High Resolution Measurements of Boiling Heat Transfer

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Personal Skills and Boiling Experience

Single Bubble Pool Boiling

Bubble Coalescence and moving contact line evaporation during flow boiling in a single minichannel

Personal Boiling Experience

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Boiling always played an important role (from undergraduate to doctorate)

2007 **Semester Abroad at Brunel University West London, UK**
„Heat transfer in single phase and flow boiling in microchannels"
(Supervisor: Prof. T. Karayiannis, Prof. D.B.R. Kenning)

2009 **Diploma Thesis, University of Hanover**
„Boiling Heat Transfer of Refrigerants on Horizontal Tubes"
(Supervisor: Prof. A. Luke, Prof. D. Mewes)

2010 (since) **Parabolic Flight Campaigns (Research Associate), TU Darmstadt**
„Single bubble pool boiling under the influence of reduced gravity"
(Co-Worker: Prof. P. Stephan, Prof. P. di Marco)

2011 (since) **Project Leader (Joint Research Project ESA&JAXA)**
„Flow boiling in mini-/microchannels under the influence of reduced gravity"
(Co-Worker: Prof. P. Stephan, Prof. O. Kawanami, Prof. A. Pattamatta)

Personal Skills

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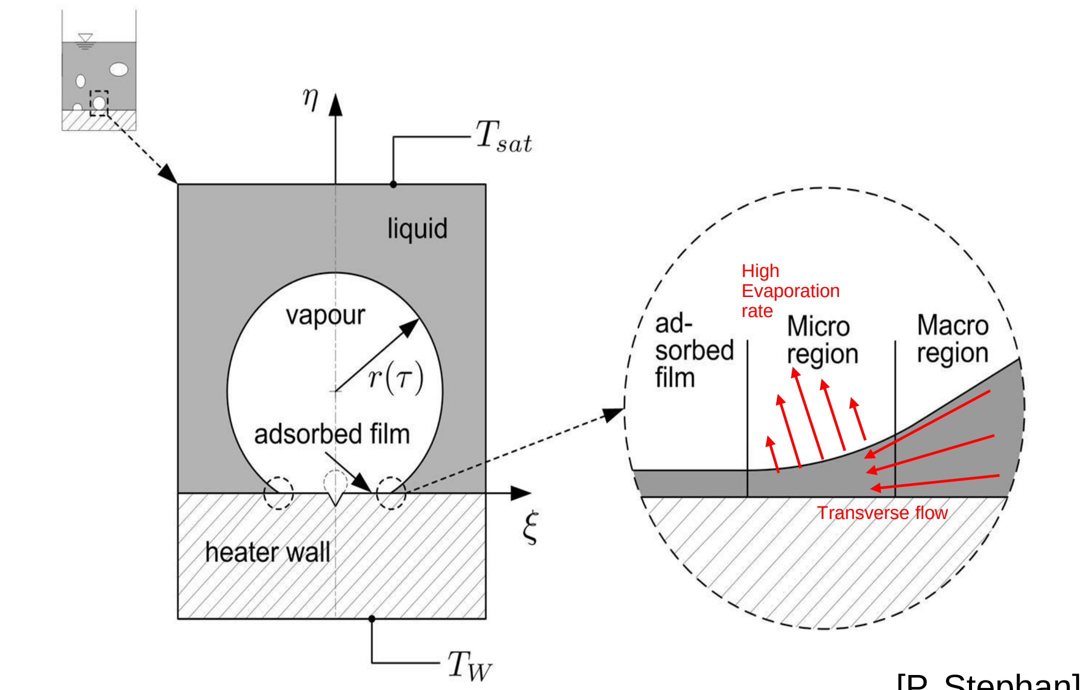
- Extensive Experience in the Design and Commissioning of experimental setups
- Sound knowledge of temperature measurement techniques (in particular high speed IR-thermography)
- Organisational skills (Parabolic Flight campaigns)
- Excellent knowledge of the fundamentals of heat and mass transfer due to assistance in lectures and design of exams
- Design of Parabolic Flight setup with modern techniques in collaboration with Chemical Department (sputtering of CrNi layers) and Institute of Production Tools (Laser-Sintering technique for microchannel test section)

Introduction
Motivation

- Extensive use of flow boiling in many technical applications
- High complexity of heat transfer and flow phenomena coupled with a free phase boundary during flow boiling
- Numerous (semi-)empirical correlations to describe boiling only valid in very narrow parameter fields

⇨ Underlying physical processes not sufficiently understood

⇨ Multiple length-scales

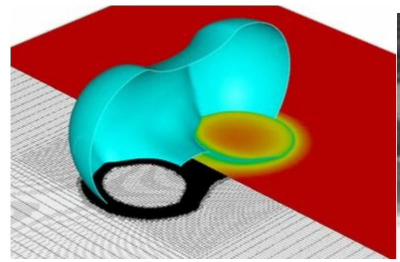


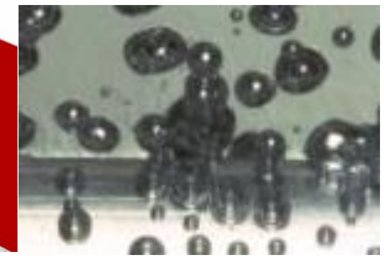
[P. Stephan]

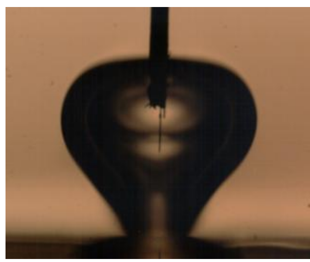
Multiple scales of interest

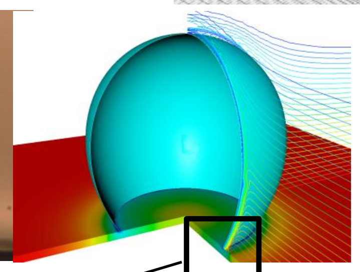
CHF

Multiple bubble regime

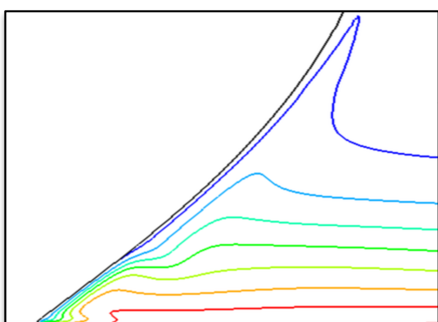








Single bubble regime



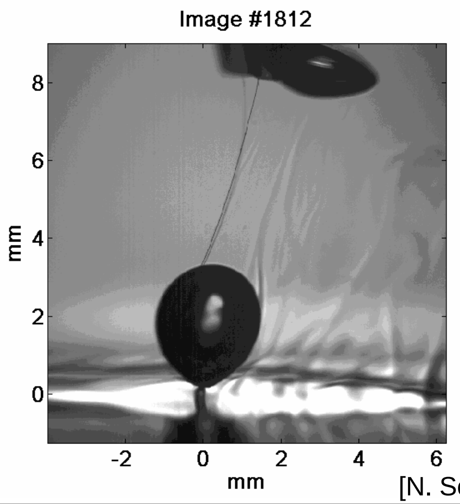
Dynamic contact line behavior
and wetting characteristics

Typical length scale

„Nano“ „Micro“ „Meso“ „Macro“ [P. Stephan]

Scientific approach
Research at TTD

Generic Experiment

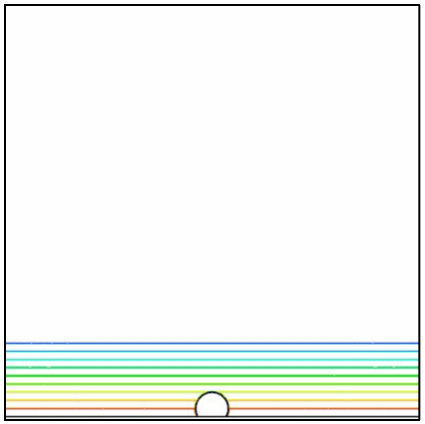


[N. Schweizer]

