Bubble Nucleation on the Solid-Liquid Interface when a Droplet Impacts a Heated Substrate

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11/06/2025

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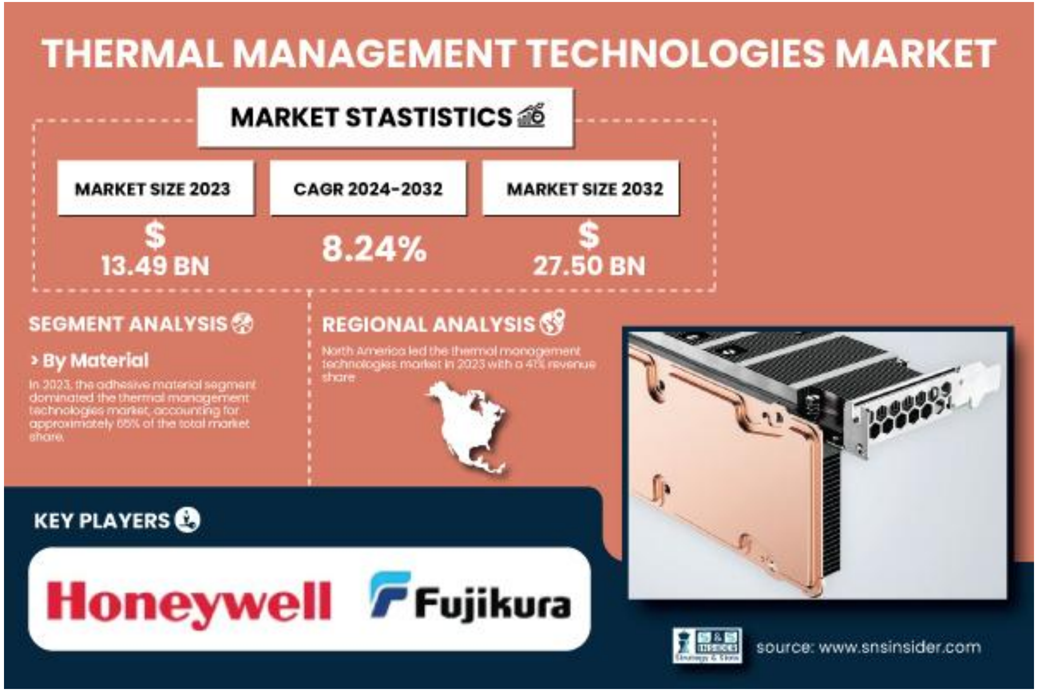
Motivation: Heat Dissipation Requirements

- Continuous evolution of electronic devices and industrial systems.
- High heat flux dissipation requirements.
- Necessity of efficient thermal management technologies.

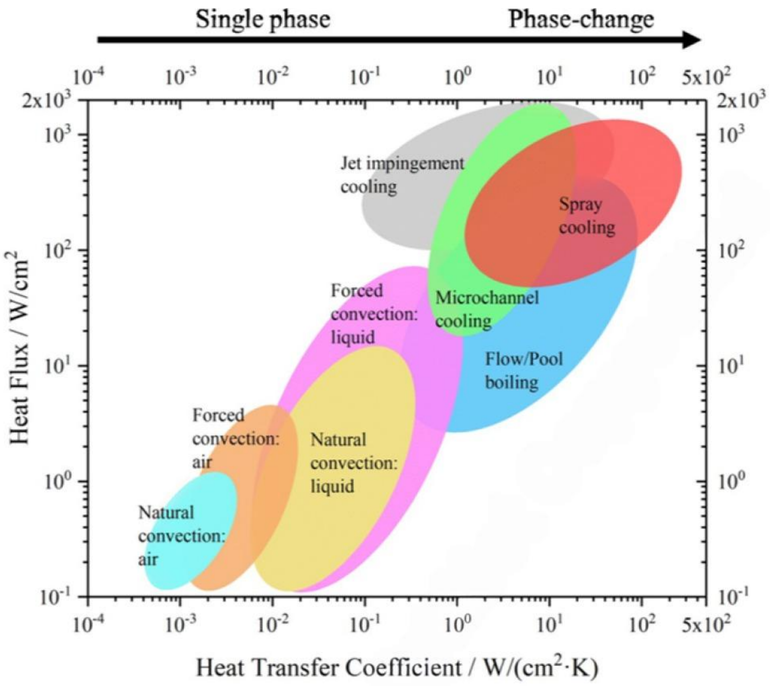


Motivation: Cooling Technologies

Phase-change approaches:

- Jet impingement cooling;
- Microchannel cooling;
- Spray cooling.

Capability to exploit the **latent heat of vaporization**, allowing for higher heat dissipation rates.



Sefiane and Koşar (2022), Applied Thermal Engineering

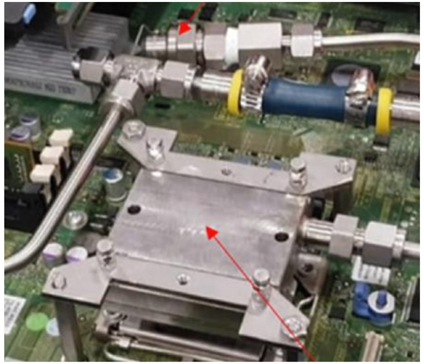
Motivation: Spray Cooling

Liang and Mudawar (2016), IJHMT

Classical applications:
- Internal combustion engines;
- Turbine blades;
- Steel industry.

Recent applications:
- Electric vehicles;
- Reactor pressure vessels;
- High power electronic equipment.

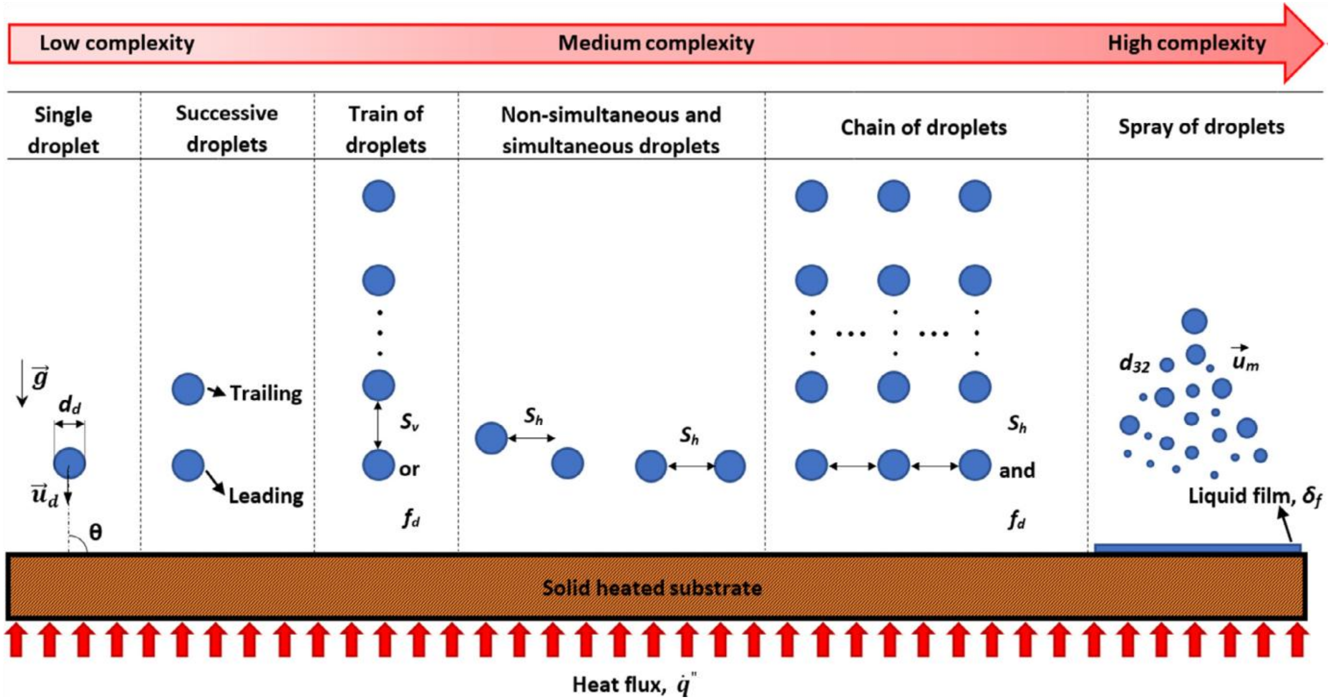
Kandasamy et al. (2022), Applied Energy



Spray cooling's problem:
- Large amount of involved parameters;
- Contradictory findings in the literature.

