Microchannel Flow Boiling of CO_2
Applications to 2D and 3D Detector Cooling

Prof. John R. Thome
Laboratory of Heat and Mass Transfer
Ecole Polytechnique Fédérale de Lausanne (EPFL)
CH-1015 Lausanne, Switzerland
e-mail: john.thome@epfl.ch
website: http://ltcm.epfl.ch

SLAC, Stanford: 9 Feb. 2011

(Based in part on Chapter 19 in Engineering Databook III at www.wlv.com)

Objectives and Topics to Be Covered:

- CO_2 flow boiling is a promising cooling process for particle detectors.
- Overview applying to 2D and 3D detectors.
- Example: 3D-IC microchannel cooled stack from Swiss NSF Nano-Tera project CMOSAIC.
- Single and multi-microchannel flow boiling videos
- Two-phase flow and heat transfer fundamentals.
- My CO_2 flow boiling/flow pattern map.
- Comparisons to the heat transfer model.
- Future plans for improvements.

Four Books Authored by J.R. Thome

Thome, J.R. (1990). *ENHANCED BOILING HEAT TRANSFER*, Hemisphere Pub. Corp. (Taylor & Francis), New York, 13 chapters, 356 pages.

Collier, J.G. and Thome (1994: hardcover, 1996: paperback). *CONVECTIVE BOILING AND CONDENSATION*, 3rd Edition, Oxford University Press, Oxford, England, 12 chapters, 596 pages.

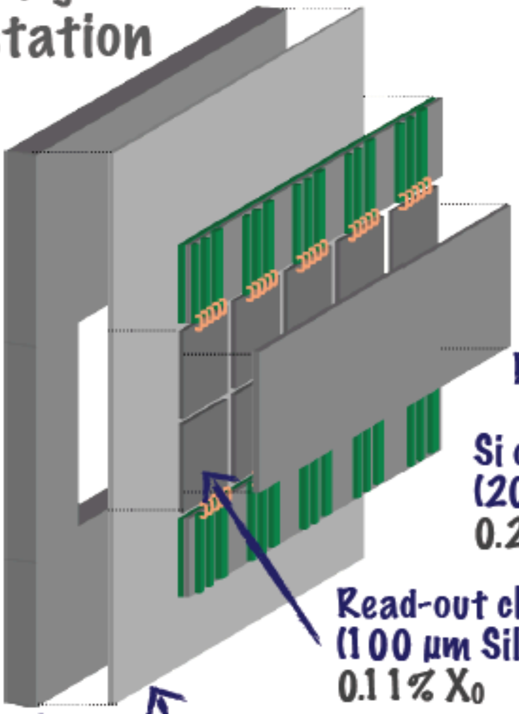
Thome, J.R. (2004). *WOLVERINE ENGINEERING DATABOOK III*. Web-based reference book with 21 chapters including one with over 200 two-phase flow videos, plus an *Excel calculator program* for numerous methods in book, updated in 2005, 2006, 2007, 2008, 2009, 2010. Available free at: http://www.wlv.com/products/databook/db3/DataBookIII.pdf.

Poniewski, M.E. and Thome, J.R. (2008): *NUCLEATE BOILING ON MICRO-STRUCTURED SURFACES*, free e-book available at:

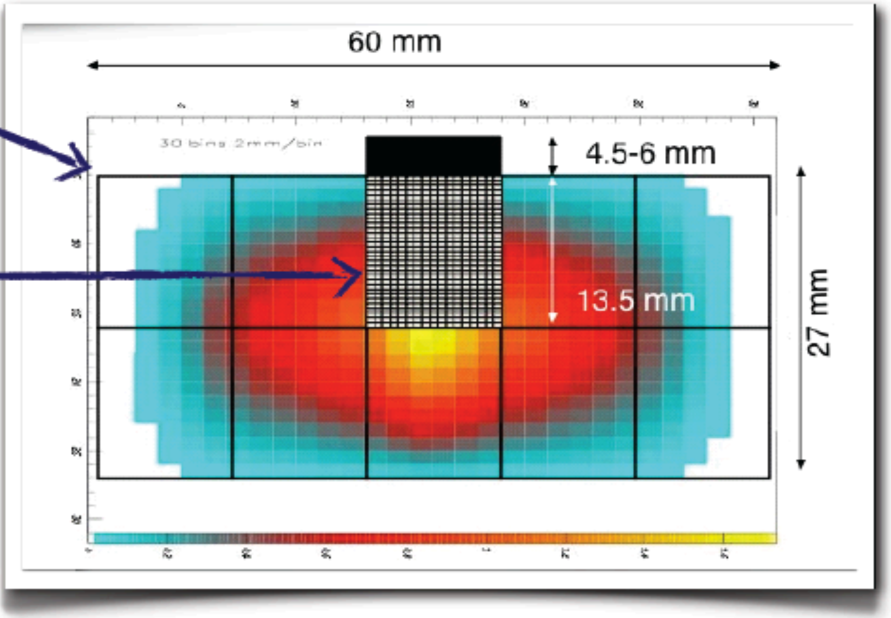
http://www.htri-net.com/ePubs/epubs.htm .

NA62-GTK cooling requirements

single GTK station



- Priority: minimize X_0
- Acceptable ΔT over sensing area: 5°C
- Dimension of sensing area: 60 x 40 mm
- Heat dissipation: 2 W/cm² (48 W)
- Target temperature on Si detector: -10°C



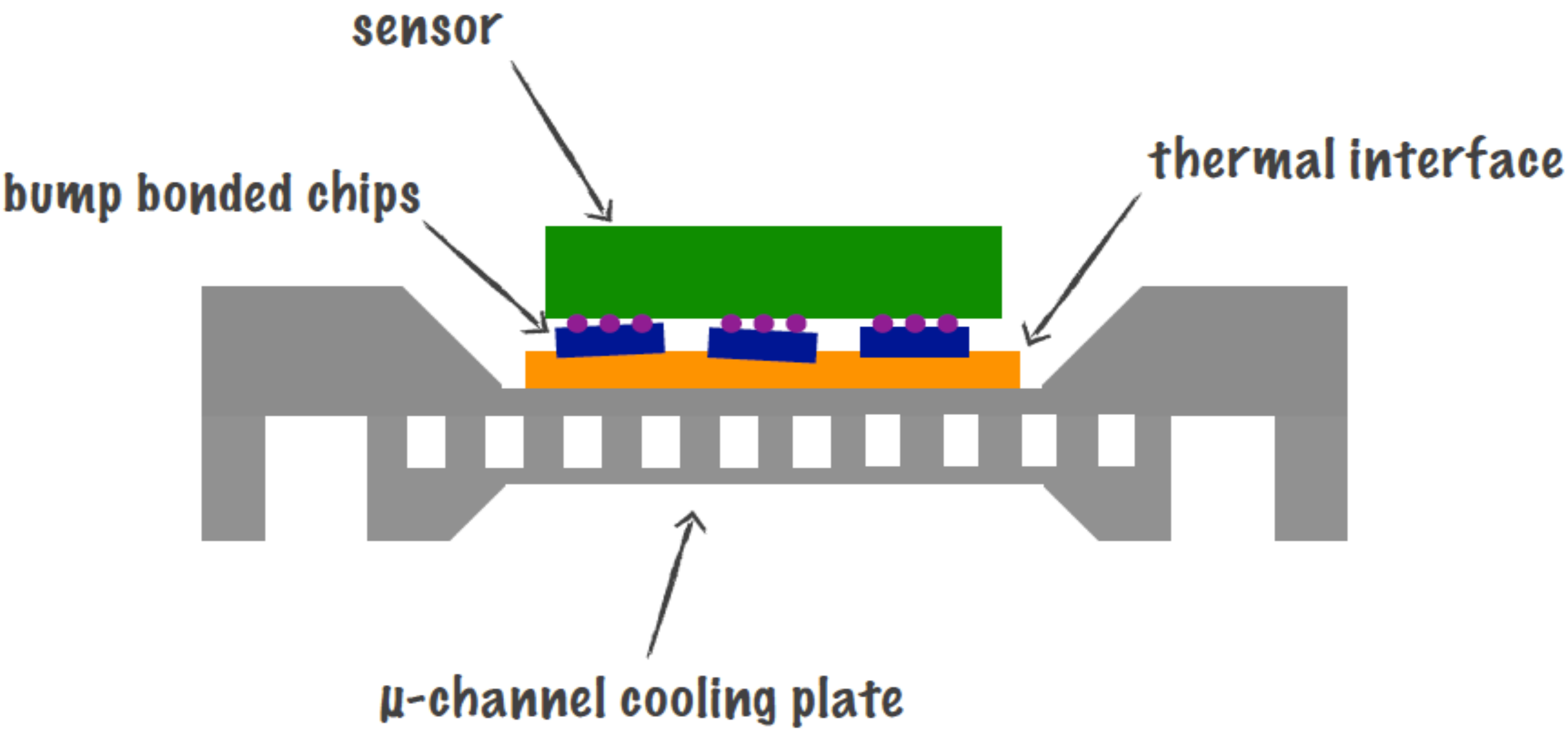
Si detector & bonds
(200 μm Silicon)
0.24% X_0

Read-out chip
(100 μm Silicon)
0.11% X_0

Cooling plate
Final target: 0.1% X_0

Support structure outside of acceptance region

thermal interface



SLAC: Photo and diagram of IBL CO_2 prototype cooling element from Hemink thesis.