Validation

Higher resolution

Numerical Simulation



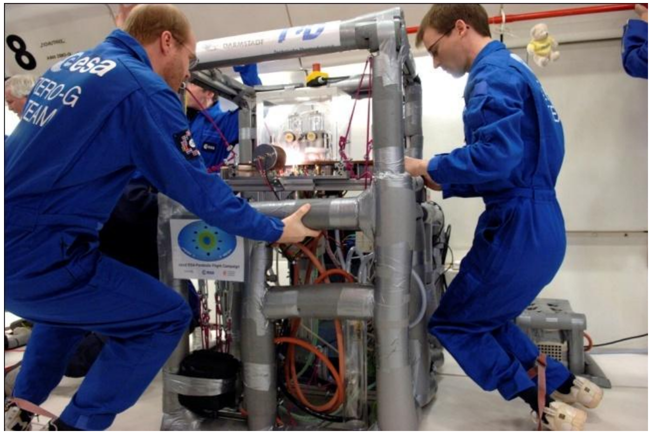
[B. Shu]

<u>Experimental and Numerical Work:</u>

Single bubble pool boiling, pool boiling with numerous nucleation sites, single meniscus evaporation, flow boiling in minichannels, evaporation of single and multiple droplets,…

Measurement technique
Background

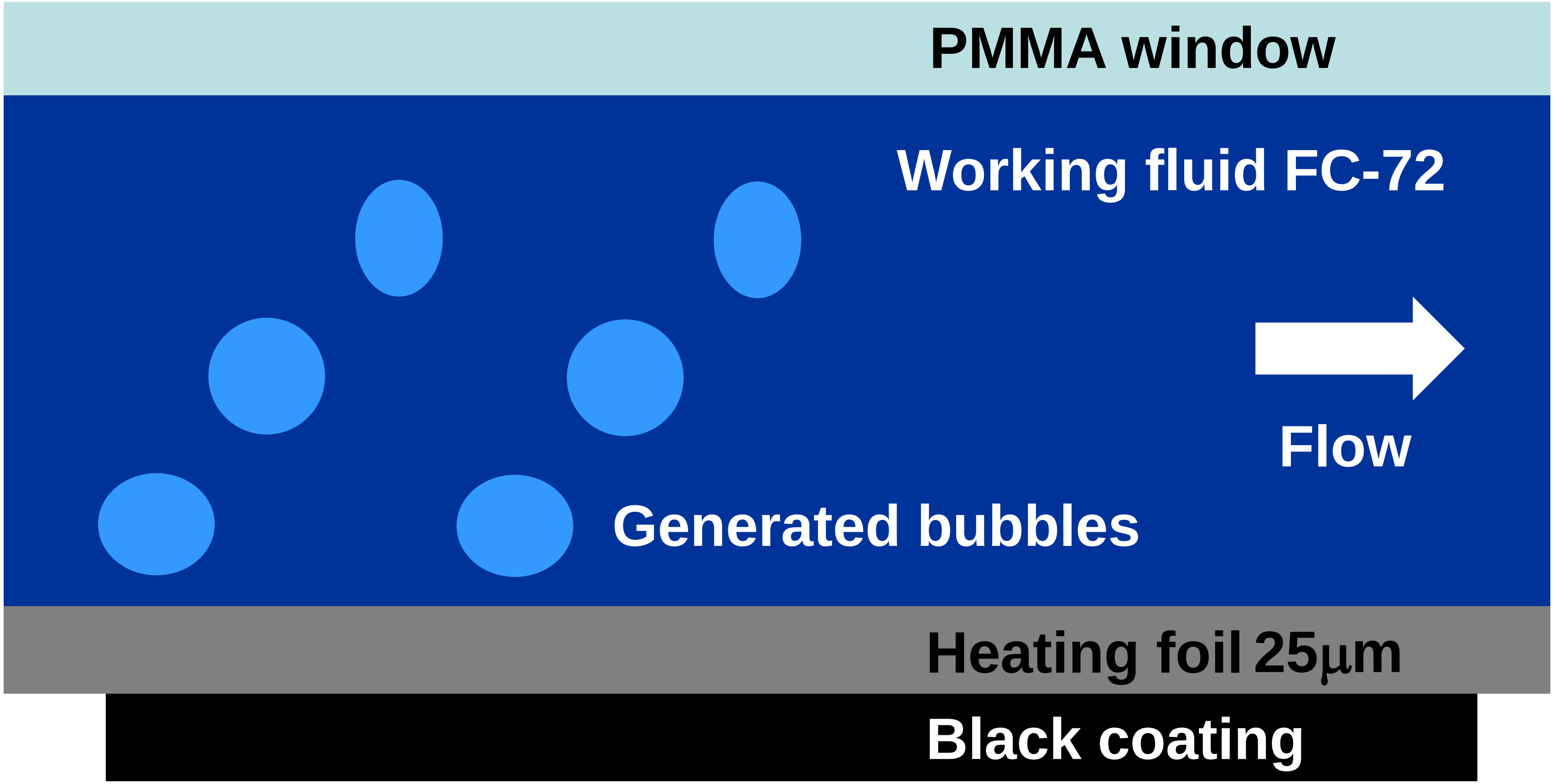
[Novespace]



<u>High Speed Infrared Thermography</u>

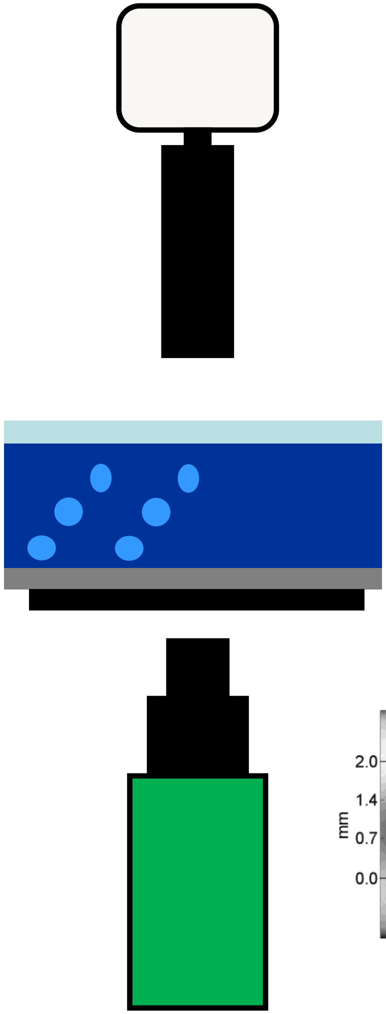
- Measurement technique developed to investigate the temperature and heat flux distribution near the three phase contact line
- Validation of contact line model (Stephan/Busse, IJHMT 1992)
- Single bubble pool boiling experiments under normal and microgravity conditions (E. Wagner 2008 (Diss.), N. Schweizer 2010 (Diss))
- Eight Parabolic Flight Campaigns (2004 – today)

Measurement technique
Method (Flow boiling)

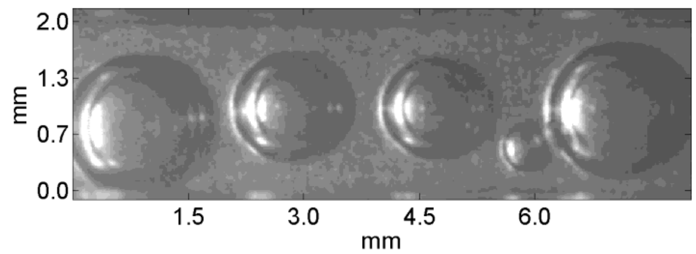


Measurement technique

Method (Flow boiling)