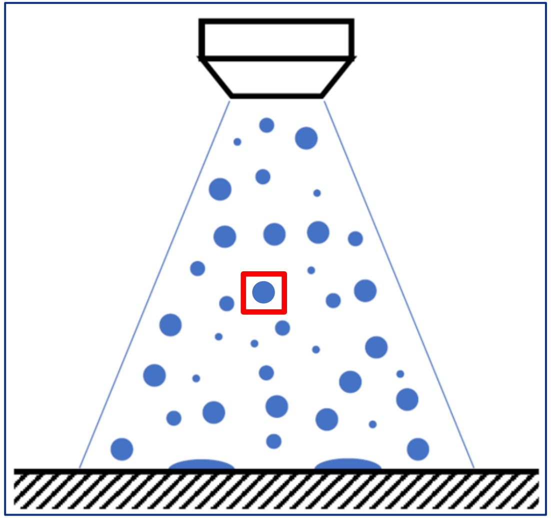
Consequences:
- Uncertainty about the relevance of hydrodynamic parameters on the cooling performance;
- **Absence of a unified heat transfer theory.**

Motivation: Single Droplets

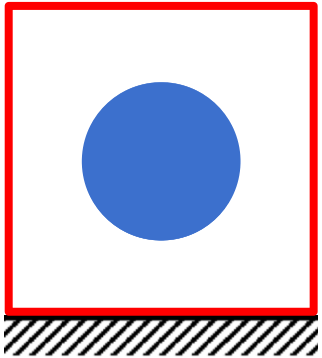


Benther et al. (2021), IJHMT

Motivation: Single Droplets



Aksoy et al. (2021), Energies



Single droplets:

- No practical applications;
- Simplifies the phenomena;
- **First step to a better understand the relation between the fluid dynamics and the heat transfer.**

Objectives

Provide a **spatio-temporal** characterization of the hydrodynamic behavior at the solid-liquid interface during the impact of a droplet on a heated substrate.

- Analyze the solid-liquid interface formed between the droplet and the substrate by using optical techniques;
- Quantify the bubble nucleation and the contact area variations during the droplet impact.

Materials and Methods: Optical techniques

Single Droplet Impact

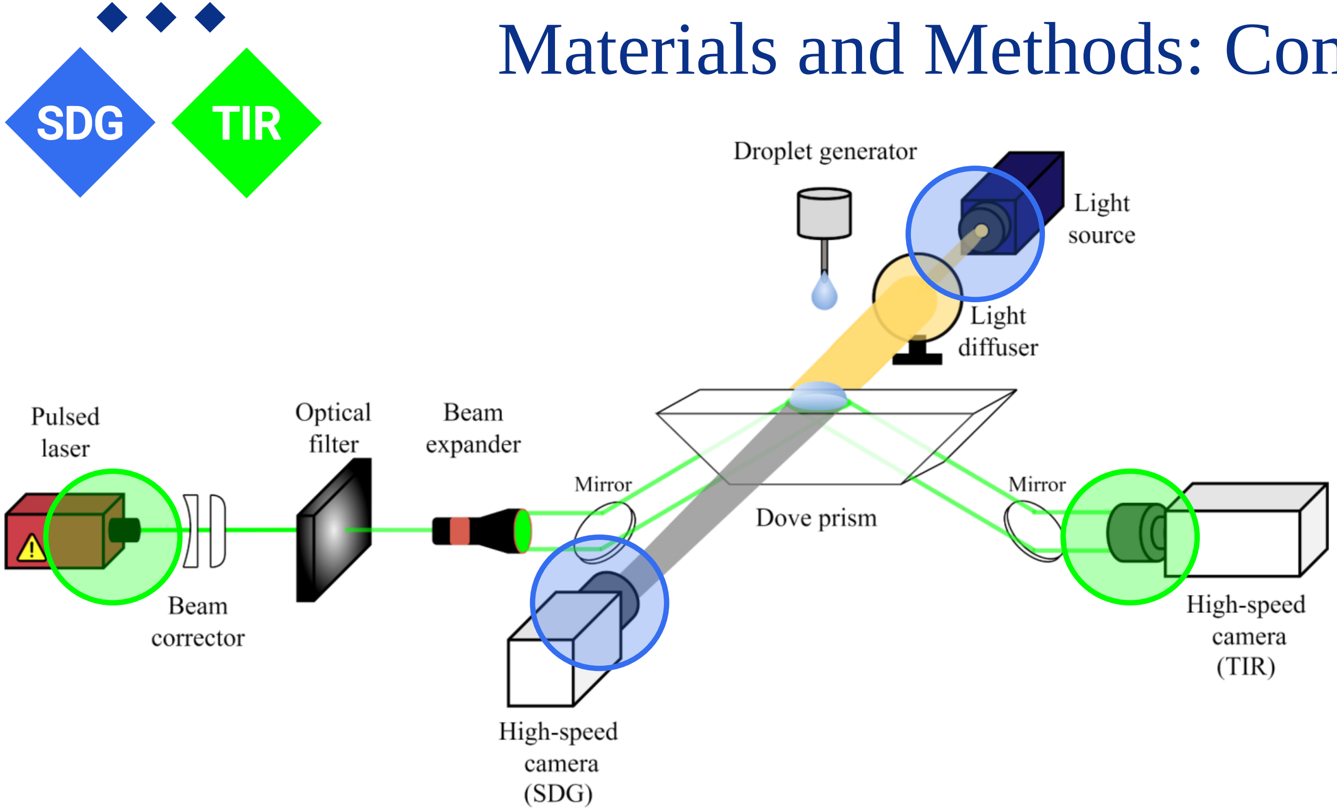
TIR — Total Internal Reflection

Solid-liquid interface view: Bubble nucleation and interface characteristics.

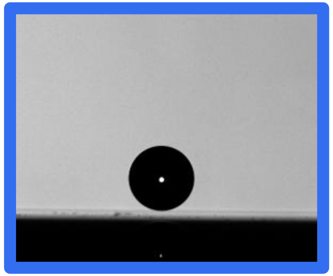
SDG — High-Speed Shadowgraphy

Impact side-view: Droplet size and impact velocity.

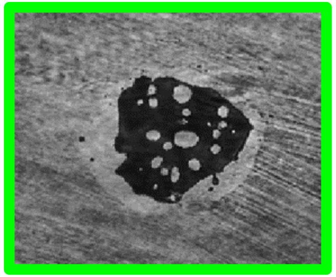
Materials and Methods: Combined setup



SDG side-view:



TIR interface-view:



Materials and Methods: Bubble detection

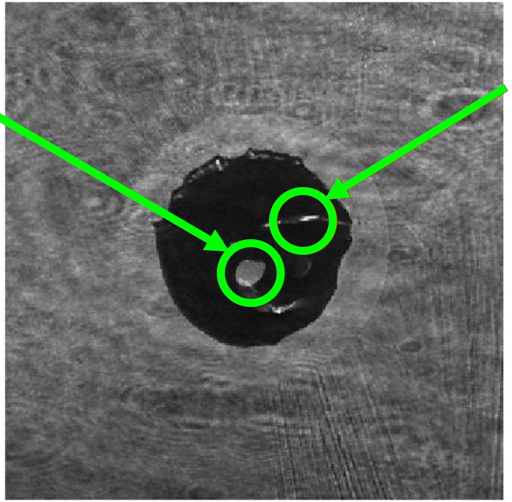
Bubble detection algorithm:

- Number of nucleated bubbles;
- Quantification of the wet, dry, and total contact area.

Segmentation criteria:

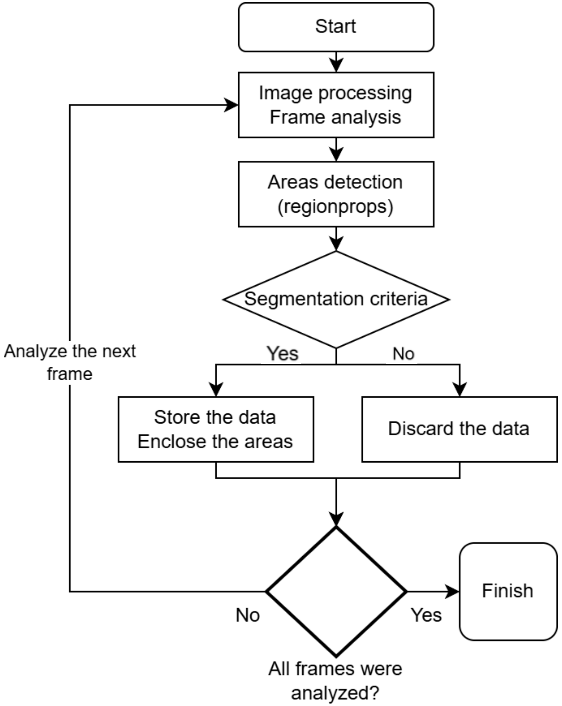
- Circularity (closeness to a perfect circle);
- Bubble size.