(a) Front view of Carbon Foam with 2 *mm* tube sticking out.

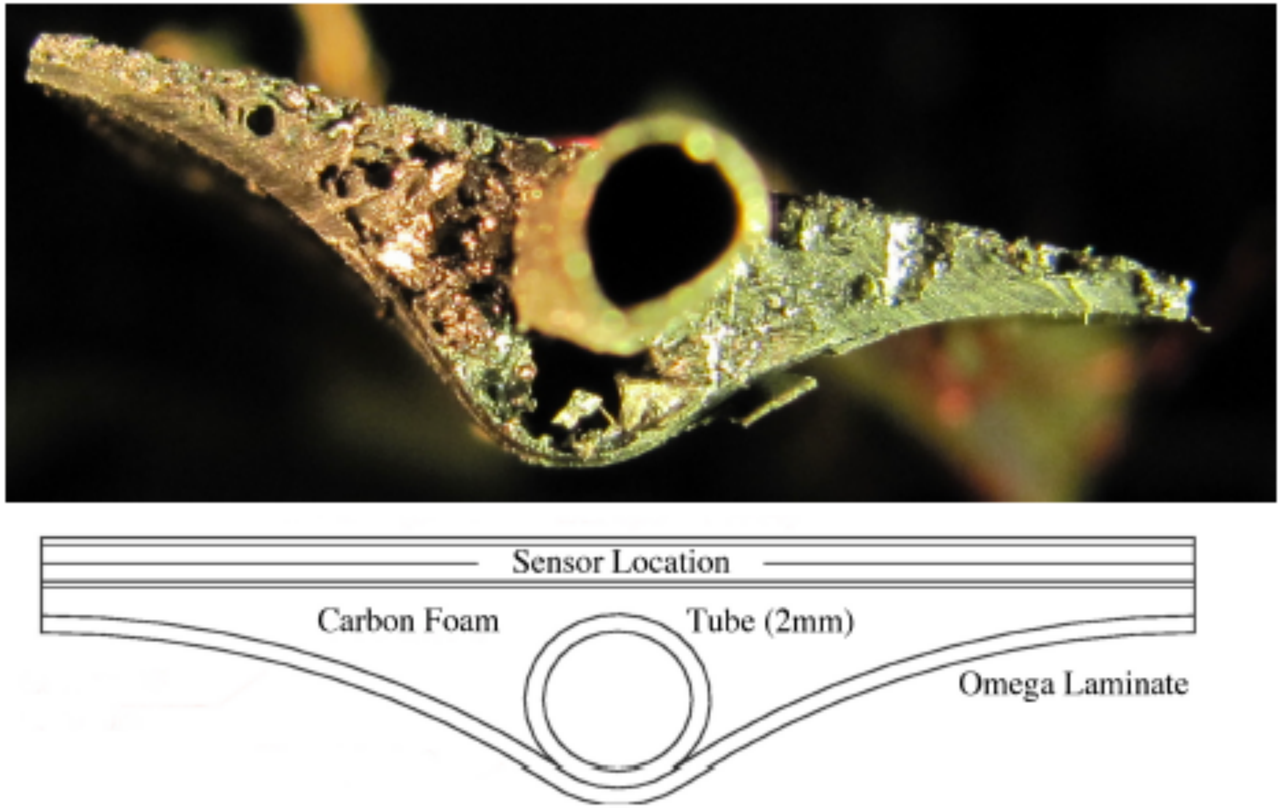
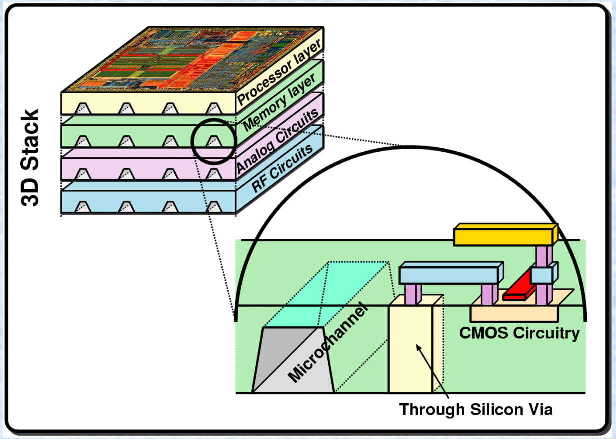
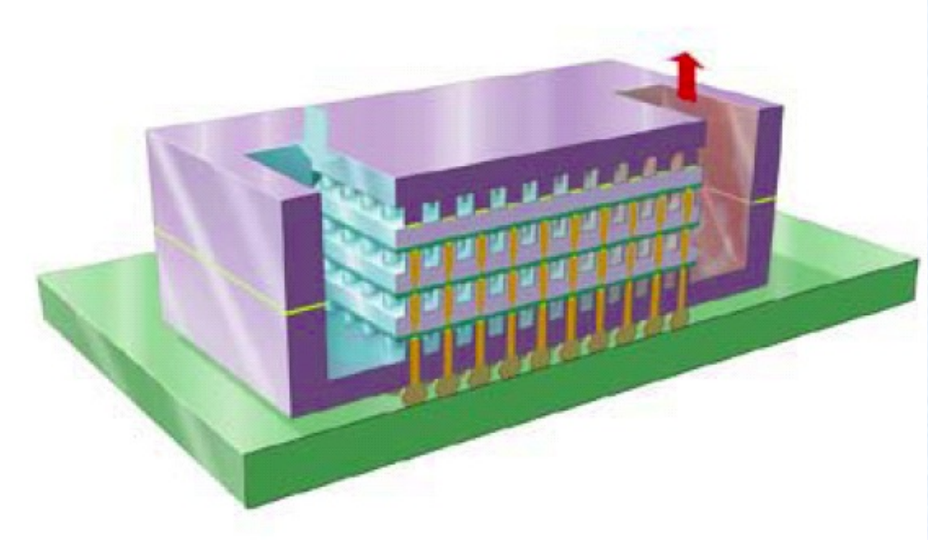


Figure 2.2: *Front view of IBL prototype stave, with on top the sensors, supported by carbon foam and the coolant tube which is sandwiched between the Omega laminate and the carbon foam.*

CMOSAIC: 3D-IC Thermal Performance with Microscale Liquid/Evaporative Cooling

- **A 3D computer chip with integrated cooling system is expected to:**
  - ***Overcome the limits of air cooling***
  - ***Compress ~10^{12} nanometer sized functional units (1 Tera) into one cubic centimeter: nearing the equivalent in human brain***
  - ***Yield 10 to 100 fold higher connectivity***
  - ***Cut energy consumption***