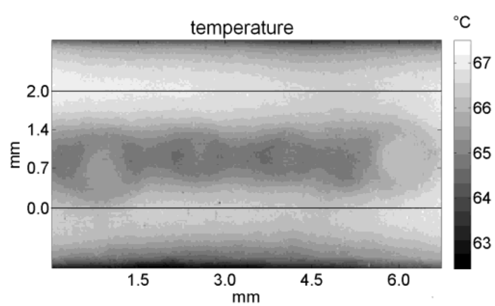


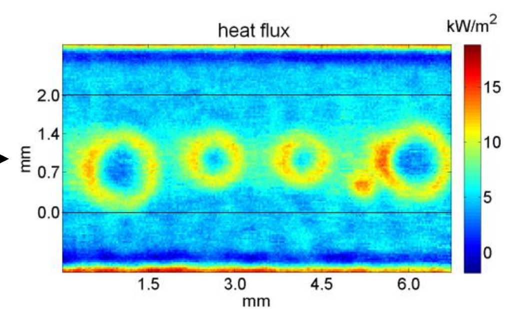
b/w camera



1000 fps
≈17x17 µm²

IR camera



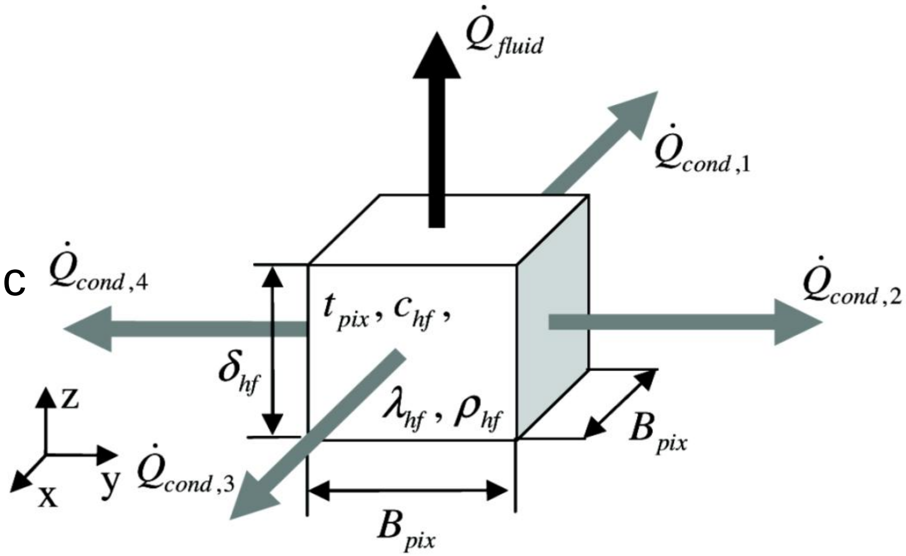


1000 fps
≈30x30 µm²

Measurement technique
Data Reduction

Calculation of local heat flux into the fluid ?!

- Discretization of the heating foil into pixel elements from the IR camera
- Temperature gradients known from IR measurement
- Backside of foil is assumed to be adiabatic
- Energy balance of the element gives the unknown wall heat flux into the fluid

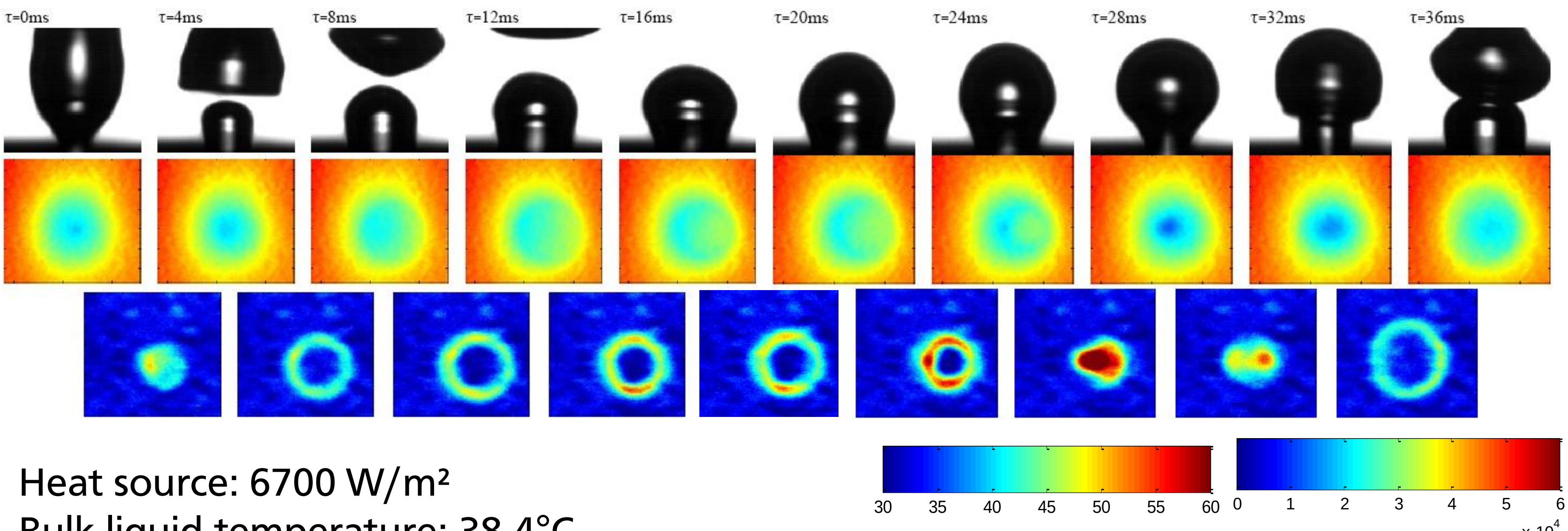


$$\dot{q}_{fluid} \cdot B_{pix}^2 + \sum_{i=1}^{4} \dot{Q}_{cond,i} + \dot{Q}_{store} + \dot{q}_{el} \cdot B_{pix}^2 = 0$$

Energy balance of a single pixel element

Experimental results
Single bubble cycle

<u>Bubble cycle in zero g (42nd ESA PFC 2006)</u>

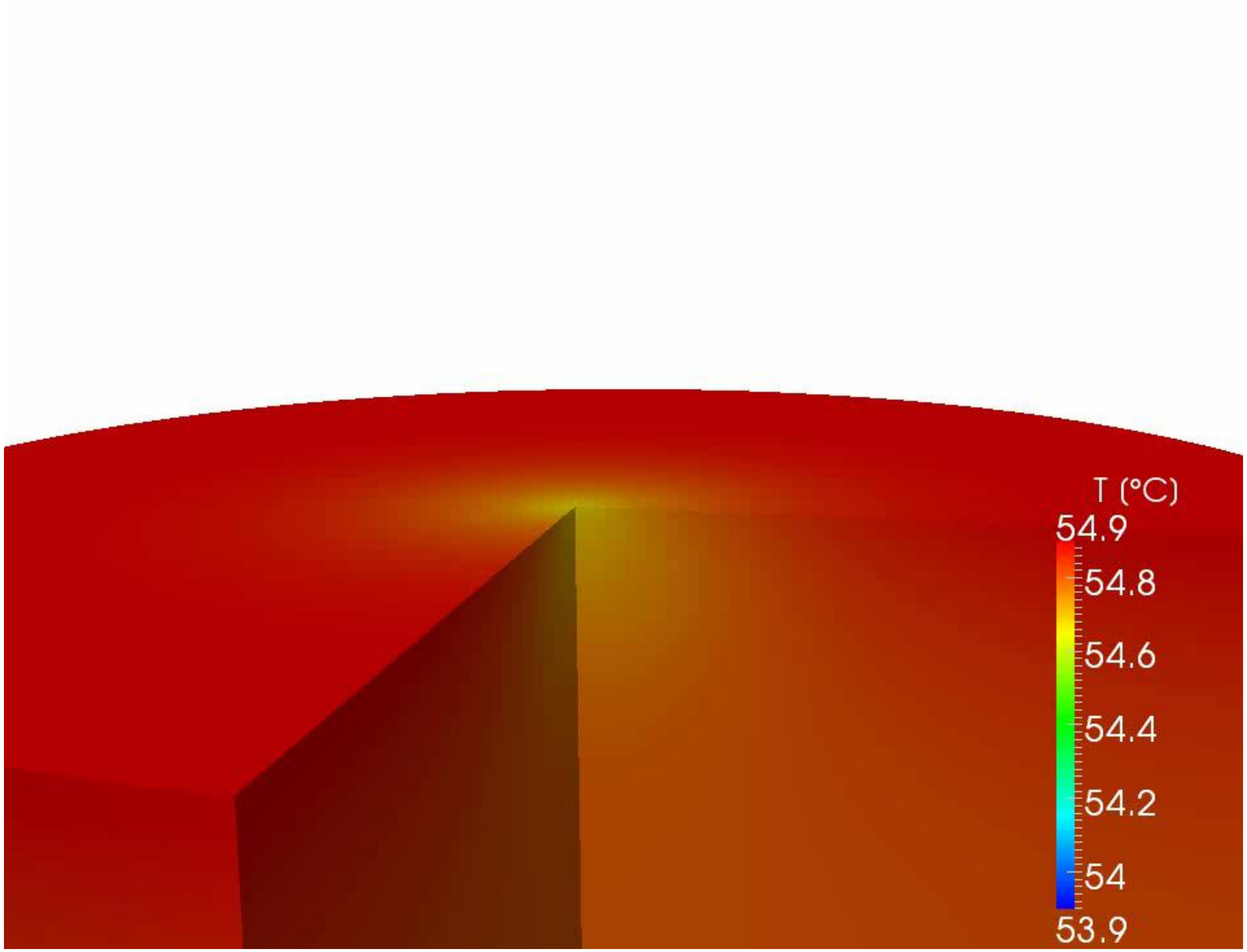


Heat source: 6700 W/m²
Bulk liquid temperature: 38.4°C

[N. Schweizer]

