LIQUID FILM DYNAMICS IN PULSATING HEAT PIPES

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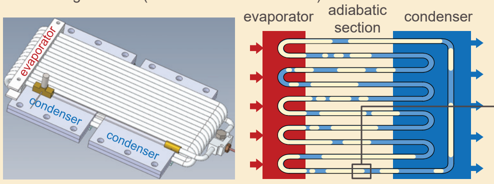
INTRODUCTION

Pulsating heat pipe (PHP, Caloduc Oscillant in French)

- Promising, high-efficient, passive heat transfer devices, particularly in thermal control system for aerospace applications.
- A capillary meandering between evaporators (heat sources) and condensers (heat sinks), with optional adiabatic sections.
- Partially filled with working fluid: vapor bubbles and liquid plugs.
- Self-sustained oscillation of liquid plugs as a result of pressure imbalance among the bubbles.
- Liquid films are deposited by receding plugs.

Motivation

- Liquid film dynamics is crucial, because heat exchange through the films is its dominant mechanism.
- Modeling of PHPs (Ph.D. thesis of X. ZHANG).



Space PHP prototype (left) and schematic (right)

01 METHODOLOGY

Thesis structure

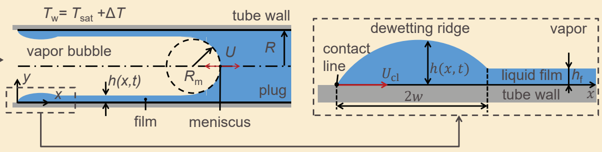
PHASE 1: Film Dynamics
- Two-dimensional axisymmetric hydrodynamics of thin liquid film, when the meniscus oscillates from pinned contact line.
- Effect of contact line receding on the liquid film.

PHASE 2: Single Branch PHP
- Simplify the film model into an 1D version that reproduces the film behaviors and integrate it to single branch PHP model (the simplest PHP configuration).

PHASE 3: Multi-Branch PHP
- Integrate the developed film model into CASCO (Code Avance de Simulation de Caloduc Oscillant) and validate the model against the experimental PHP prototypes.

Key phenomena related to the liquid film:

- Length variation: meniscus oscillation and contact line motion (receding) determined by local superheating and contact angle.
- Thickness variation: liquid evaporation and condensation of the film.



Film dynamics with pinned contact line and meniscus oscillation

- The lubrication approximation and Kelvin effect.
- local contact angle θ and meniscus curvature R_m are oscillating.
- meniscus velocity U is low; shape determined by surface tension (hemispherical).
- Films: mostly flat and thin (~100 μm), low *Re* number and strong viscous forces.

Contact line motion: dewetting problem

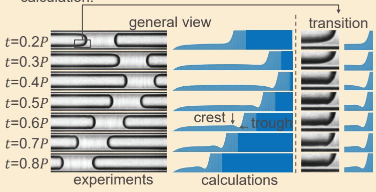
- contact line receding because of capillary action and liquid evaporation.
- dewetting ridge forms by collecting the liquid.

02 LIQUID FILM DYNAMICS

Film profile with pinned contact line and oscillating meniscus, under adiabatic condition.

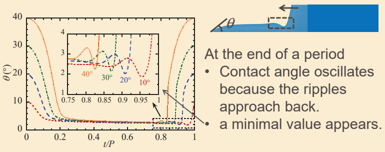
1. Comparison to experiments of Lips et al. (2010)

- An oscillating liquid plug in a cylindrical capillary tube.
- When the meniscus advances over the liquid film, the interface has a wavy appearance (ripples). The crest and the trough are truthfully captured by the numerical calculation.



2. Contact angle variation

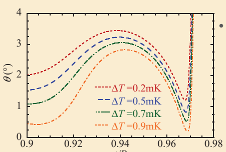
- Variation of θ is periodic, because θ is imposed by the film shape (controlled by the meniscus motion).
- The initial θ is the maximum value achieved during oscillation. θ remains nearly constant for a large part of a period, because the meniscus is away from the contact line.



At the end of a period
- Contact angle oscillates because the ripples approach back.
- a minimal value appears.

Film profile with pinned contact line, oscillating meniscus and tube wall heating ΔT

1. Contact angle variation

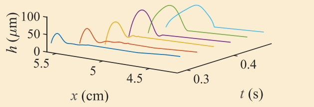


- Minimal contact angle decreases with ΔT, which implies that it will reach zero for certain ΔT. For larger ΔT, the solution does not exist.

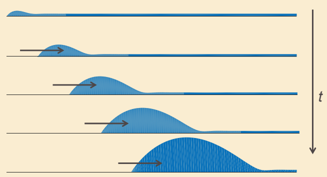
- ΔT here is merely around 1mK, which is very small, compared to the value we encounter in PHP.
- Contact line receding must be included in calculation.

Contact line motion: dewetting problem under adiabatic condition.

1. Dewetting ridge growth



Experiments of L. Fourgeaud et al. (2016)
- An ethanol film is first deposited on solid substrate by a receding liquid meniscus.
- Dewetting occurs and the contact line recedes. A growing dewetting ridge has been observed.