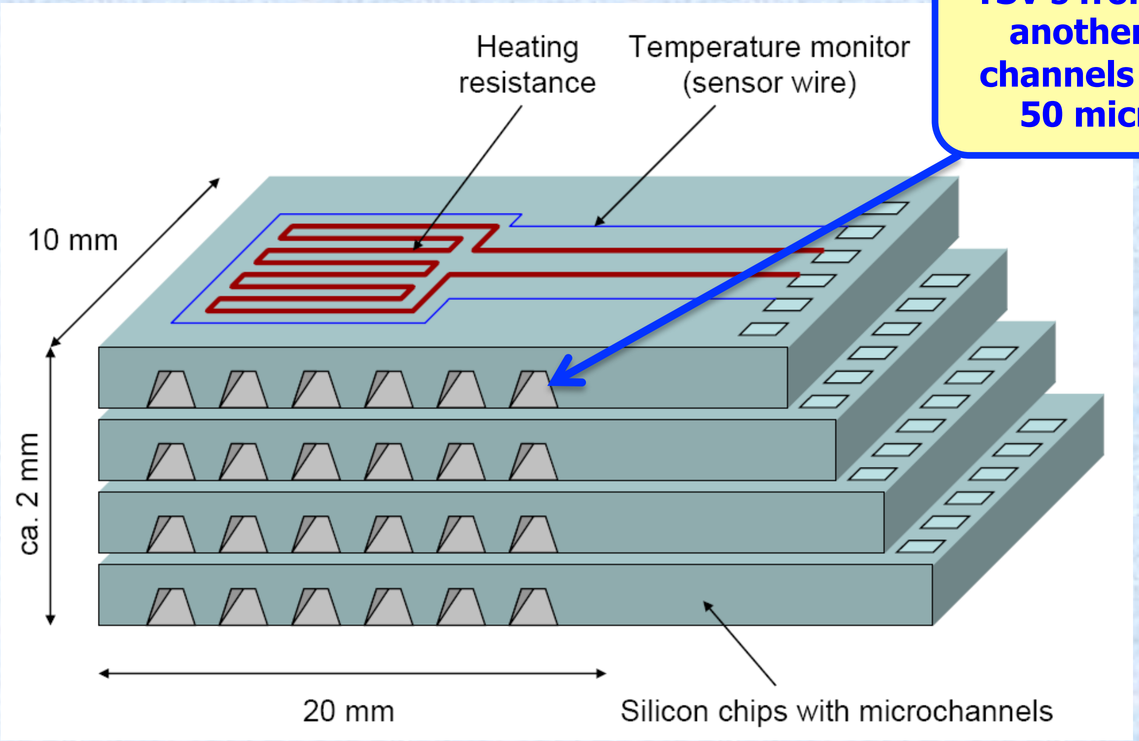




$4million Swiss consortium lead by JR Thome (IBM, ETH, EPFL)

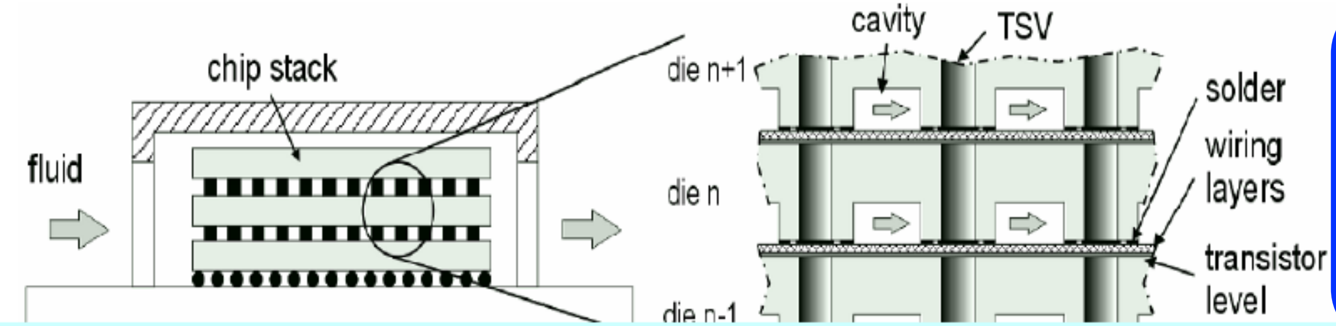
3D-IC Thermal Performance with Microscale Two-Phase Evaporative Cooling

CMOSIAC Nano-Tera Project Plan: Build, test and simulate 3D module for 3D-IC heat flow: in progress.



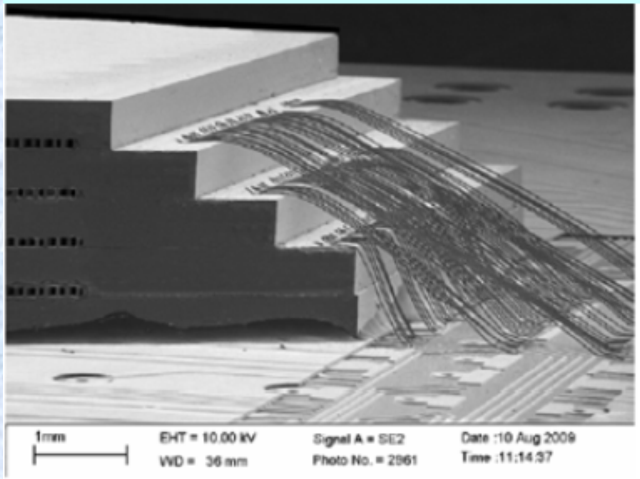
TSV's from one layer to another will permit channels of only about 50 microns in size!

3D-IC Thermal Performance with Microscale Two-Phase Evaporative Cooling



TSV's from one layer to next (10-100 per mm^2 with microchannels for 2-phase fluid

Initial energy savings of 90% at chip level with air-cooling techniques



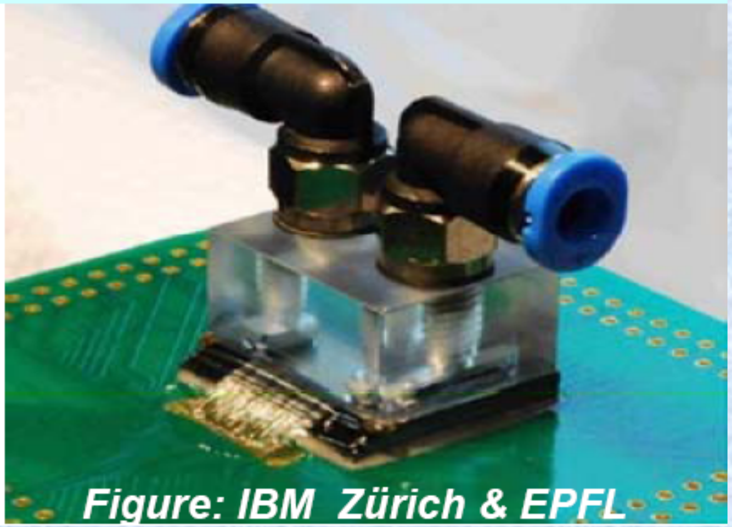
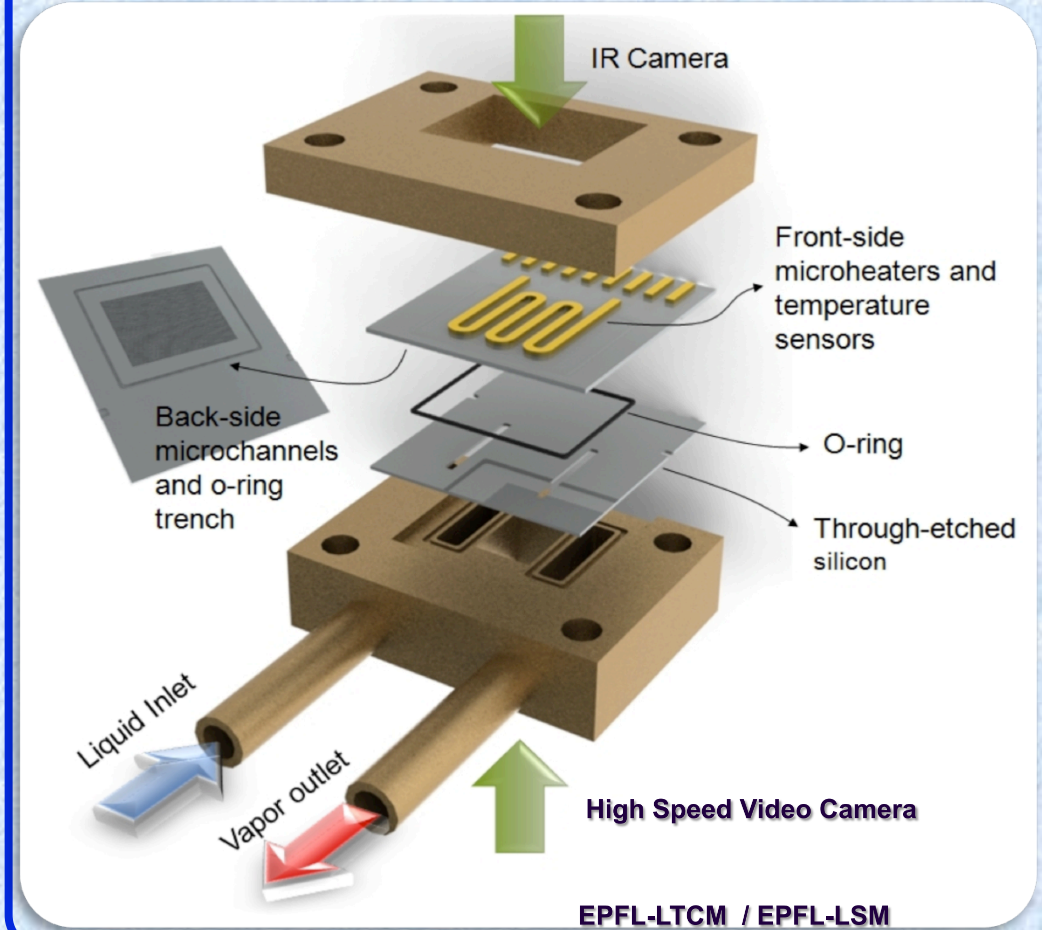