- Contact line can be clearly identified as region of high local heat transfer
- Larger departure diameter and frequency in reduced gravity is increasing the resolution and comparison with numerical results is much easier

Numerical results
Single bubble cycle



[C. Kunkelmann]

Bubble cycle:

38 ms

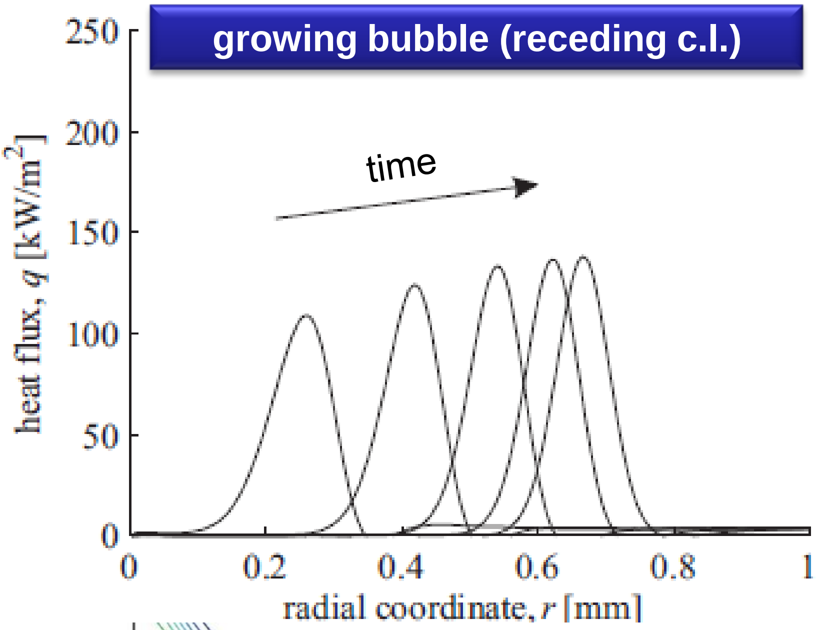
(13 ms growth + 25 ms waiting)

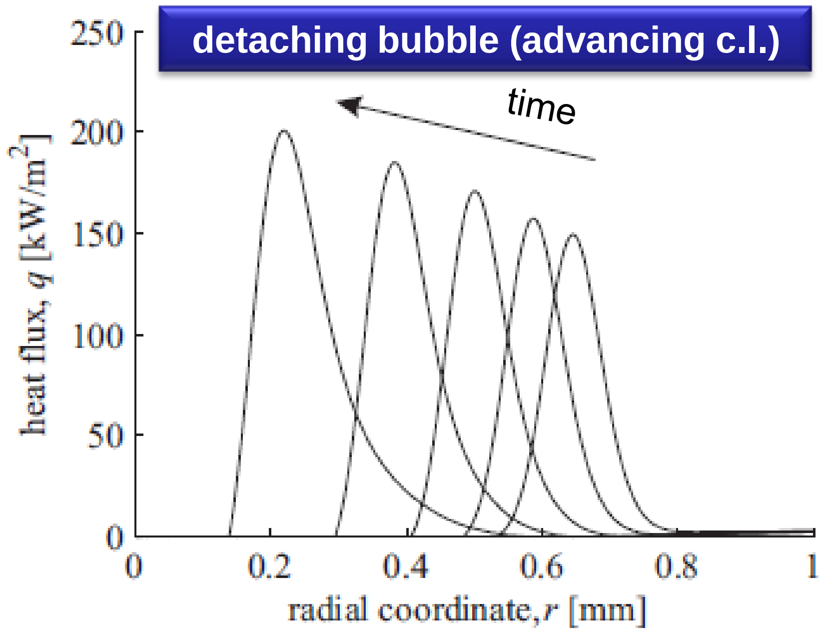
Fluid: HFE-7100 (T_{sat} = 39.8°C)

Heating power: q = 5.4 kW/m²

CaF heater: thickness 2 mm

Numerical results
Local wall heat flux near contact line





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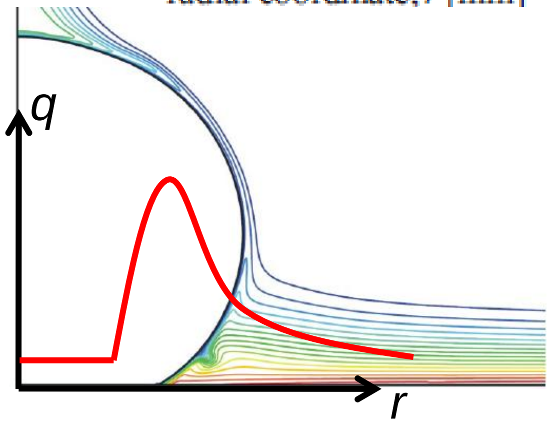
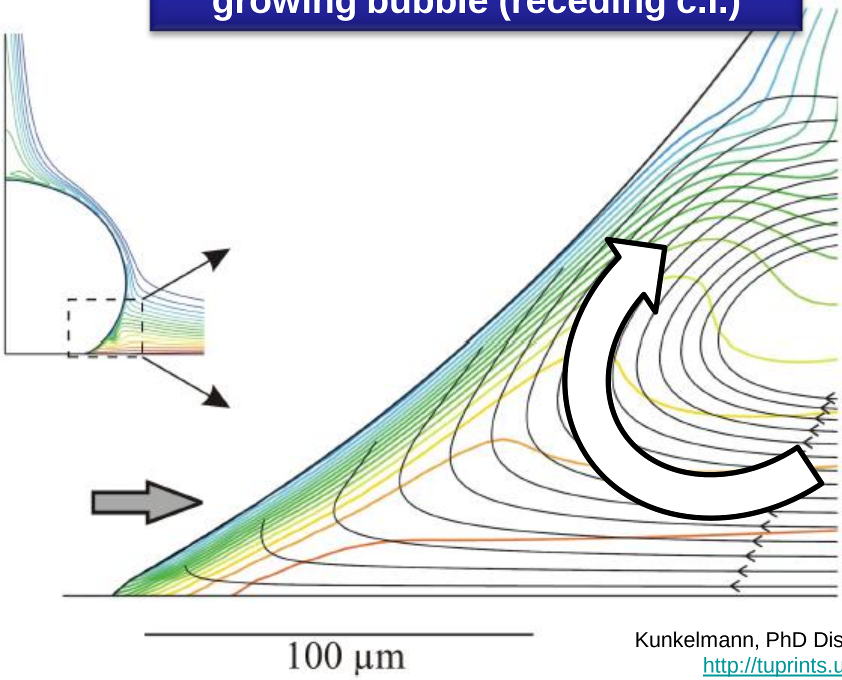


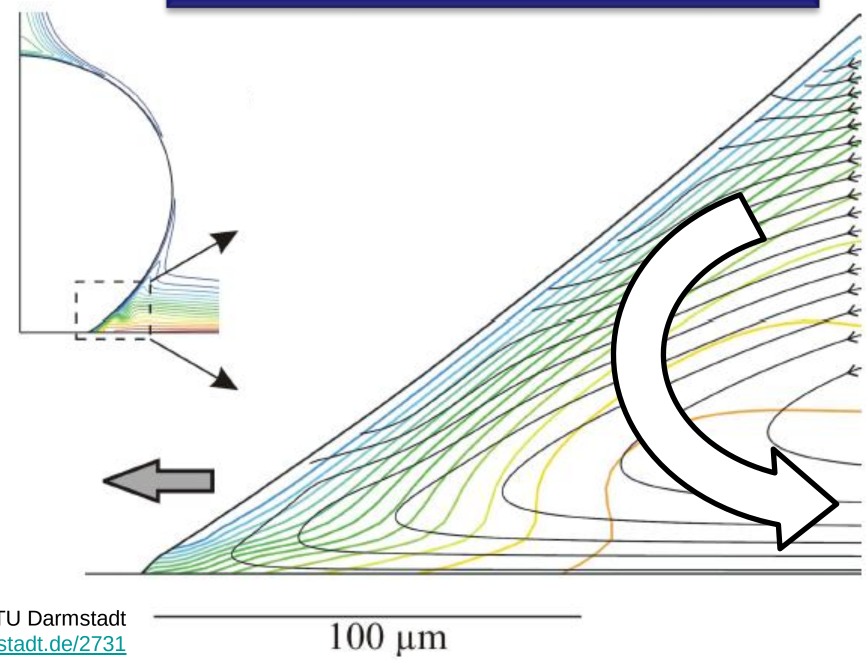
- Experimental results show the same characteristic
- No information about physical effect for the increase in local wall heat flux

Numerical results
Local temperature and flow near contact line

growing bubble (receding c.l.)



detaching bubble (advancing c.l.)



