

- ✓ New type of heat pipe developed by our group
- ✓ Meandering sealed channels (Similar to PHP)
- ✓ Operates at ultra-low fill ratio (**~10 vol.%**)
- ✓ Extremely high heat transport
- ❓ The underlying heat transfer mechanism remains unclear

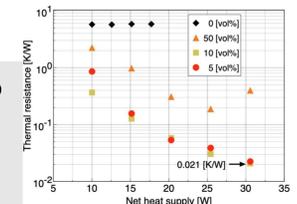


Fig. Thermal resistance of MLFHP^[2]

Objective

To evaluate the influence of working fluid properties on the heat transfer performance of the MLFHP.

Method

Thermal Performance Evaluation Method

$$R = \frac{T_h - T_c}{Q}$$

R : Thermal resistance
 T_h : Temperature of heating section
 T_c : Temperature of cooling section
 Q : Heat input

The test was terminated when T_h reached 120 °C.

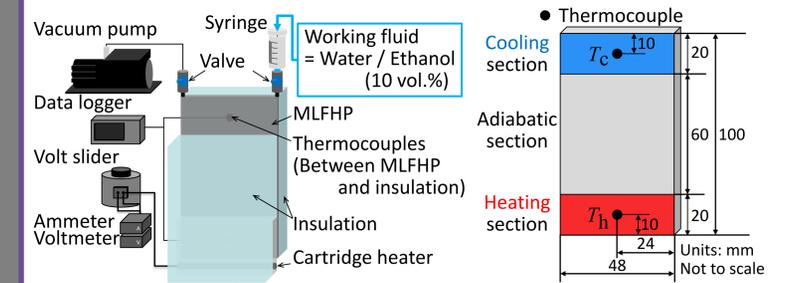


Fig. Schematic of experimental setup. Fig. Test section and thermocouple layout.

Visualization Method (Neutron Radiography)^[3]

Neutrons are particularly sensitive to hydrogen atoms, to visualize the distribution of liquid and vapor

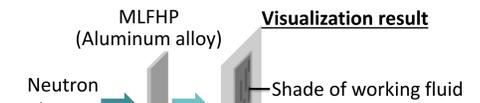


Fig. Schematic of neutron radiography.

Results

Filling Ratio: 50 vol.% vs. 10 vol.%

To compare thermal performance at conventional (50 vol.%) and low (10 vol.%) filling ratios, the same MLFHP device was tested with varying filling volume of water.

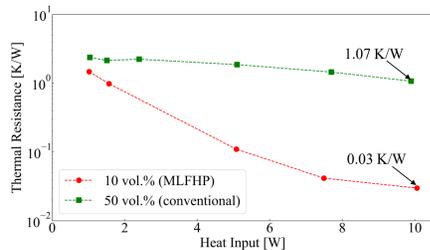


Fig. Thermal resistance (10 vs. 50 vol.%).

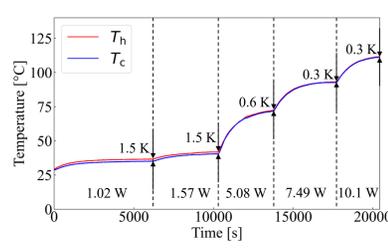


Fig. Temperature-time history of MLFHP (10 vol.%).

Working Fluid: Water vs. Ethanol

To evaluate the effect of fluid properties, water and ethanol were tested under identical conditions (10 vol.%).

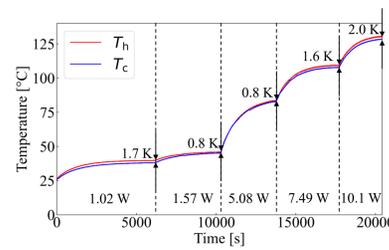


Fig. Temperature-time history of MLFHP (ethanol).

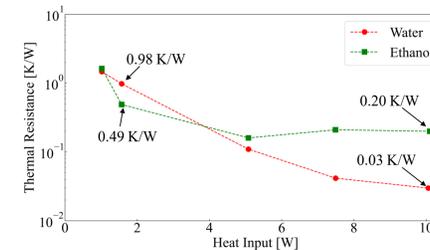


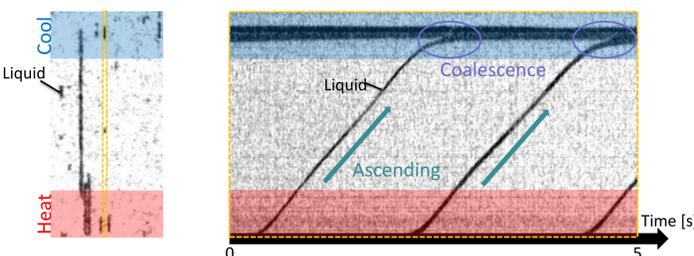
Fig. Thermal resistance of MLFHP (water vs. ethanol).

- ✓ **MLFHP (10 vol.%)** showed significantly lower thermal resistance than 50 vol.%
- ✓ **Stable, non-oscillatory temperature profiles** were observed at 10 vol.%
- indicating that **phase-change heat transfer was dominant mode**

- ✓ **Ethanol initiated thermal activity at lower input power**
- ✓ **Water required higher input power to start**, but maintained stable performance
- **Ethanol was more responsive at startup; water was more stable under load.**

Visualization via Neutron Radiography

To supplement the thermal performance evaluation and provide insights into internal flow behavior, neutron radiography was conducted using water and ethanol (10 vol.%).



(a) full view. (b) time-series (single channel).
Fig. Neutron radiograph of MLFHP using water at 10 vol.%.
Time [s]

Table Thermophysical properties of working fluids.

Property	Water	Ethanol
Boiling Point [°C]	100	78.6
Latent heat [kJ/kg]	2257	854.8

- ✓ **Liquid slugs moved upward** in both fluids
- ✓ **Unlike conventional PHPs, no self-excited oscillations were observed**
- ✓ **Water:** slugs remained in multiple channels, supporting stable phase change
- ✓ **Ethanol:** vapor accumulated in most channels under high heat input
- **Higher latent heat of water enabled steadier phase-change cycling**

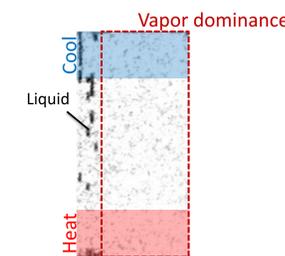


Fig. Neutron radiograph of MLFHP using ethanol at 10 vol.%.
Heat
Cool
Liquid
Vapor dominance

Conclusion

- ❑ **MLFHP showed stable operation** at low filling ratio (10 vol.%)
- ❑ **Ethanol enabled earlier start up** due to its lower latent heat
- ❑ **Water maintained stable performance** at higher heat input
- ❑ **No oscillation observed**, suggesting that MLFHP operates via a **different mechanism** than conventional PHPs
- ❑ **Neutron radiography revealed internal flow differences**, supporting the above findings

Future Research

- ❑ Investigate MLFHP performance under **different orientations**, e.g., **top-heated** and **horizontally oriented**
- ❑ Conduct **neutron radiography** in **top-heated configuration**
- ❑ Clarify **liquid return mechanism** through further visualization

References

- [1] Akachi, H., U.S. patent#4, 041, 921, (1990).
- [2] Fumoto, K., and Ishii, K., Appl. Therm. Eng., Vol. 228, (2023), 120468.
- [3] Kurita, K. et al., J. Phys.: Conf. Ser., 2605, (2023), 012005.