Figure: IBM Zürich & EPFL

Fabrication of 2-P Cooling Test Vehicles

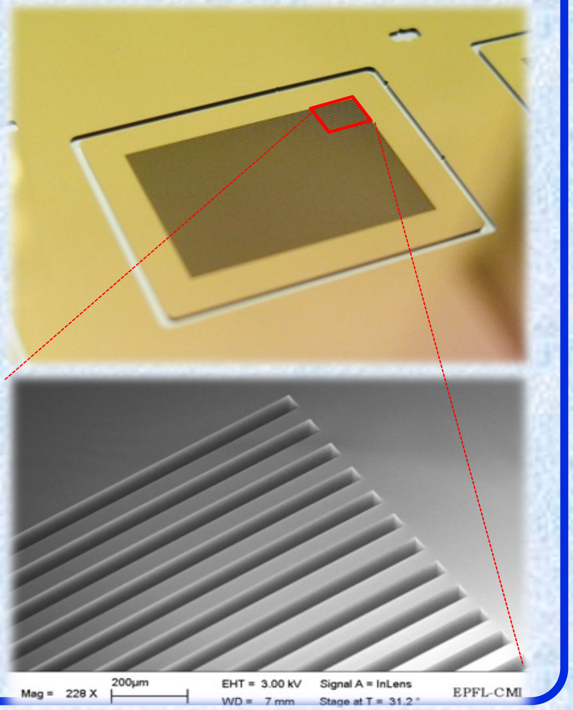
Ph.D. Student: Sylwia



EPFL-LTCM / EPFL-LSM

Sealed test device for two-phase micro-channel cooling experiments with front-side hotspot heaters, completely designed and manufactured at EPFL (LTCM/LSM).

Channel dimension: 50um width, 100um depth



CO2 Flow Patterns in 6 mm Horizontal Tube

Above: Annular flow of CO_2 at 5°C, 350 kg/m^{2}s and x=15% (Univ. Napoli II);

Below: Annular flow of CO_2 at 5°C, 500 kg/m^{2}s and x=15% (Univ. Napoli II).

CO2 Flow Patterns in 6 mm Horizontal Tube

Above: Stratified-wavy flow at 5°C, 200 kg/m^{2}s and x=75% (Univ. Napoli II);

Below: Intermittent flow at 5°C, 200 kg/m^{2}s and x=35% (Univ. Napoli II).

R410A Flow Patterns in 6 mm Horizontal Tube

[redacted]

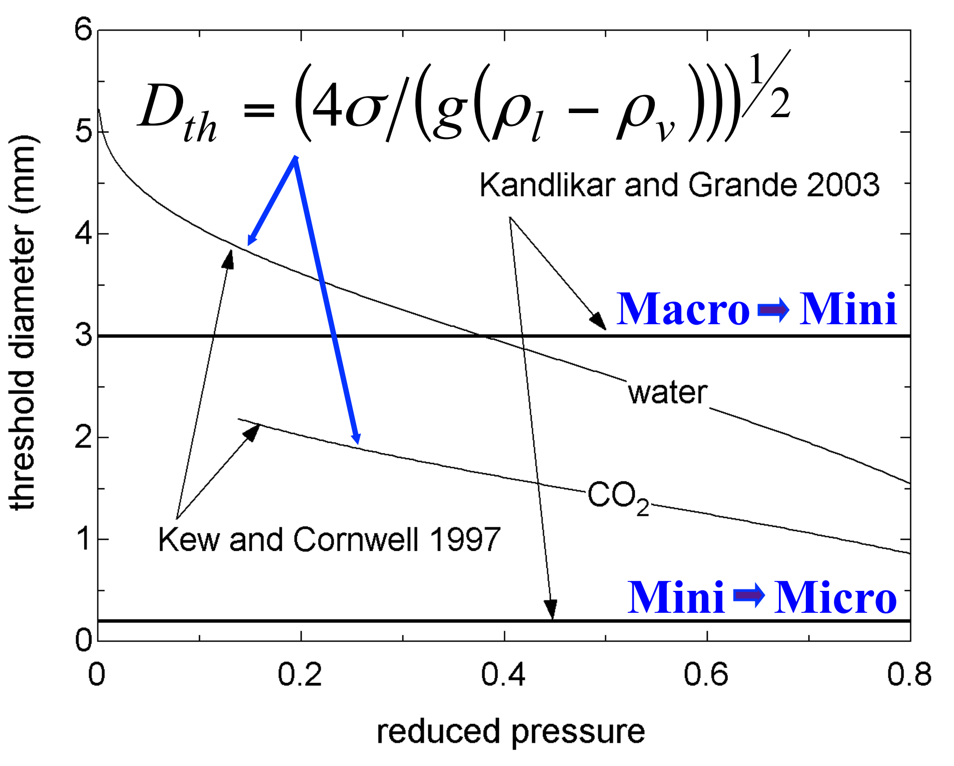
Above: **Intermittent flow at 42°C, 200 kg/m^{2}s and x=35% (Univ. Napoli II);**

Below: **Annular flow at 42°C, 350 kg/m^{2}s and x=75% (Univ. Napoli II).**

[redacted]

Where is Threshold between Macro- and Micro-Scale Two-Phase Flow for CO2?

Kandlikar and Grande (2003) and Kew and Cornwell (1997) suggestions are shown here, the later whose Confinement Diameter D_{th} is shown for CO_2 and water.



$$D_{th} = \left(4\sigma/\left(g\left(\rho_l - \rho_v\right)\right)\right)^{1/2}$$

CO2 Flow Patterns: Ozawa et al. (IJTS)