Bubble ☑

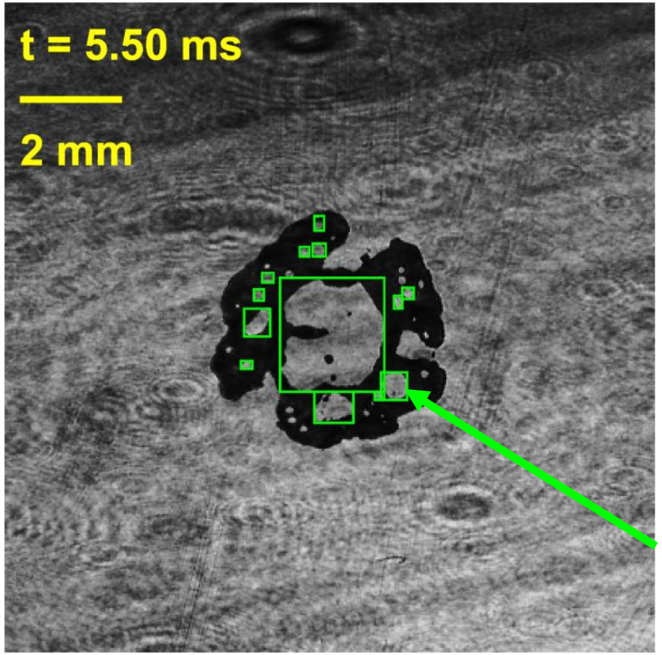


Light reflection ☒

Materials and Methods: Bubble Detection



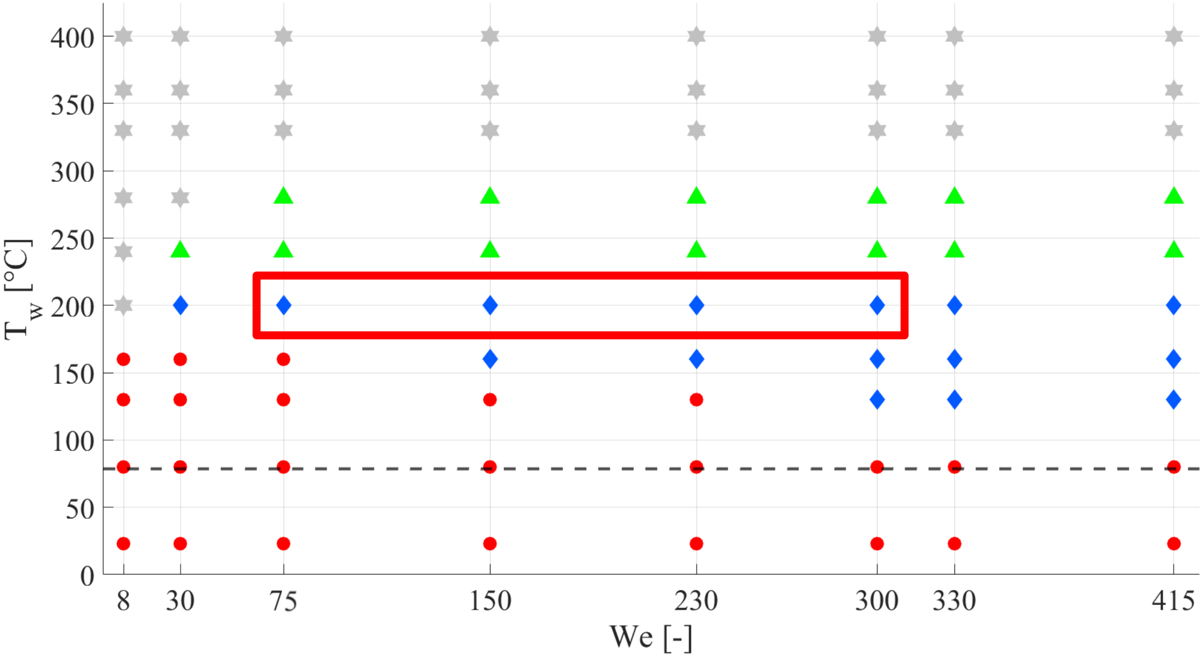
Single frame after bubble detection:

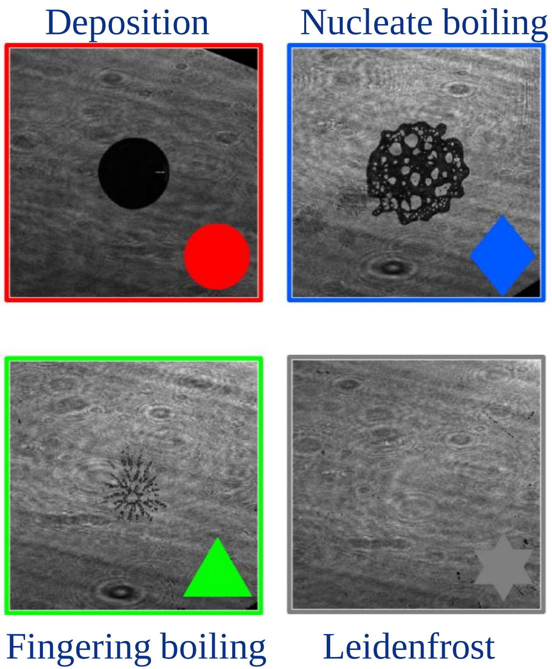


Gas-solid contact

Pure ethanol
Droplet size: 1.43 ± 0.07 mm
Frame rate: 6000 fps
SDG pixel size: 47.4 µm
TIR pixel size: 31.9 µm