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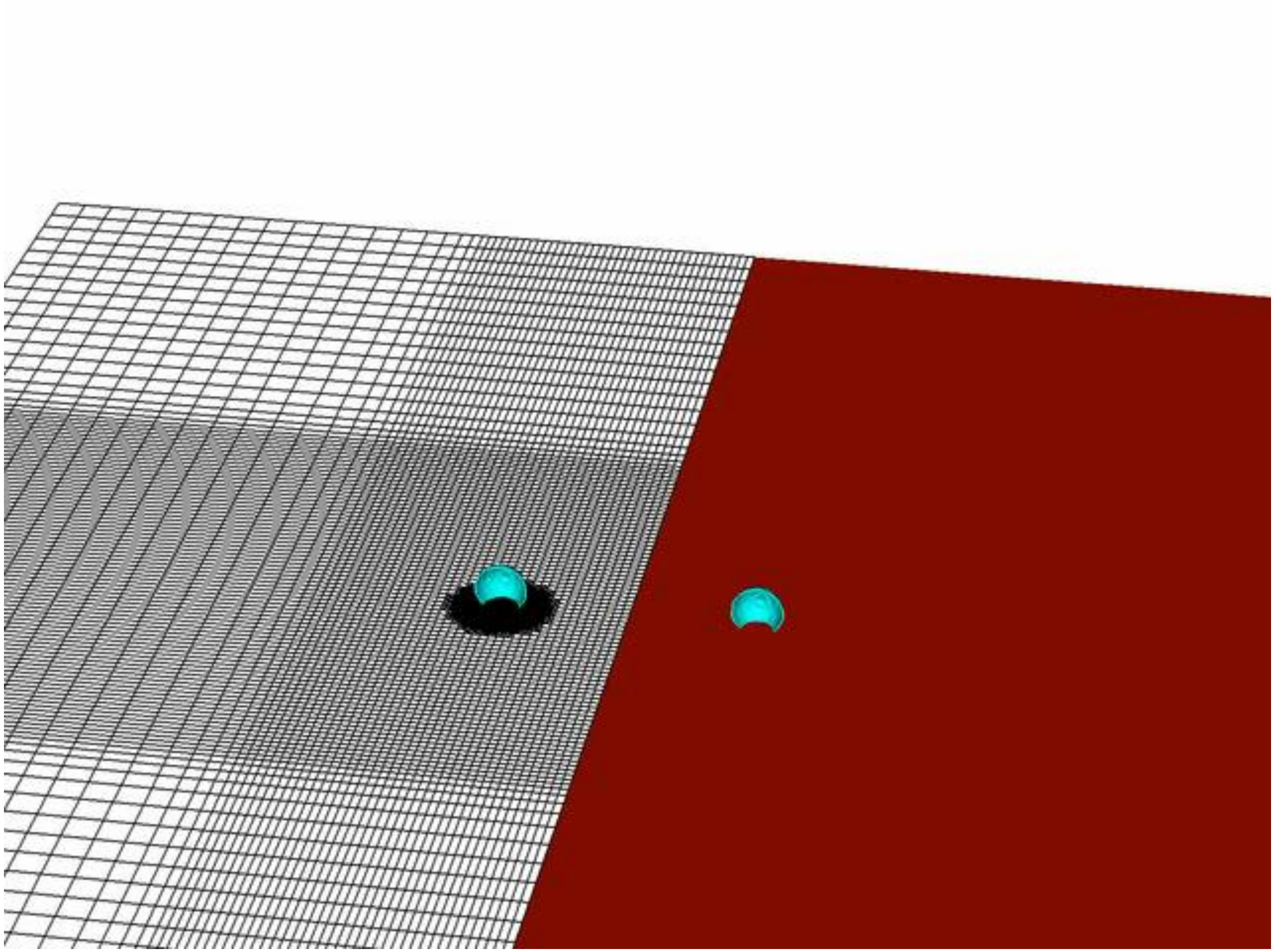
- Opposite liquid flow direction near contact line position for receding and advancing
- Micro convection enhances the heat transfer for the advancing contact line

Numerical results
Bubble merger



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Pool boiling ↔ Flow boiling

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Pool boiling

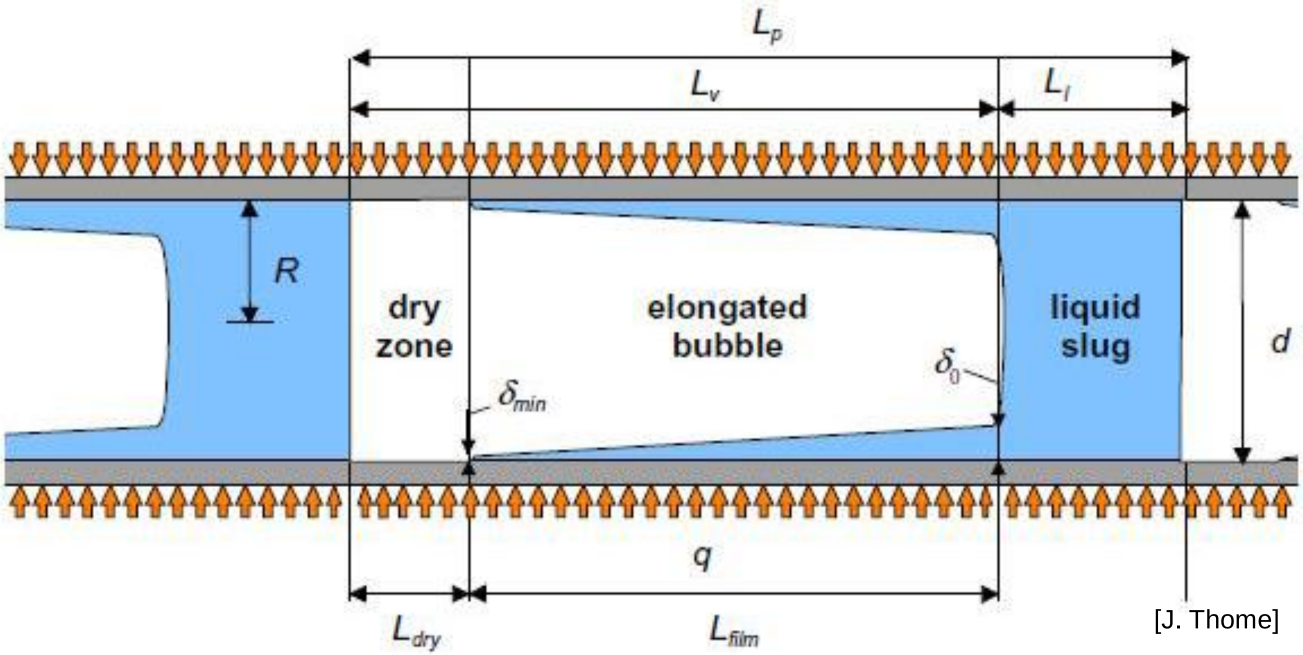
- High local heat transfer at contact line region can be clearly identified
- Validation data for numerical methods available due to Parabolic Flights
- First insight into micro convection near contact line

Flow Boiling

- Transfer of high speed infrared measurement technique
- Basic physical phenomena of heat transfer in small length scales

  (most of published work with focus on global measurements of heat transfer and pressure drop → derived correlations for only a very limited parameter range)
- Validation of heat transfer models (e.g. Three-zone model)
- Experimental data for the validation of numerical results