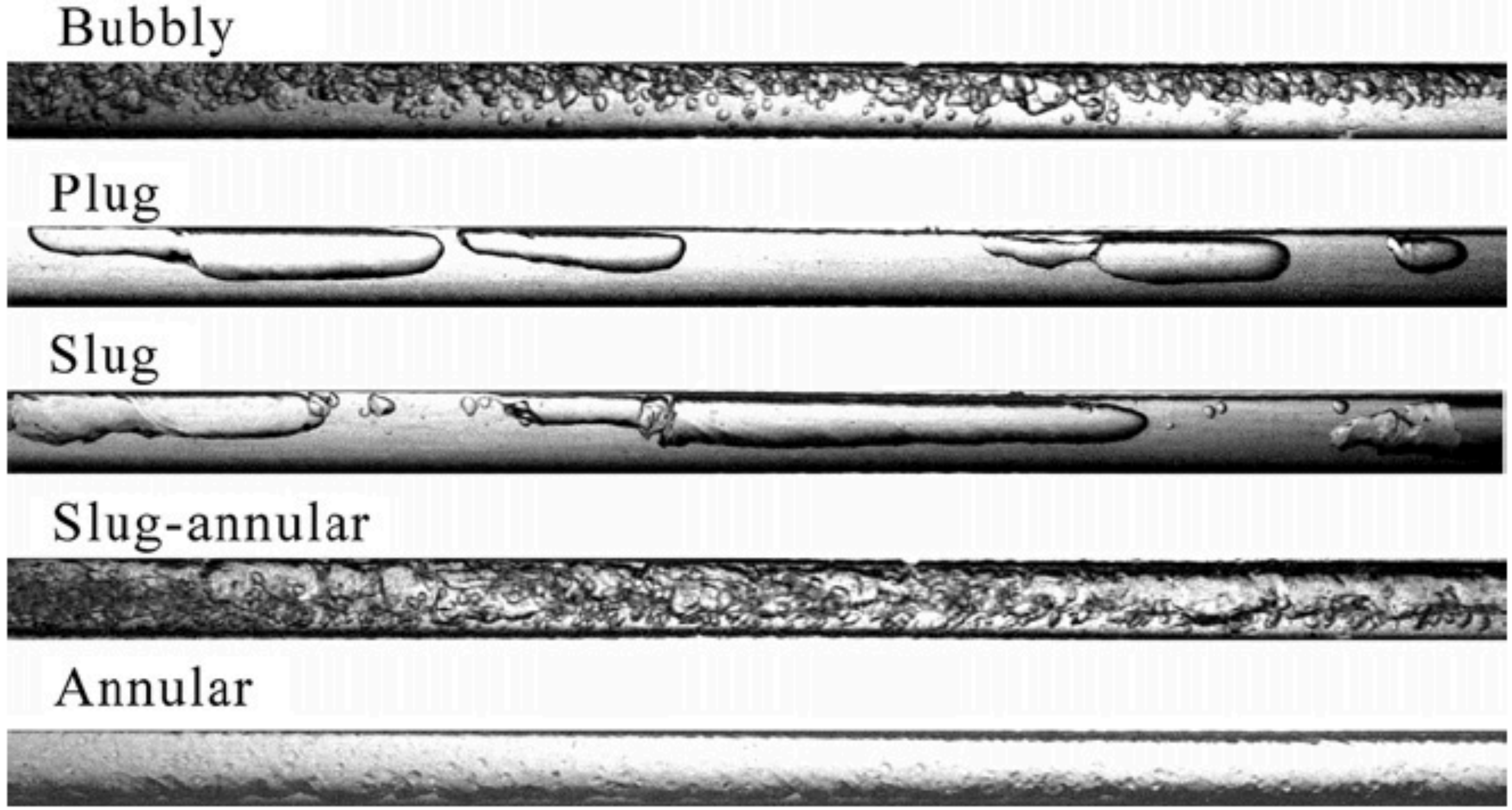
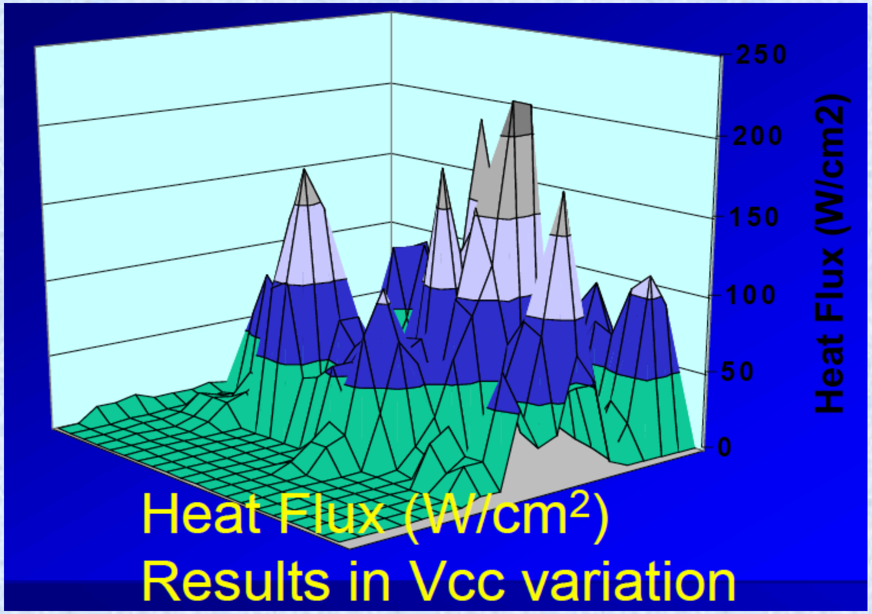
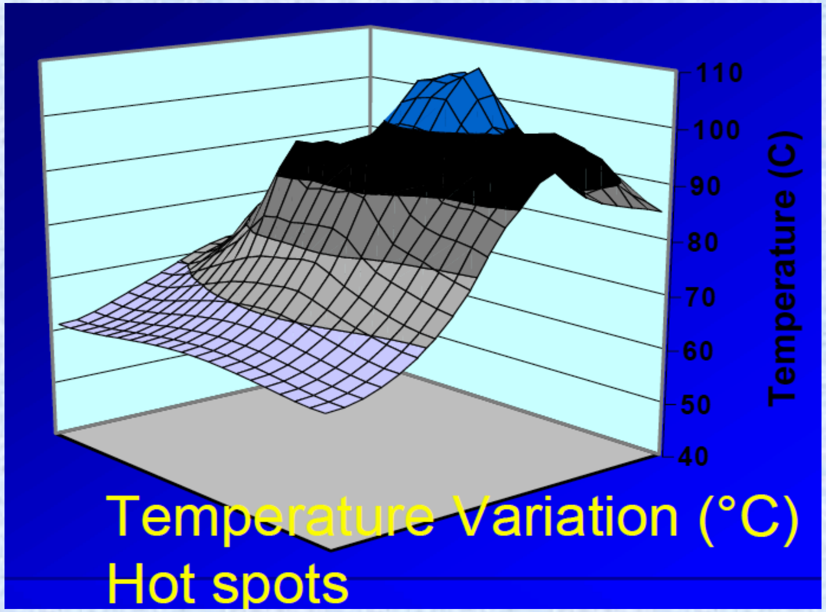


Fig. 5. Flow pattern of CO_2 ($D_p = 2.0$ mm, $p = 5.0, 6.5$ MPa, flow direction: left to right).