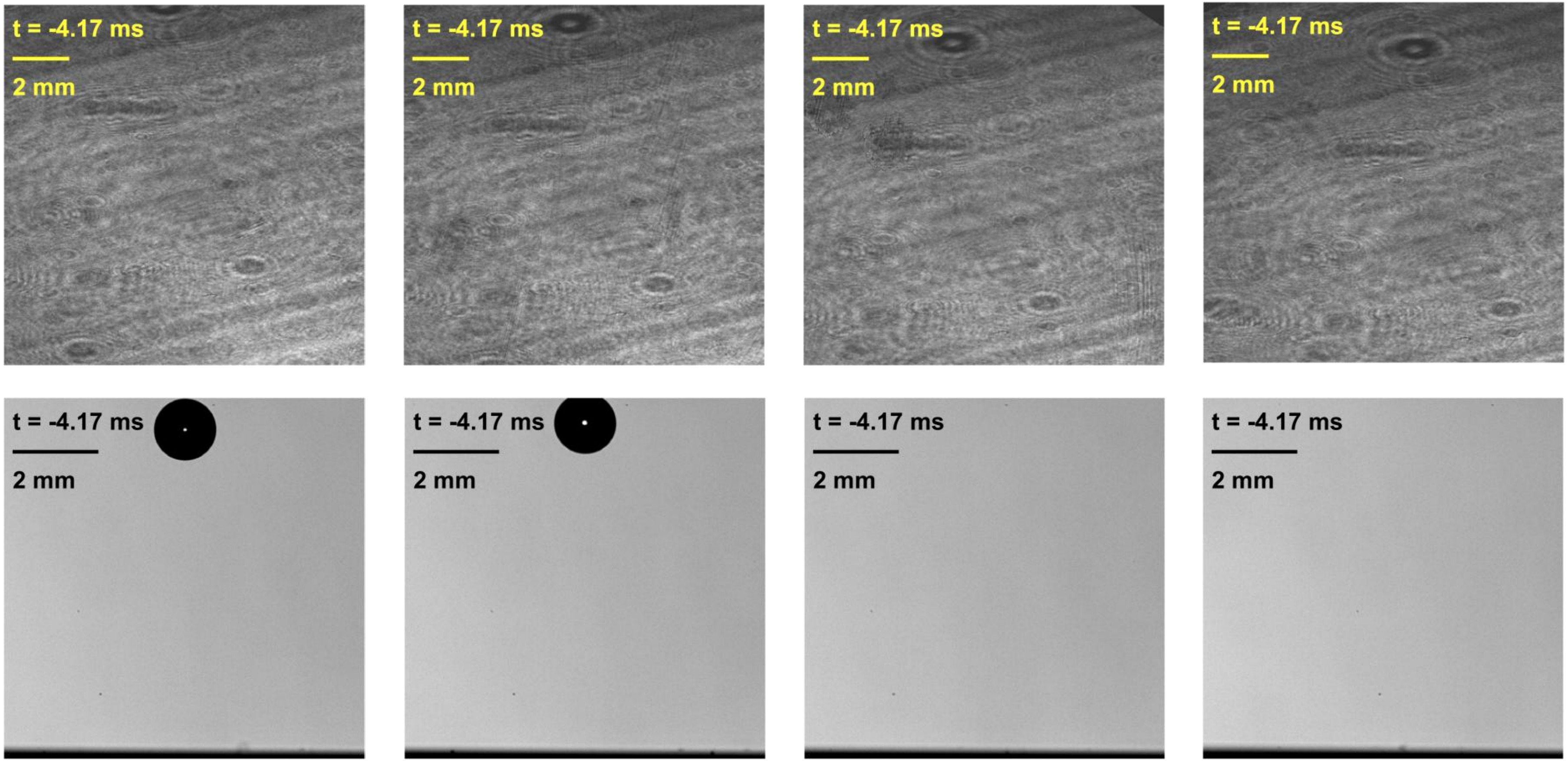
Results: TIR Regime Map



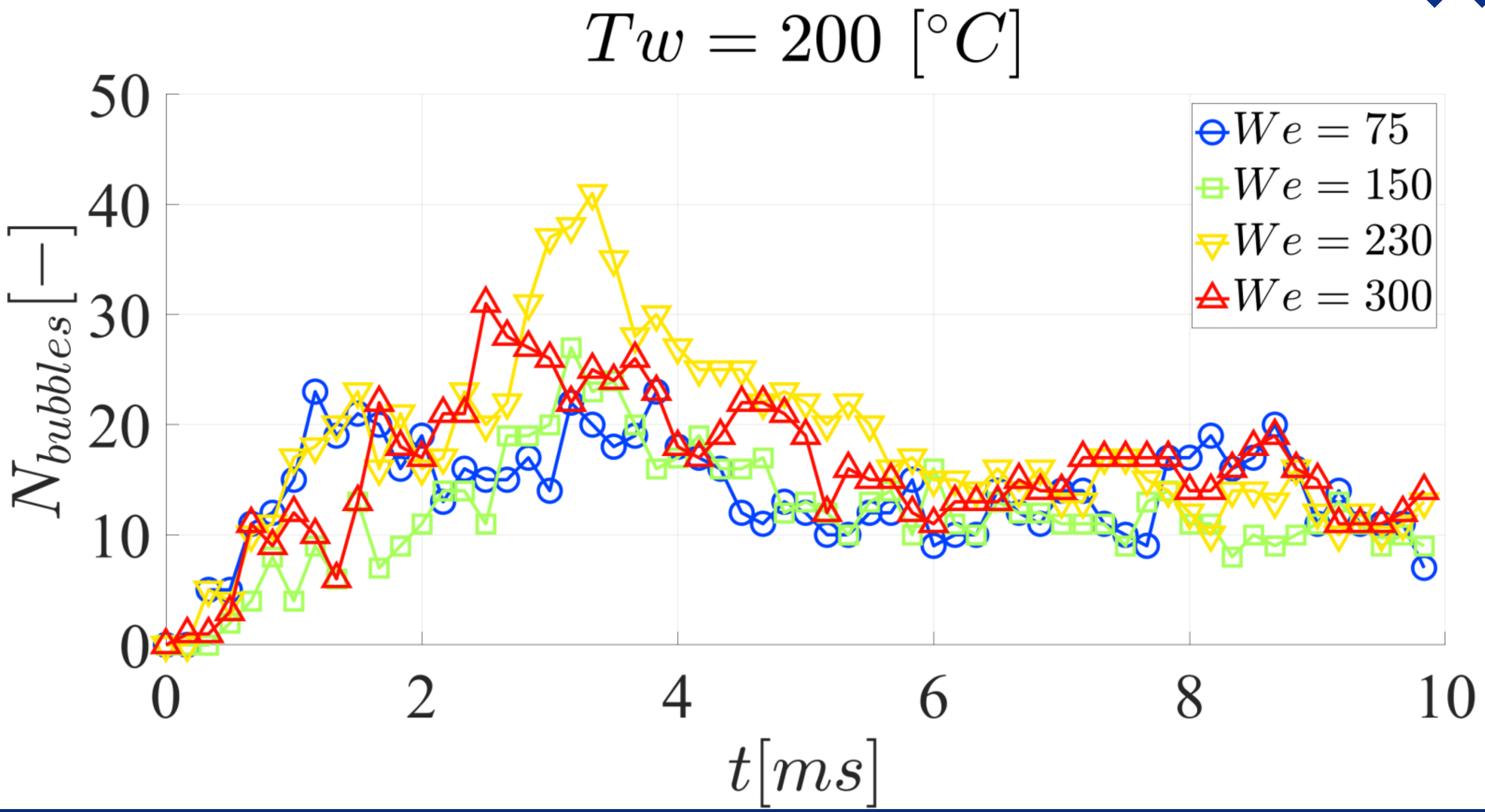


Results: Bubble Detection, Tw = 200 °C

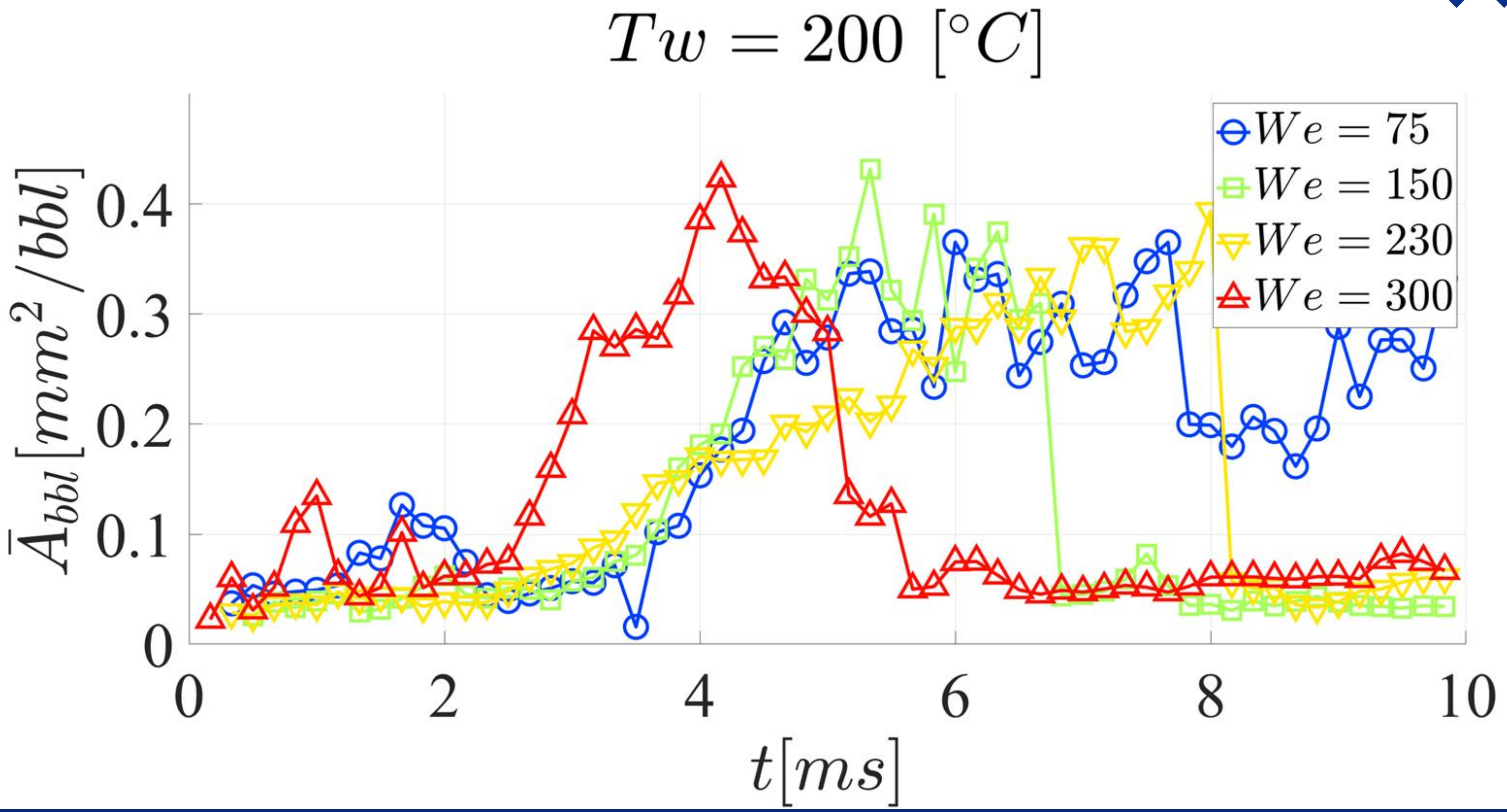
We = 75 | We = 150 | We = 230 | We = 300