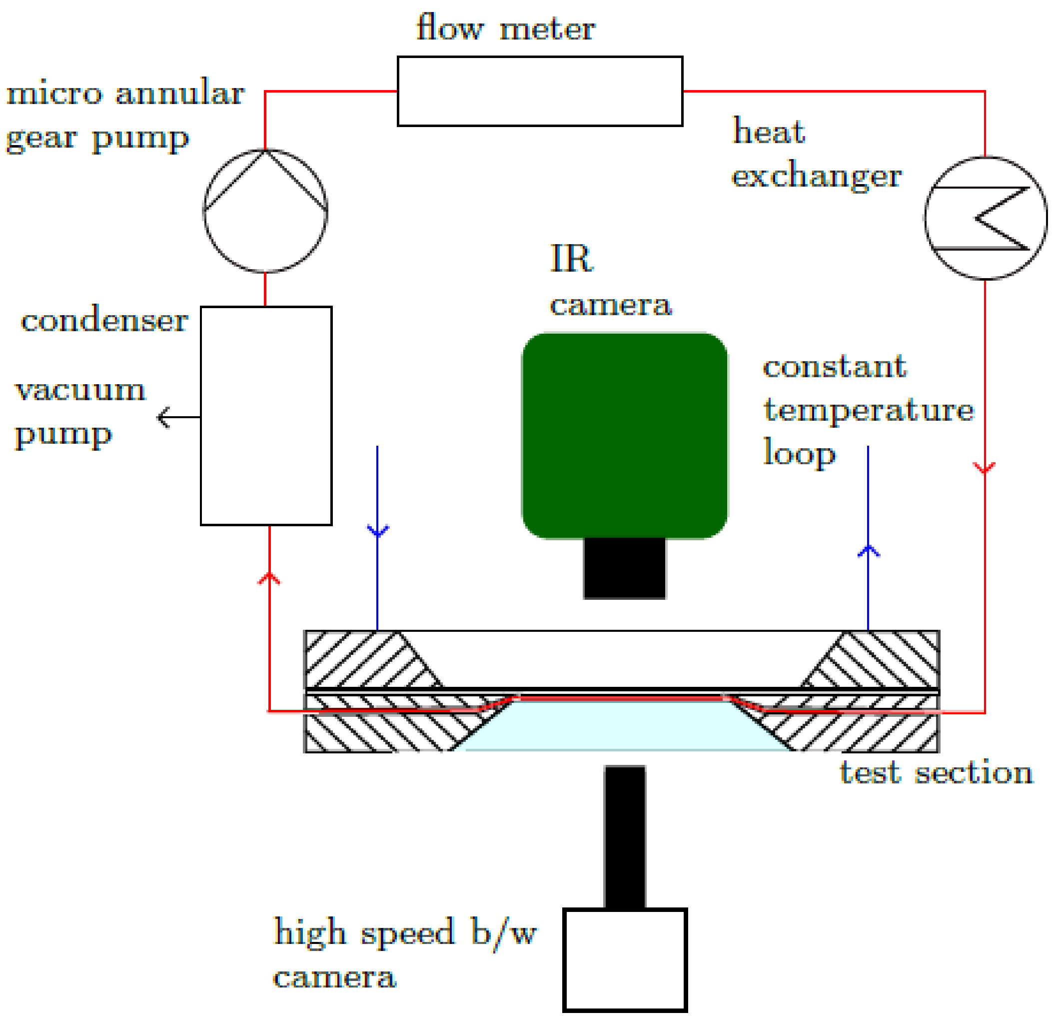
Flow boiling
Three-zone model



[J. Thome]

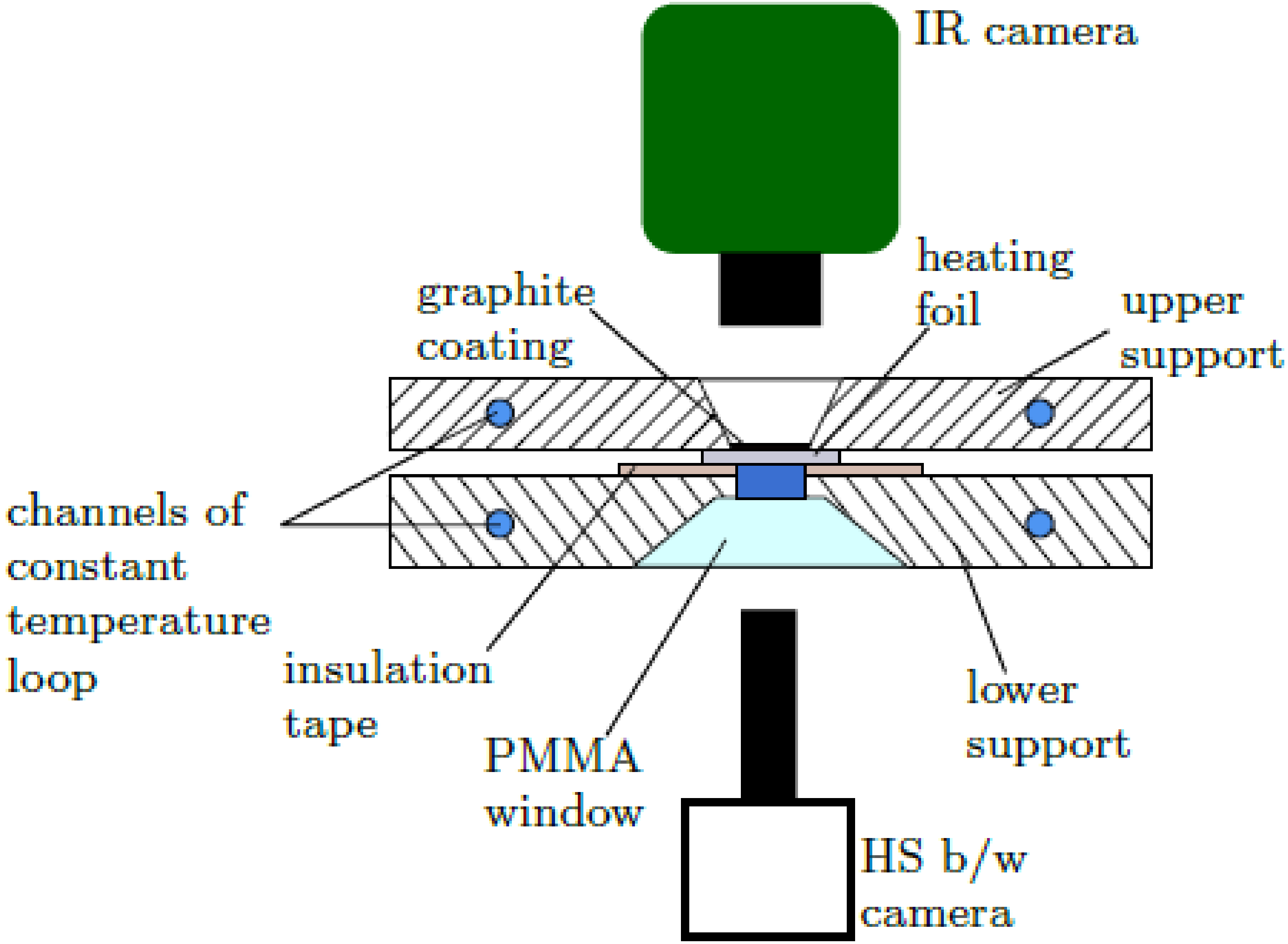
- Periodic sequence of liquid slug, thin film evaporation and dry zone
- Validation of the model ?!