Example of Power Density Distribution on a Chip Hot Spots



Heat Flux (W/cm^2)
Results in Vcc variation



Temperature Variation (°C)
Hot spots

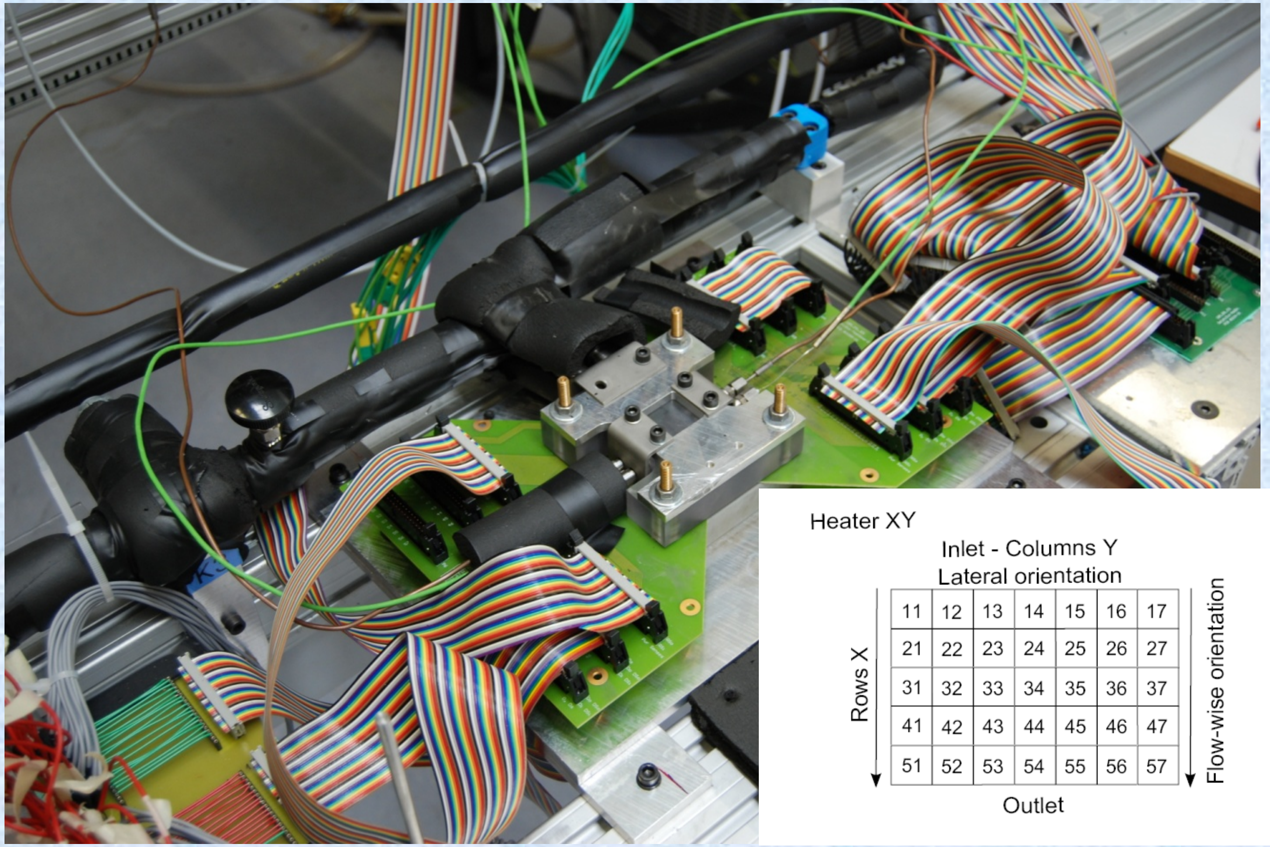
Borkar, S., 2004, Exponential Challenges, Exponential Rewards – The Future of Moore's Law, Intel report

LTCM "35 Heater CPU" Flow Boiling Test Section

We test both liquid cooling (subcooled refrigerants) and two-phase cooling:

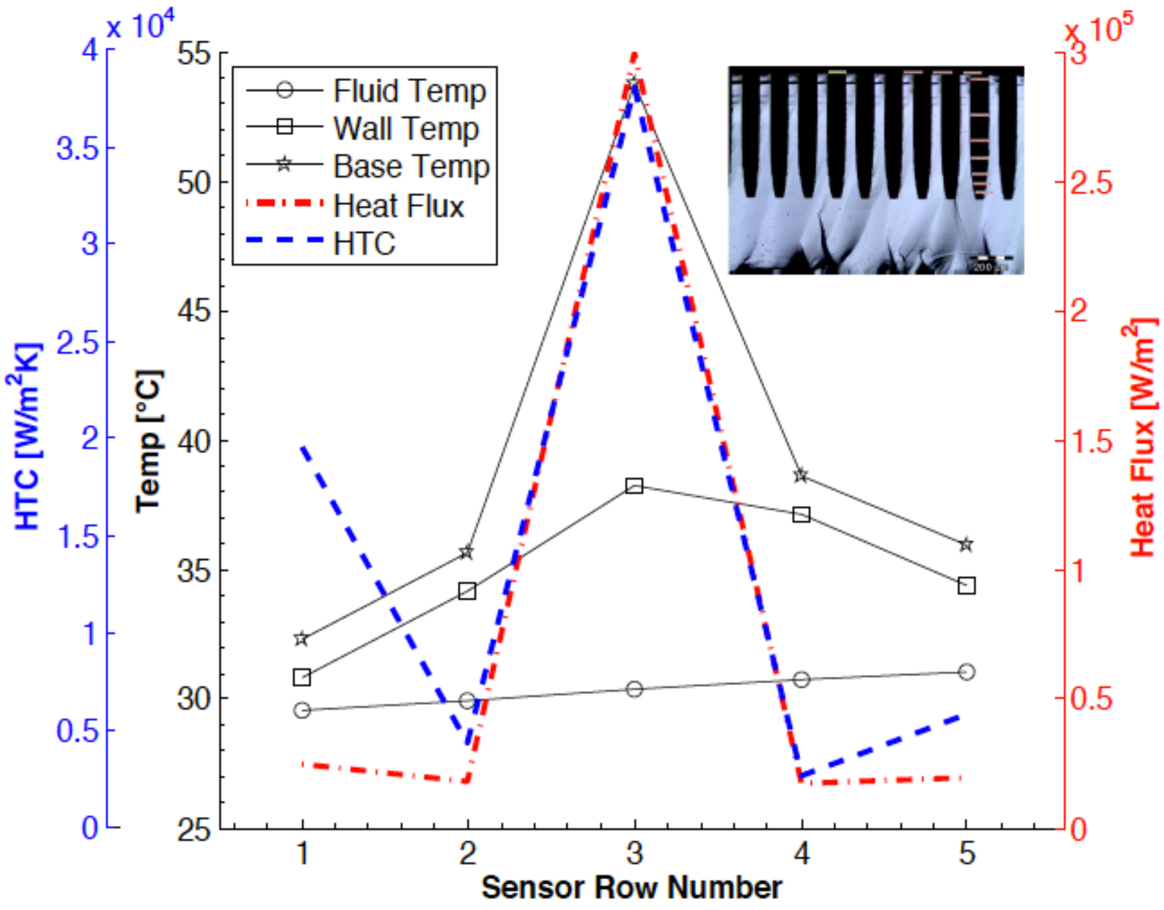
Hot spots up to 15 times base heat flux have been tested so far.

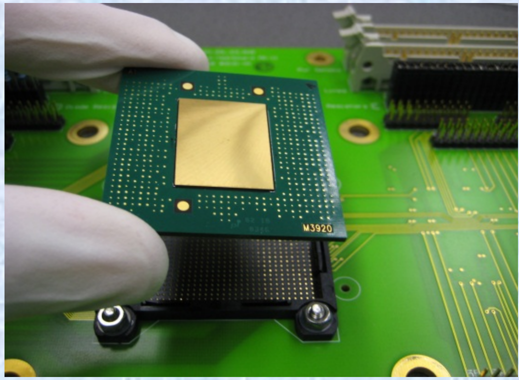
One or more hot spots can be placed anywhere in 5x7 grid.

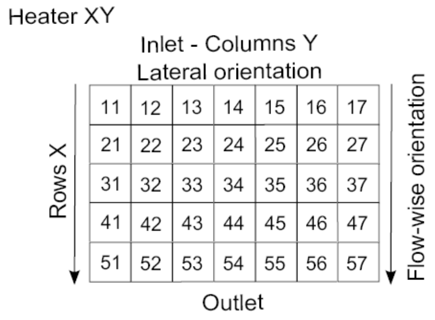


11	12	13	14	15	16	17
21	22	23	24	25	26	27
31	32	33	34	35	36	37
41	42	43	44	45	46	47
51	52	53	54	55	56	57

Two-Phase Hot Spot Cooling: Boiling Response





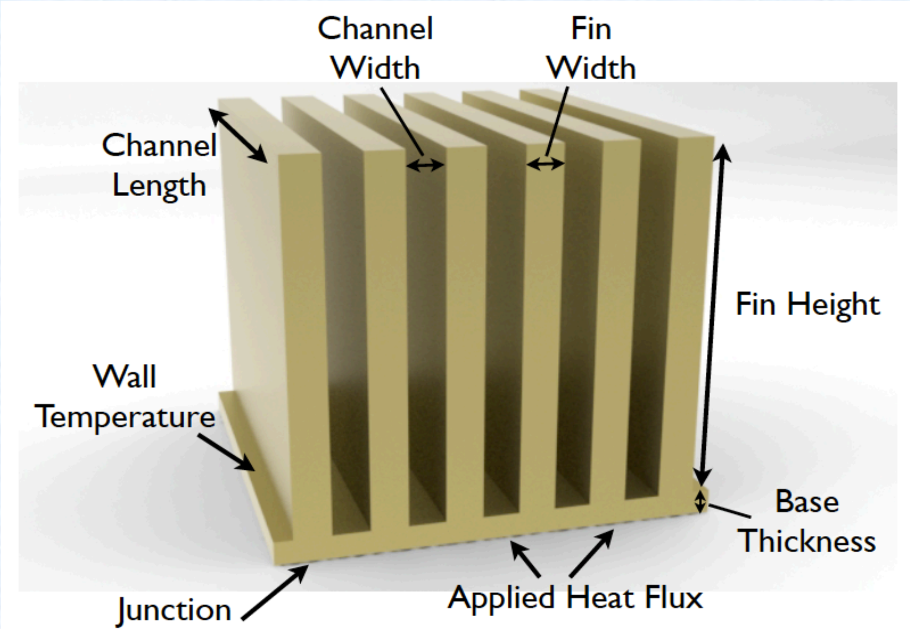


11	12	13	14	15	16	17
21	22	23	24	25	26	27
31	32	33	34	35	36	37
41	42	43	44	45	46	47
51	52	53	54	55	56	57