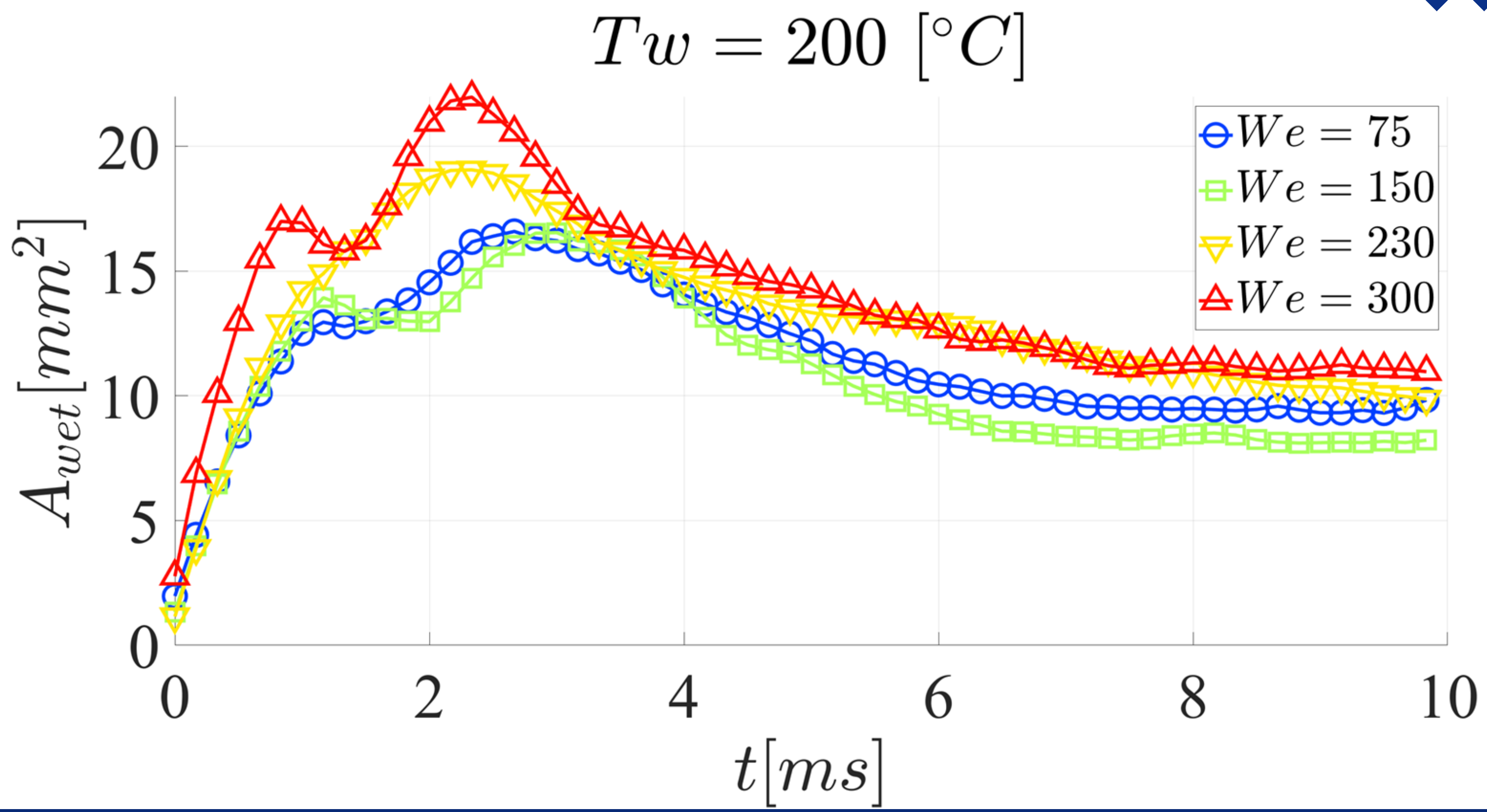
Results: Number of Bubbles Evolution



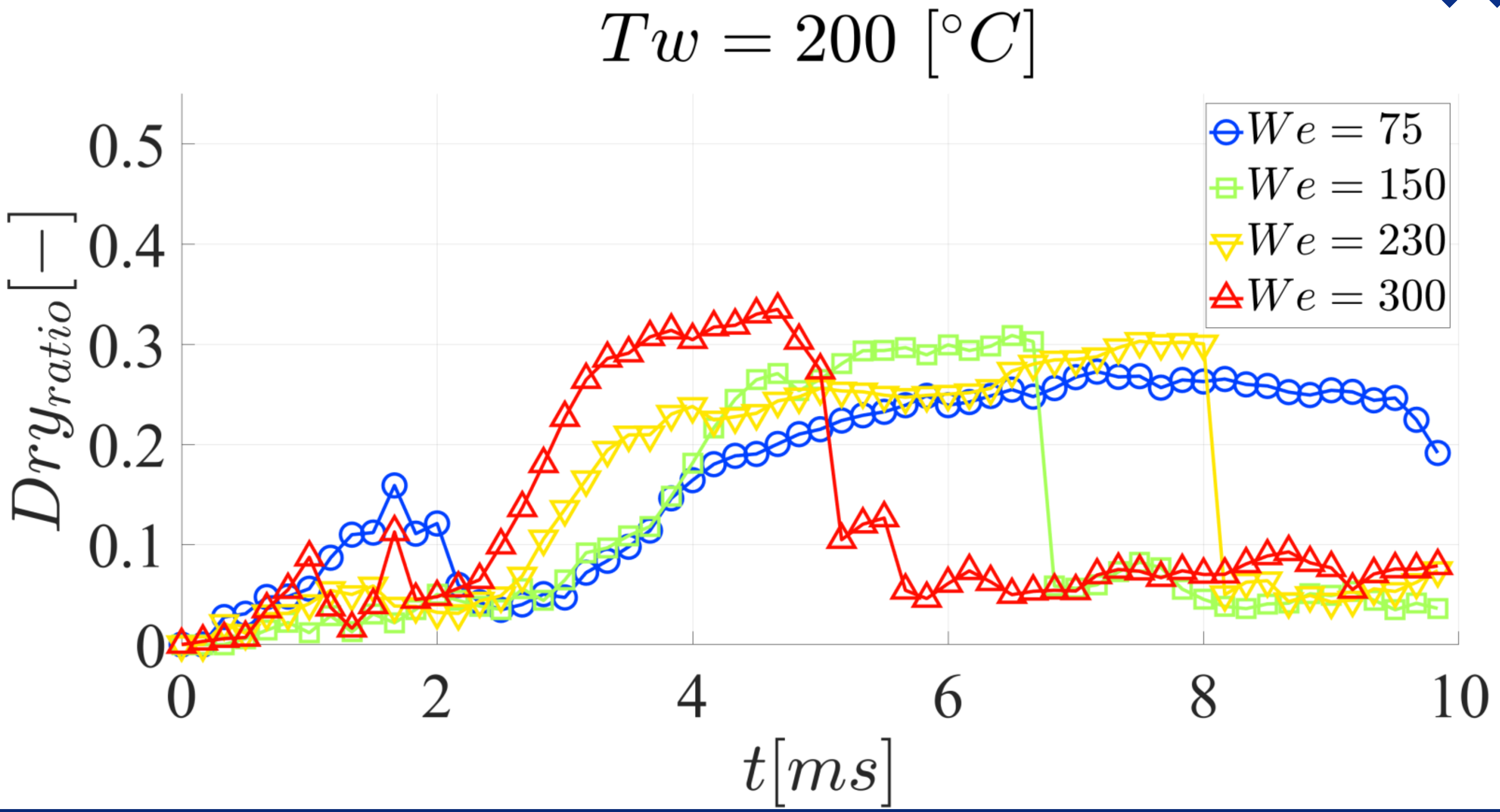
Results: Average Bubble Size Evolution



Results: Wet Area Evolution



Results: Dry to Total Area Ratio Evolution



Conclusions

- Nucleated bubbles reach a peak approximately 2–5 ms after impact across all cases, with dry areas increasing proportionally to the Weber number during the early spreading stage;
- Droplet breakup causes a suppression of bubble nucleation, disrupting the formation of vapor pockets at the interface;
- The detection algorithm struggles to accurately detect the bubbles close the liquid lamella rim.