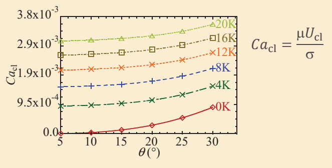


Numerical calculations demonstrate
- The growth of the dewetting ridge
- Contact line receding speed logarithmically decreases with the ridge size: nearly constant under most experimental conditions

Results are verified by comparison to analytical formula proposed by J. Snoeijer & J. Eggers(2010)

Contact line motion: dewetting problem with substrate heating

1. Receding speed as a function of ΔT and θ

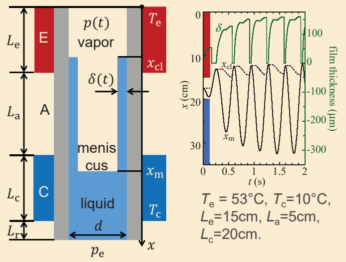


- Ca_{cl} monotonically increases with both ΔT and θ.
- For large ΔT, the dependence of Ca_{cl} on ΔT is more significant than that on θ, which signifies that the evaporation effect prevails.

03 PHP MODELING AND SPACE EXPERIMENTS

Single Branch PHP Modeling

- A capillary tube with an end sealed and the other open connect to pressure reservoir of constant p_e.
- It consists of an evaporator (E), an adiabatic section (A) and a condenser (C). Inside the tube a bubble, a meniscus (film) and a plug.

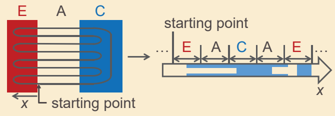


T_e = 53°C, T_c=10°C, L_e=15cm, L_a=5cm, L_c=20cm.

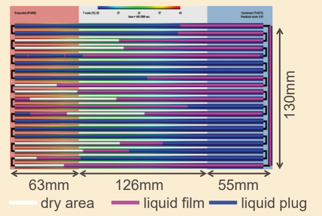
- Curvatures are replaced by the model lumped shape.
- Vapor is superheated, described as the ideal gas.
- Liquid-vapor interface has the saturation temperature corresponding to vapor pressure *p*.
- Film deposited by the receding meniscus is a function of meniscus speed (from film dynamics).
- Contact line recedes as a function of local superheating and contact angle (from film dynamics).
- Film thickness δ is uniform, but evolves with time.
- Results will be compared to experimental data.

Multi-Branch PHP simulation: CASCO Code (Code Avance de Simulation de Caloduc Oscillant)

- One dimensional PHP simulation code, developed by V. Nikolayev in CEA.
- Complex PHP loops are projected on a straight tube from a starting point, applied with repeating wall conditions: evaporator (E), adiabatic section (A) and condenser (C)…
- Currently, liquid films are represented by a constant thickness (input parameter).

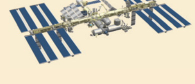


- PHP simulation using CASCO: copper tube ∅3.2mm outer, ∅1.4 inner.

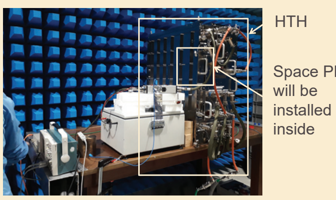


PHP experiments in space

PHP development for the satellites
- ESA MAP (Microgravity Application Program) project, TOPDESS (Two-phase Passive Thermal Devices for Deployable Space Systems).
- ESA Space PHP experiment on HTH (Heat Transfer Host) on board of International Space Station (foreseen for 2026).
- CNES R&T DSO/TB/TH-2020,0026119: collaboration of Airbus DS and CEA.



Objectives
- PHP performance in space: PHP with large inner diameter (to reduce the viscous resistance); can only function under microgravity condition.
- Test of PHP prototype for cooling electronic devices in satellites.
- Obtain and use experimental data for validation and improvement of numerical design tools.



05 CONCLUSION

Attempts of establishing empirical correlations for predicting PHP performance have failed, because of the large number of system parameters and the complexity of PHP behavior. Therefore, the thermo-hydrodynamic simulation that reflects the physical phenomena remains the most promising way for developing PHP design tools in the future. Compared to more complicated numerical models, the one-dimensional description of PHP appears as an optimal choice that can produce accurate results without oversimplification.

- Film dynamics: The future PHP models should account for the liquid film phenomena presented above: spatial and temporal variation of the film thickness during meniscus oscillation and film thinning due to liquid evaporation; contact line recedes in fluid channel as a result of capillary action and liquid evaporation, which may be simplified as a function of local contact angle and superheating and be integrated into PHP system modeling.
- In the next stage of CASCO (Code Avance de Simulation de Caloduc Oscillant) development, the constant liquid film thickness, as an input parameter, will be replaced with the liquid film model presented in single branch PHP. To validate the model, extensive comparisons with experimental data will be conducted.

Presented by
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06-08 Oct. 2021, Toulouse, France
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Publications:
- Zhang, X., & Nikolayev, V. (2021). Liquid film dynamics with immobile contact line during meniscus oscillation. Journal of Fluid Mechanics, 923, A4. doi:10.1017/jfm.2021.540
- Zhang, X., & Nikolayev, V. Liquid film dynamics during meniscus oscillation. Proceedings of IHPC (International Heat Pipe Conference) / IHPS (International Heat Pipe Symposium), Gelendzhik, Russia, September, 7-10, 2021

Acknowledgements
- EU-CEA Numerics program.
- CNES co-finding for the Ph.D. thesis.
- ESA (European Space Agency) TOPDESS project.