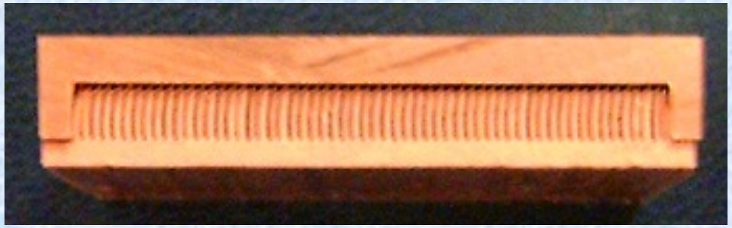
Hot spot heat flux is 15 times higher, htc is 8 times higher so wall superheat is only 2 times higher!

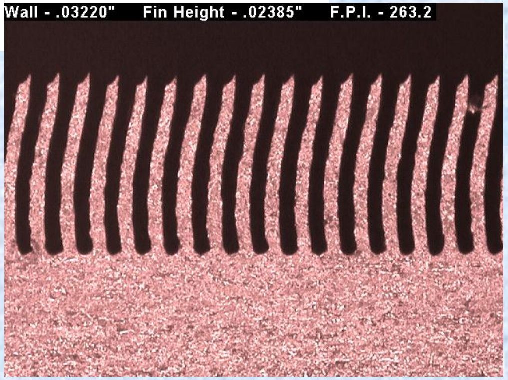
Thermal profile of pseudo-chip with 35 local heaters and 35 local temperature sensors, being cooled by a two-phase refrigerant evaporating in 135 parallel microchannels of 87 micron width engraved in opposite face of the silicon die (*Costa-Patry et al of LTCM at THERMINIC 2010 Barcelona*).

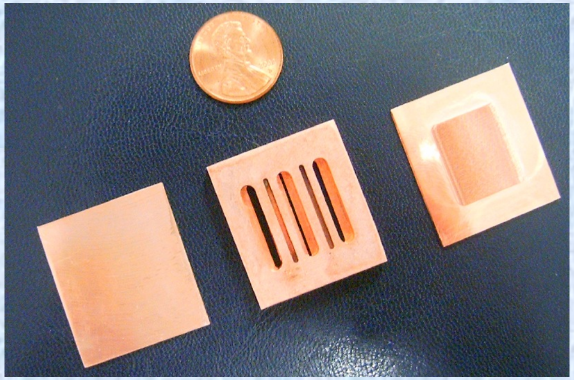
Two-Phase Hot Spot Simulations: LTCM Code



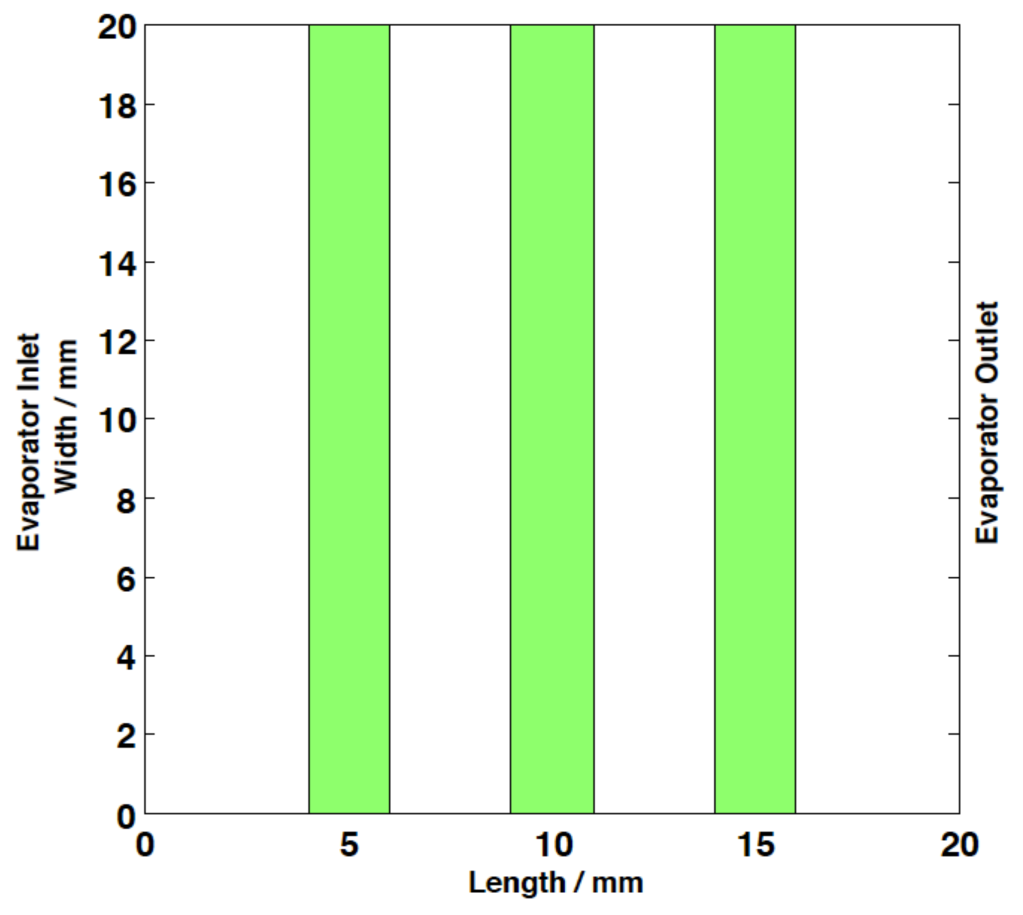
- Footprint 19.3 mm x 13.2 mm (Intel Xeon 5500)
- 60°C saturation temperature
- Fin height : 1.7mm
- Fin width : 170µm
- Channel width : 170µm