Next Steps

- Improve bubble detection accuracy by incorporating additional parameters such as aspect ratio or solidity, and the addition of an adaptative contour to improve accuracy on the liquid lamella rim;
- Develop expressions to describe the variation of dry and wetted contact areas and implement them into a physical model to estimate the heat flux;
- Infrared Thermography experimental data to quantify the heat transfer characteristics associated with the impact phenomena.

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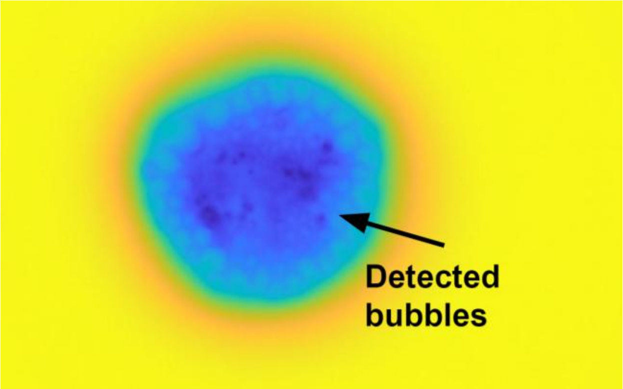

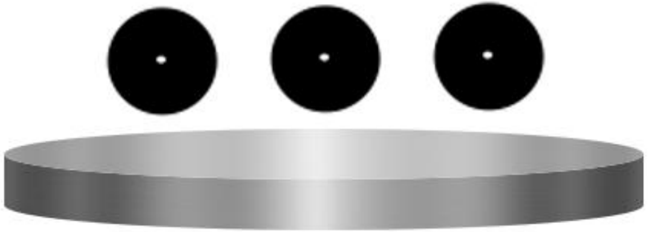

Acknowledgements

Young Investigator Grant:
2021/01897-0
Scholarships for the candidate:
2023/15397-5 and 2024/17883-7

Thanks for your attention!

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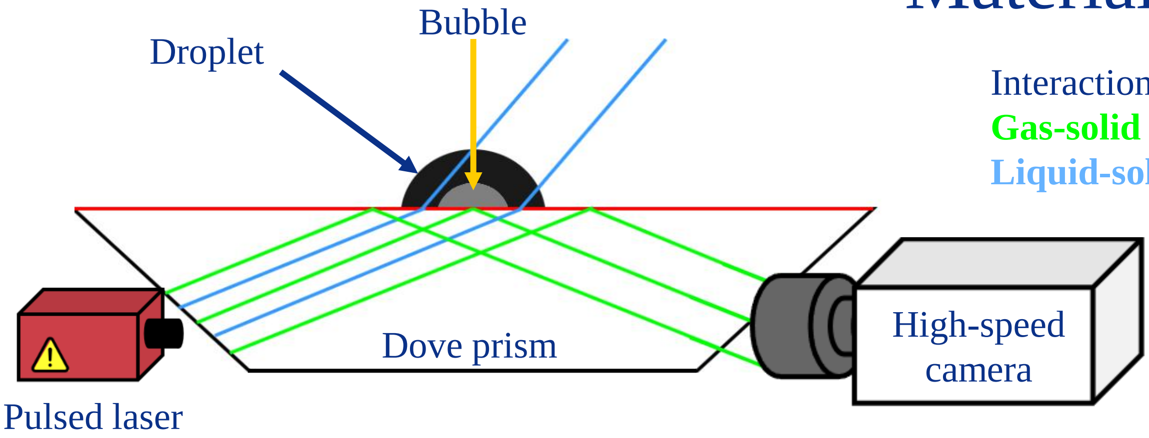
Materials and methods: TIR



Interactions at the interface:

Gas-solid contact: Laser beams reflection;

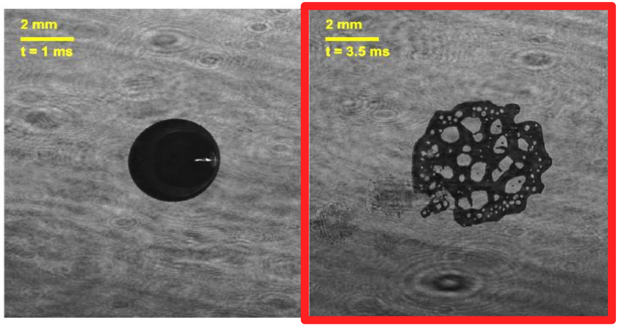
Liquid-solid contact: Laser beams refraction.

Snell's law:

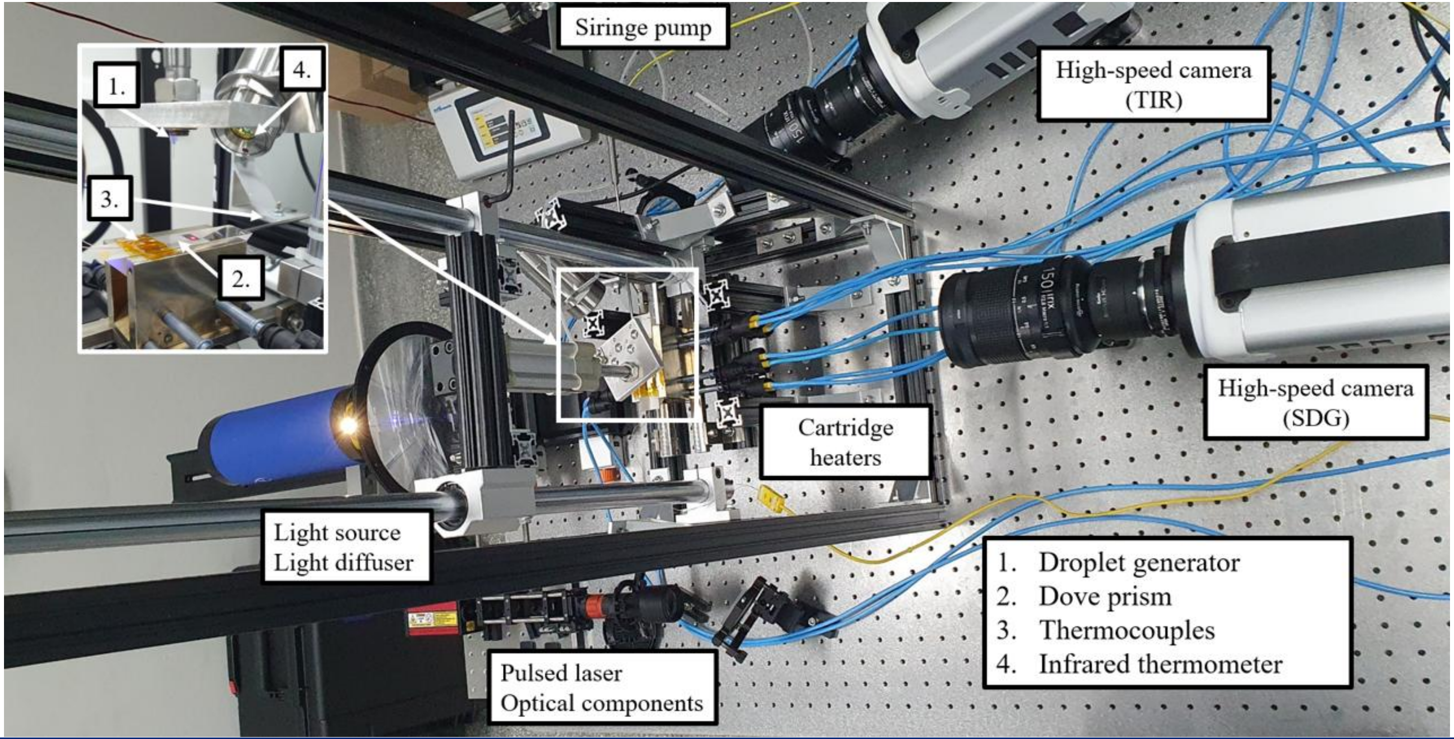
$$\frac{\sin(\theta_2)}{\sin(\theta_1)} = \frac{n_1}{n_2} \quad \theta_c = \arcsin\left(\frac{n_1}{n_2}\right)$$

Interface view examples:

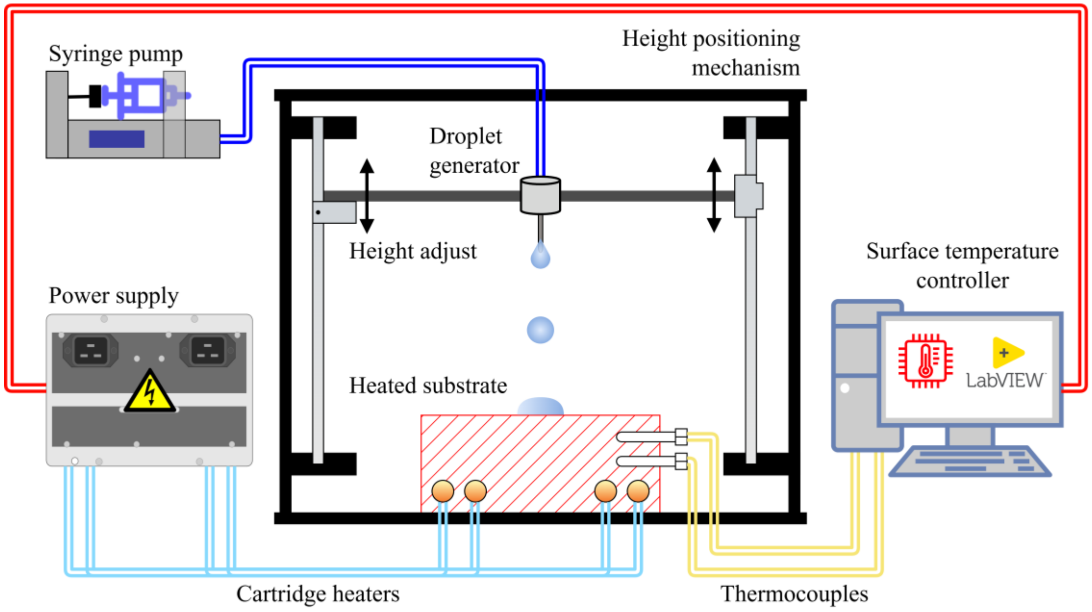
Significant heat flux variations



Materials and methods: Experimental Setup



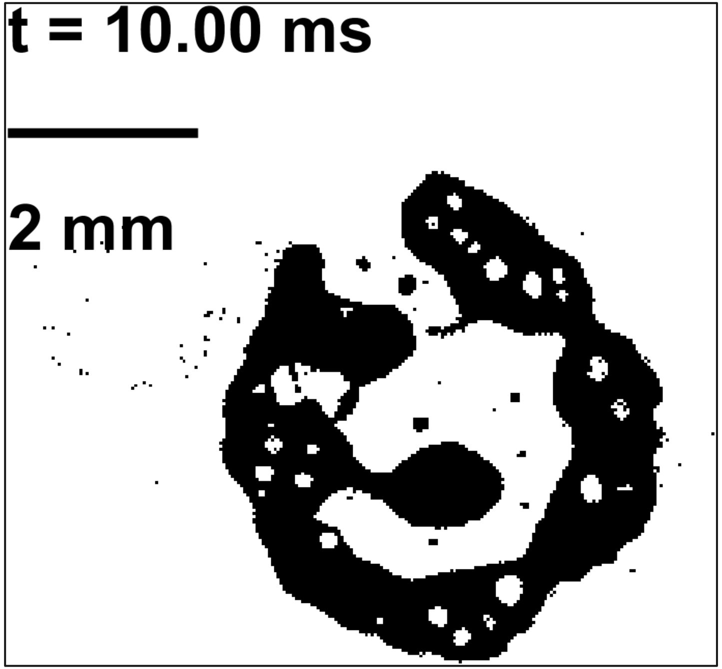
Materials and methods: Auxiliary systems

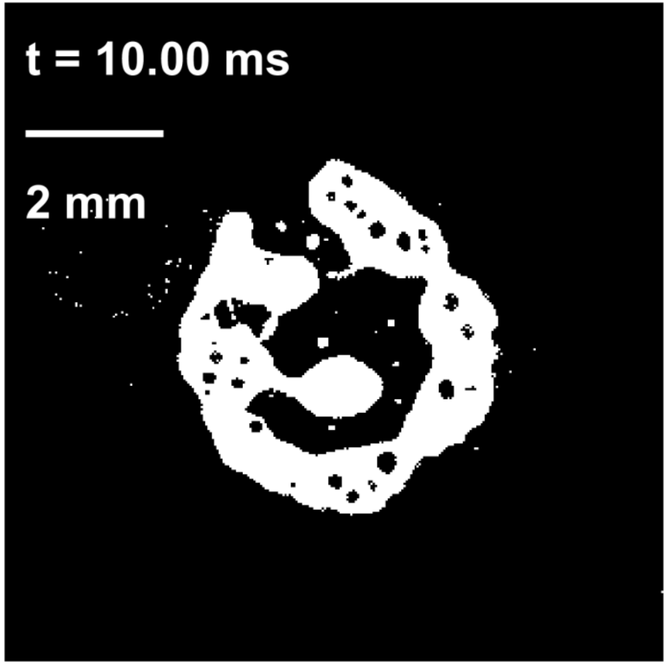


Auxiliary systems:

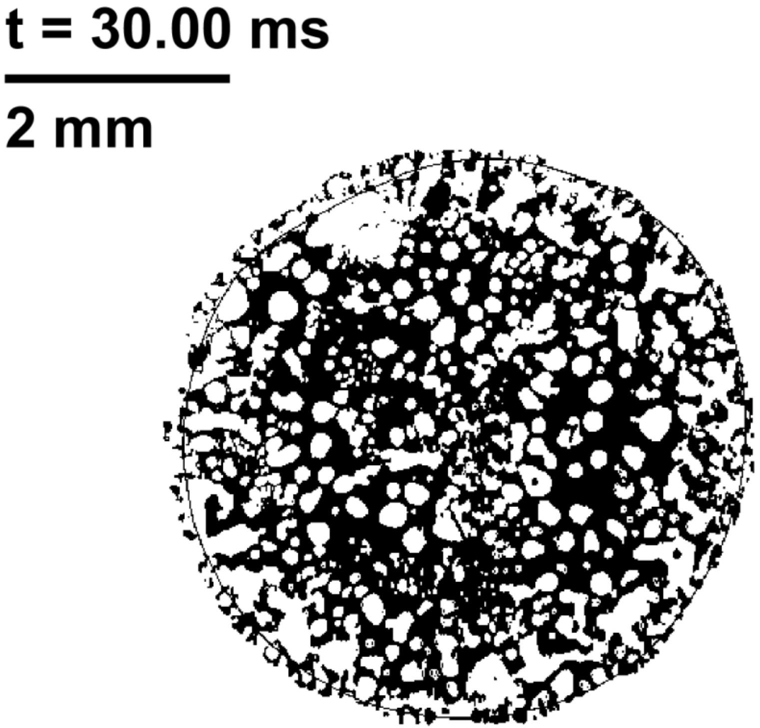
- Droplet generator;
- Height positioning mechanism;
- Substrate temperature controller.

Materials and methods: Bubble detection





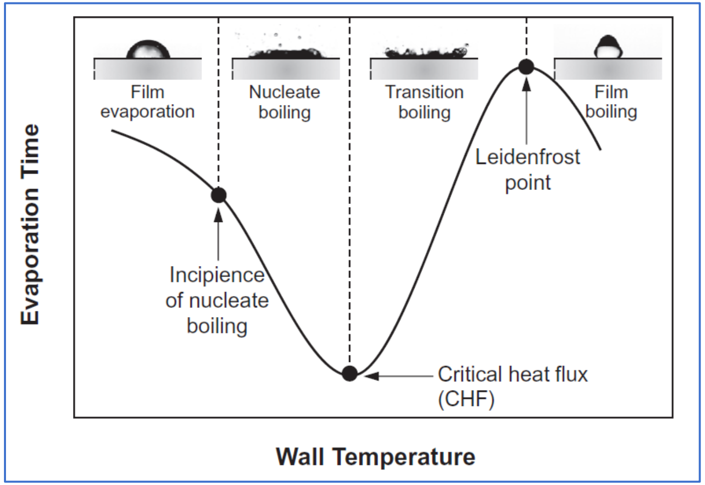
Materials and methods: Adaptative Contour



Contour addition by the snake's method:

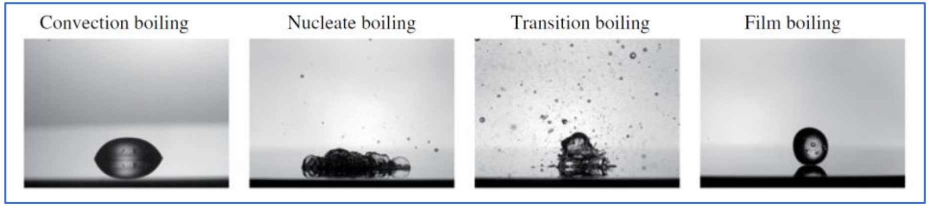
Literature Review: Single Droplet

Droplet impact on heat substrates:



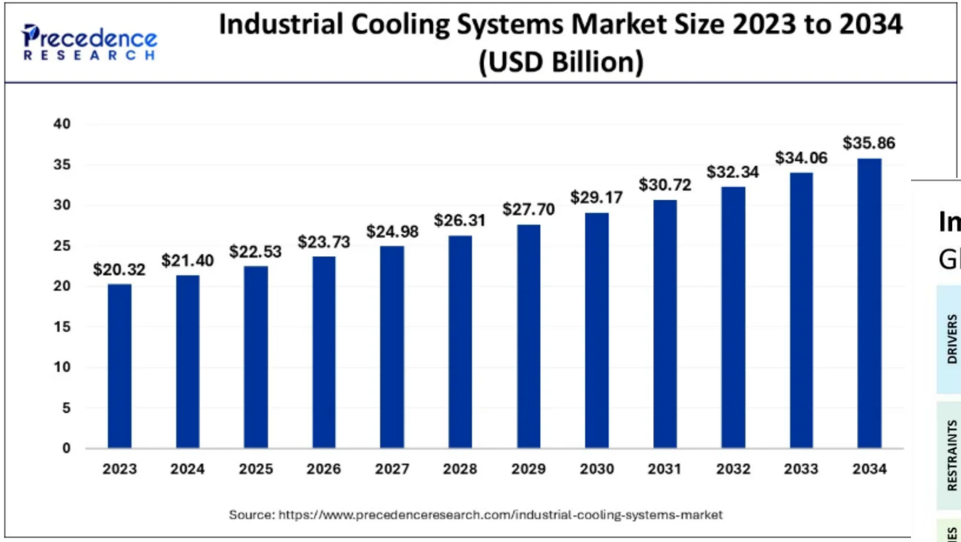
Liang and Mudawar (2017), IJHMT

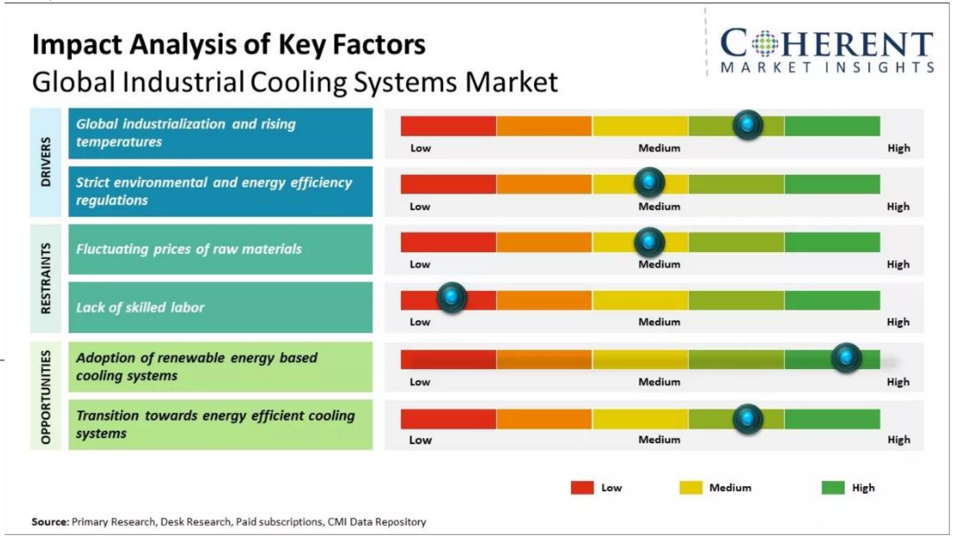
- Film evaporation: conduction and natural convection;
- Nucleate boiling: vapor bubbles generation at the interface;
- Transition boiling: formation of a non-continuous vapor film;
- Film boiling: the vapor film separates the liquid and the surface (Leidenfrost effect).



Roisman, Breitenbach and Tropea (2018), IJHMT

Industrial Cooling Systems

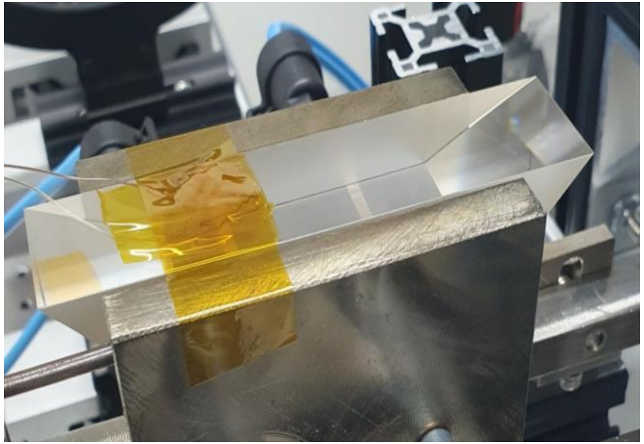




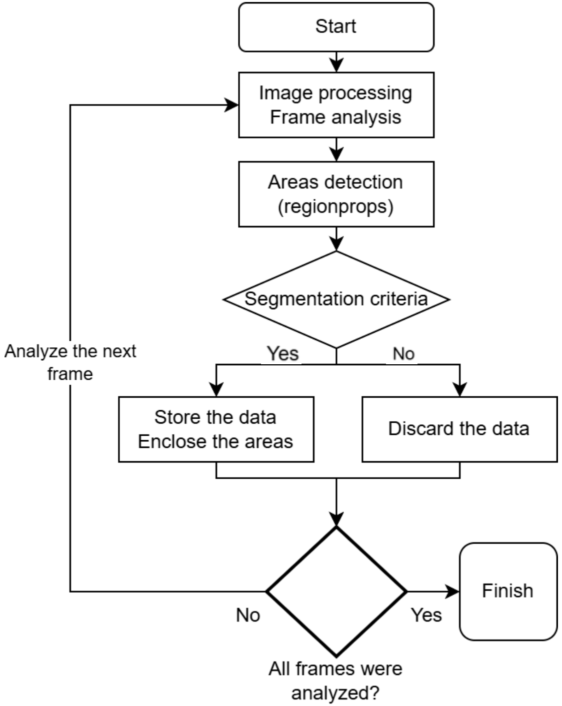
Experimental Conditions

Total experiments: 80
Fluid: pure ethanol
Droplet size: 1.43 ± 0.07 mm
Weber: 10 – 600
Tw: 23 – 400 °C
Frame rate: 6000 fps
SDG pixel size: 47.4 µm
TIR pixel size: 31.9 µm

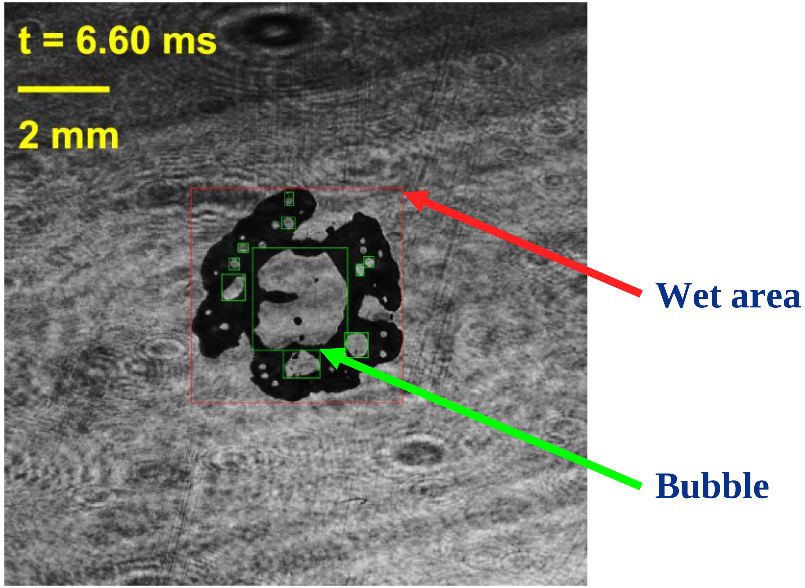
N-BK7 Dove prism



Materials and methods: Bubble detection



Single frame after bubble detection:



Partial Results : SDG and TIR