Flow boiling
Fluid loop

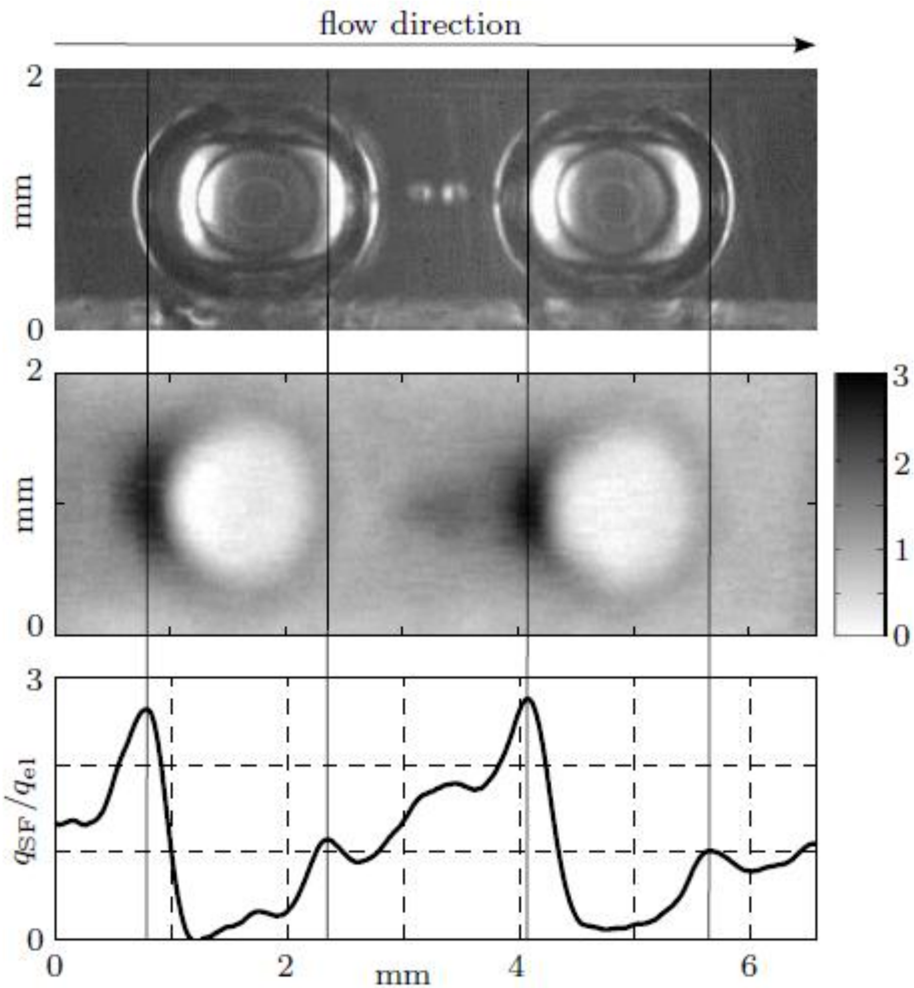


Fluid:	FC-72
Pressure:	1 bar
T_{sat}:	56.6°C
Channel:	2x2 mm²
	0.5x2 mm²

Flow boiling
Test section



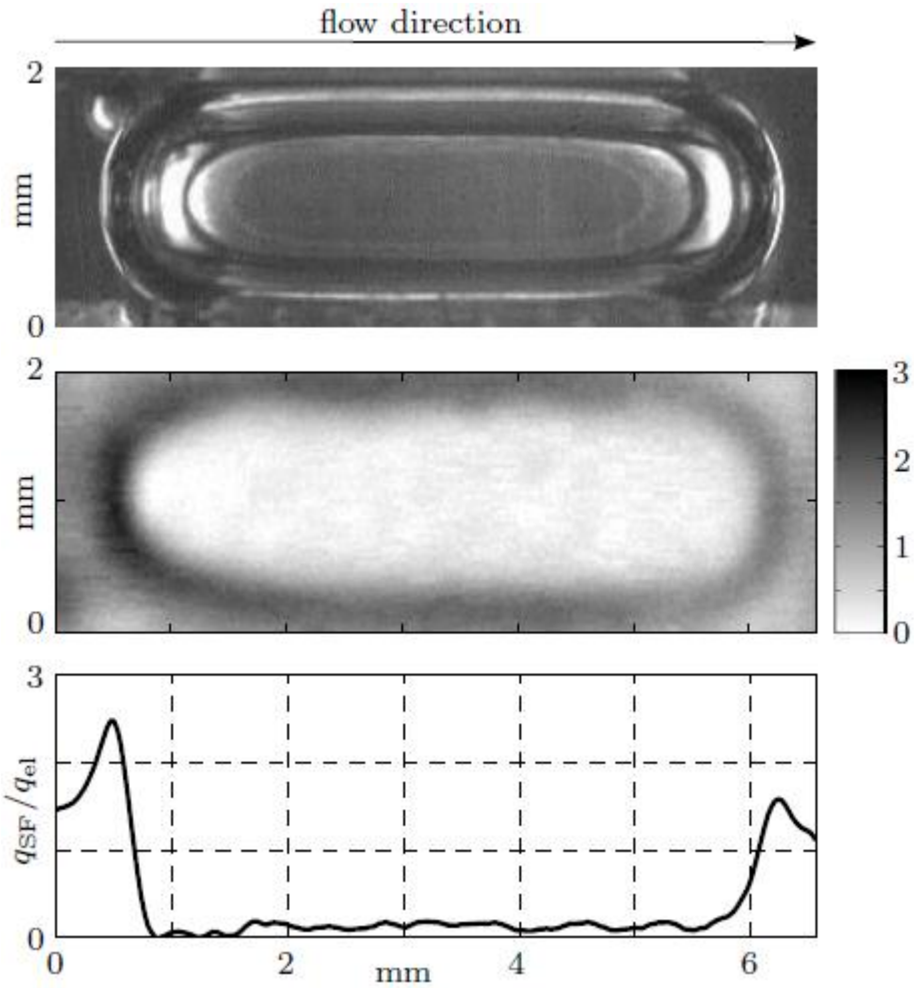
Flow boiling
Bubbly flow



- Three phase contact line can be clearly identified by area of high local heat flux
- Bubbles are sliding over the heating surface
- Temporal development of average heat flux in the middle cross section of the field of view allows the detection of the liquid vapor interface
- Contact line heat transfer at the back of the bubble higher
  → as seen in pool boiling (num.&exp.)

Flow boiling

Slug flow / elongated bubble

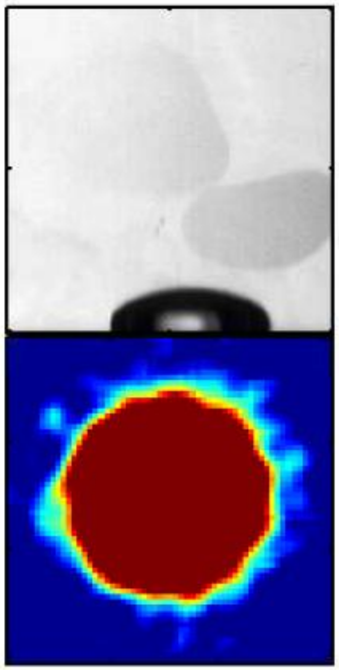


- Size of bubbles confined by channel geometry
- Contour of bubble can be clearly identified by high heat flux areas near the three phase contact line
- Heat transfer at the back higher (as already seen for bubbly flow)
- No long thin film region visible

Conclusion

Three-zone model not valid ?!

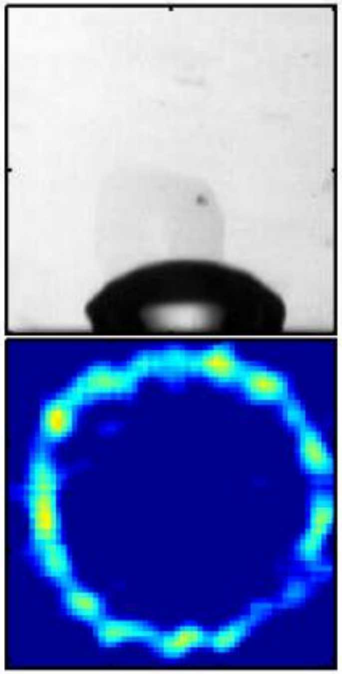
Microlayer vs. Contact line



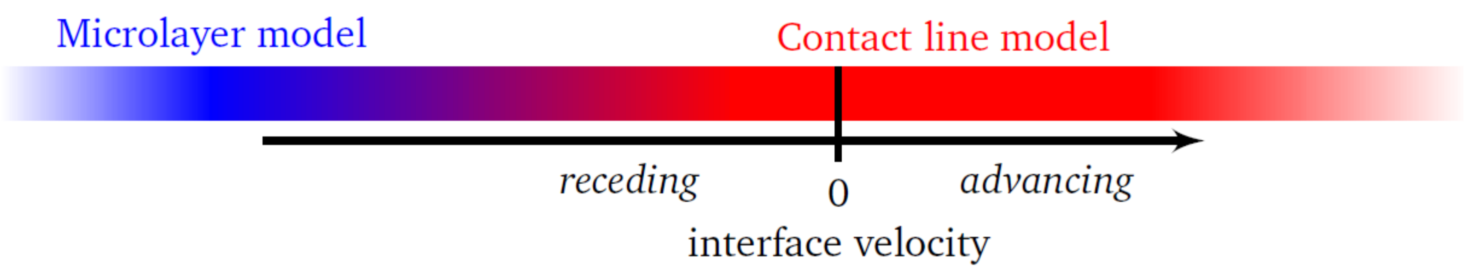
[A. Sielaff]

More influencing parameters

- Contact angle
- heat of vapor
- …



[A. Sielaff]



Microlayer vs. Contact line

- Thin liquid evaporation for flow boiling of FC-72 not visible (or very short region)
- Results of pool boiling indicate that the models are not competing but equivalent (only for different parameters) [PhD Thesis A. Sielaff, 2014]
- Experimental results showing microlayer evaporation mostly with water
- Contact line behaviour with electronic liquids (FC-72, HFE-7100,…)

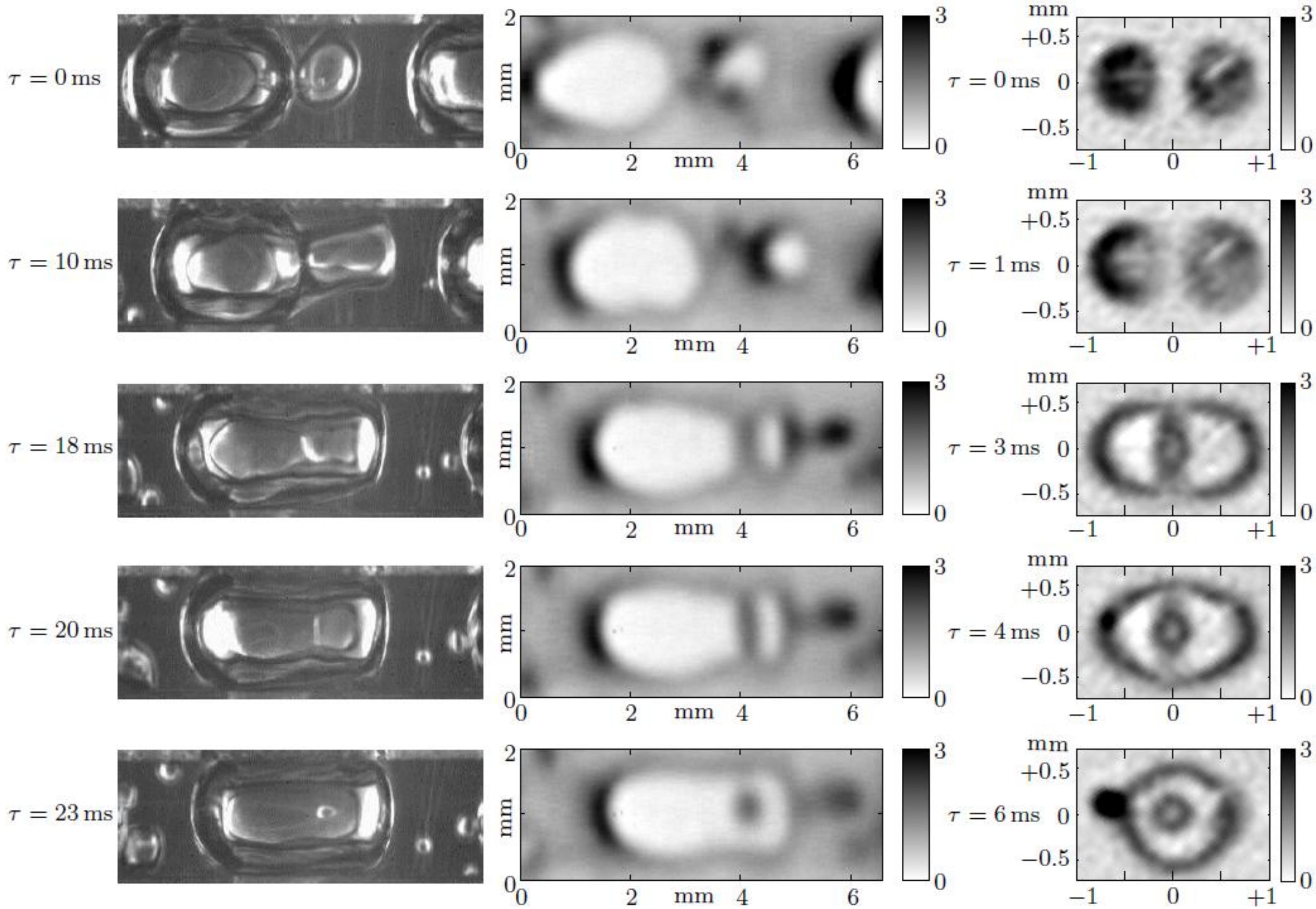
→Due to heating foil technique and limited heating power during parabolic flight, FC-72 is used as working fluid

→ Comparison and validation of three-zone model for a wide parameter range not yet possible

→ <u>Analogy between pool boiling and flow boiling phenomena ?</u>

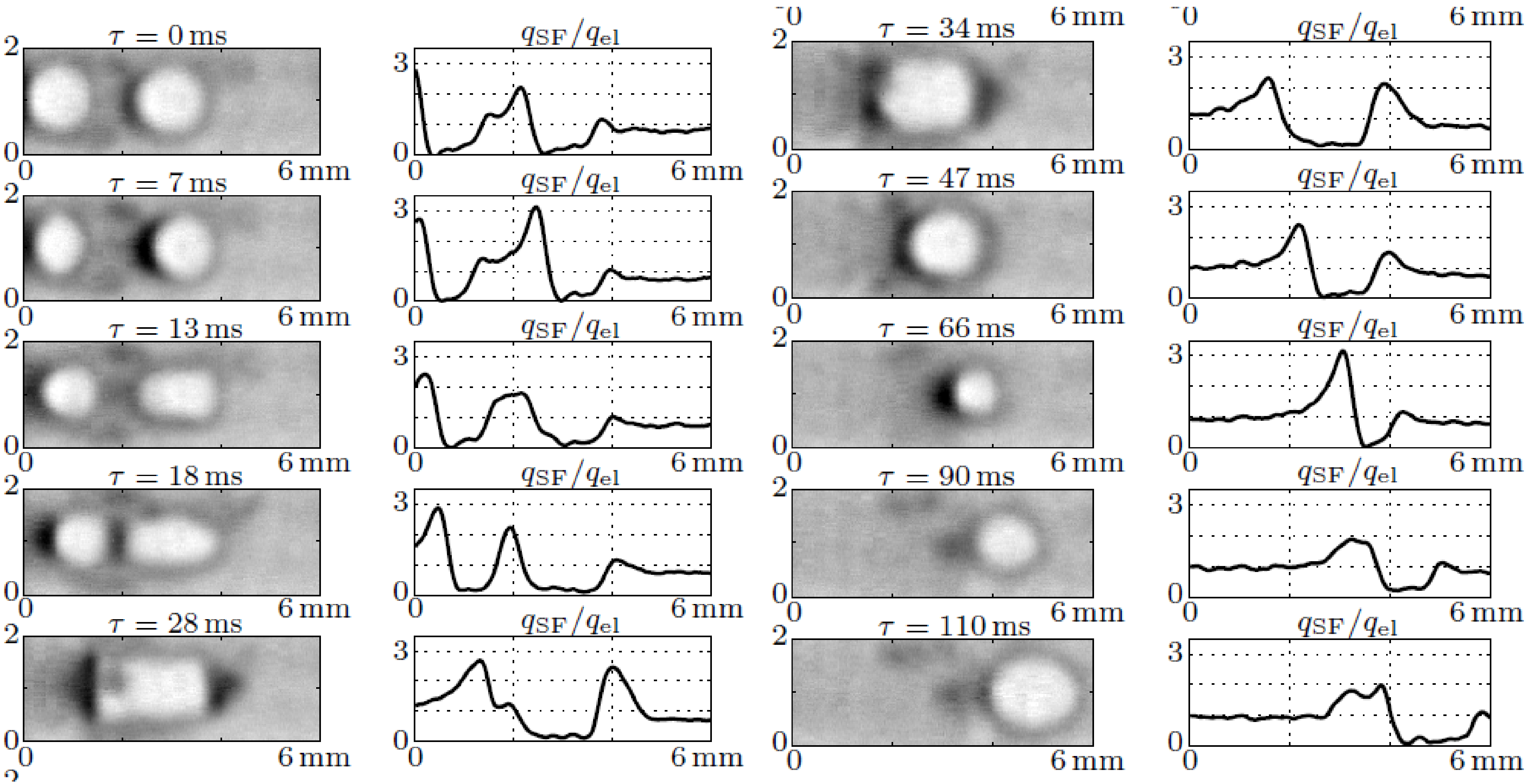
Flow boiling (analogy)

Bubble merger with residual droplet



Flow boiling (analogy)

Coalescence with pulsating bubble



Summary

- Measurement technique successfully adapted to flow boiling experiments
- Analogy between pool and flow boiling can be seen for moving contact lines, coalescing bubbles or residual droplets
- First step to the validation of models (change of working fluid planned 2015/16)
- Development of new heater comparable to a technical heating surface (IR-transparent substrate with a 100nm thick sputtered CrNi heating layer)

Acknowledgements

European Space Agency (ESA) providing the possibility to carry out the experiments under low gravity conditions during the 53rd, 55th and 58th ESA Parabolic Flight Campaigns and Novespace for their support during the experiment preparation.