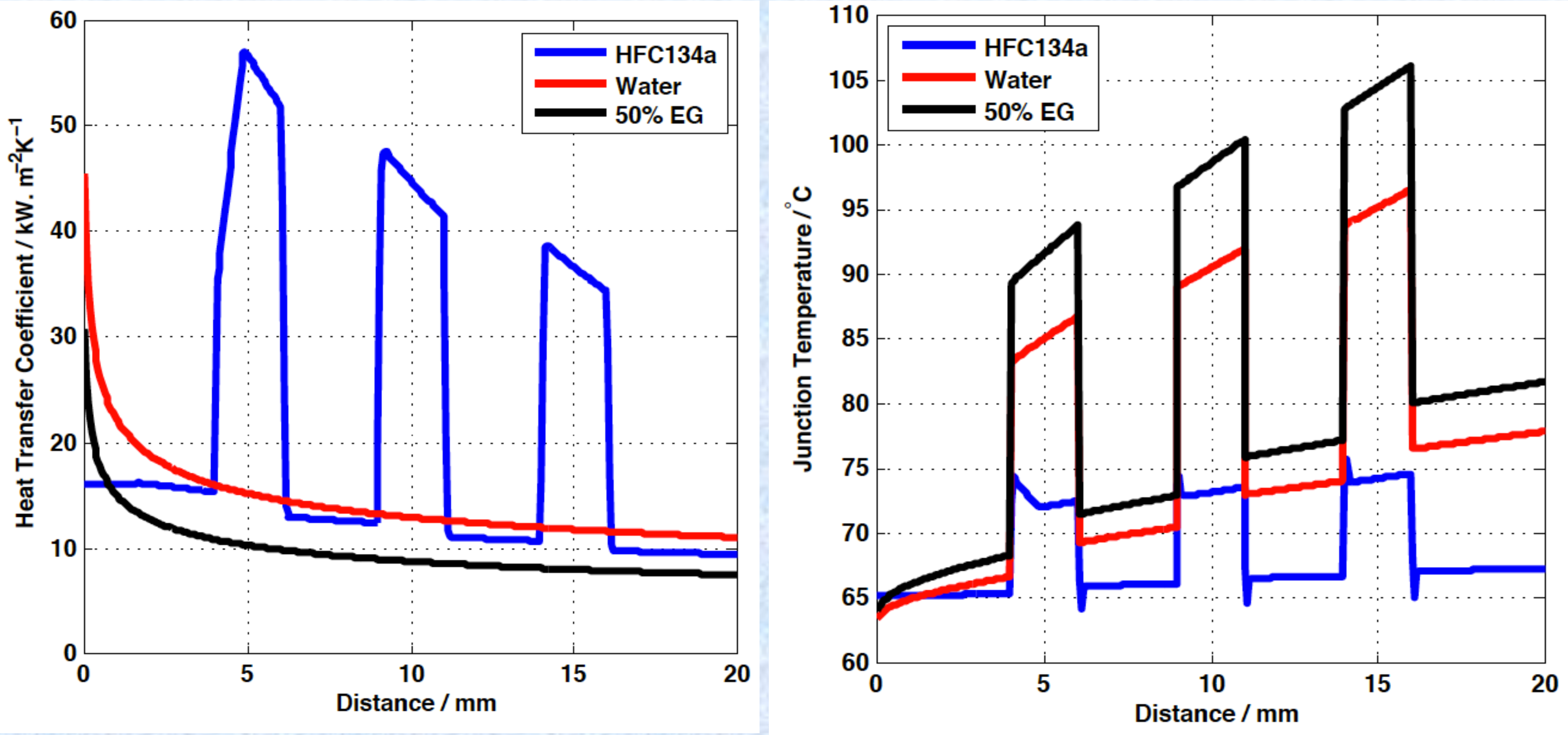


Hot Spot Cooling Simulations

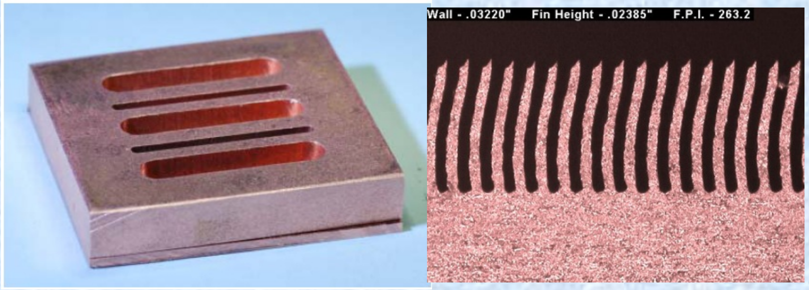


Base heat flux:
50 W/cm^2
Hotspot heat flux:
200 W/cm^2

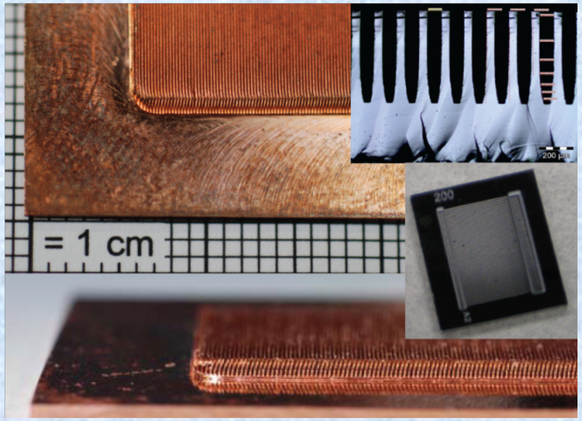
Heat Transfer Coefficient & Junction Temperature



Two-Phase On-Chip Cooling of Blade Server



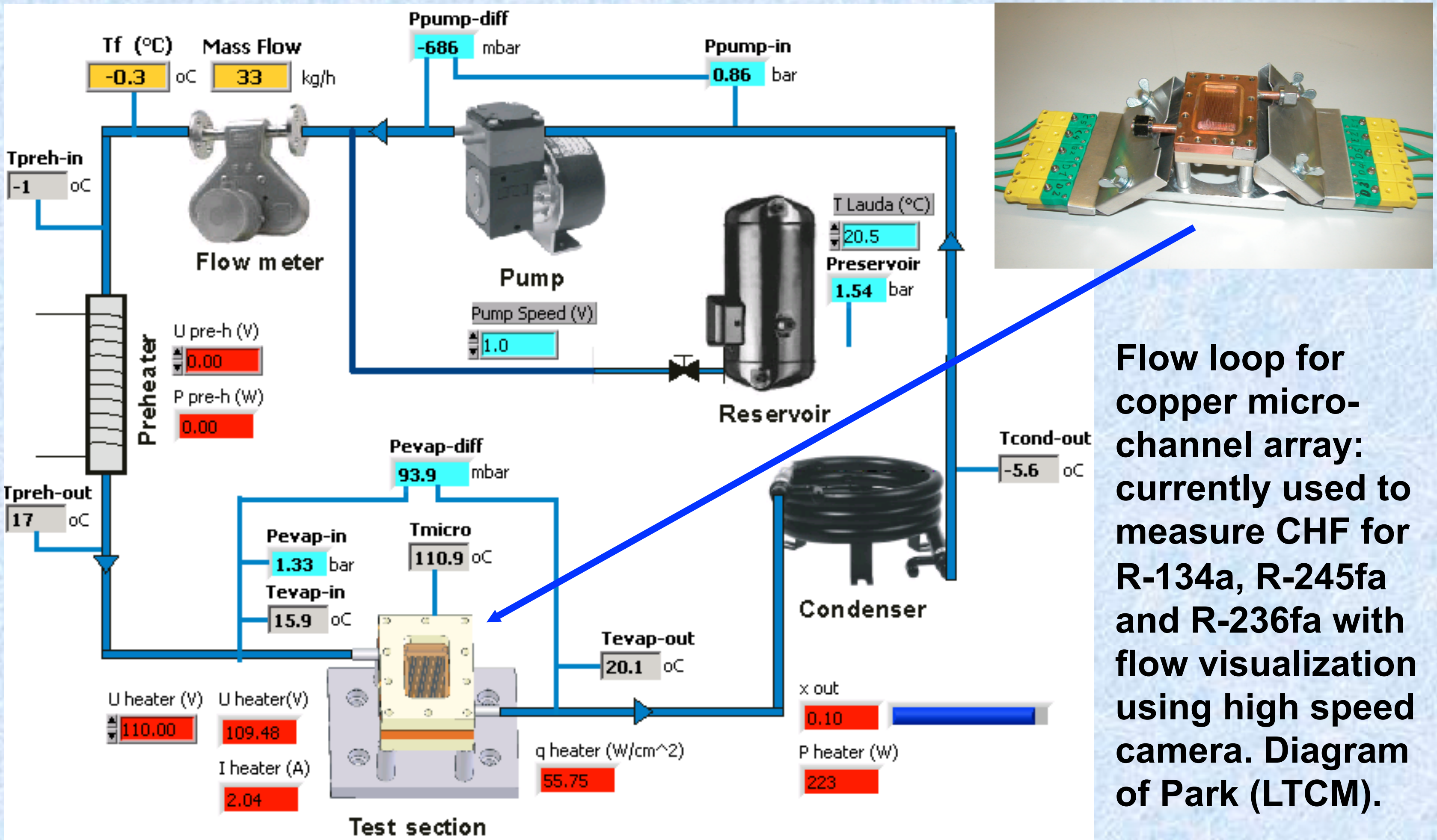
- 60% or more improvement in energy efficiency
- Heat can be recovered
  - Reused elsewhere
  - Reduce CO_2 footprint
- Can operate at higher temperatures and still be cooled efficiently
  - No chiller required
- Occupies less space



Water-Cooled IBM BladeCenter HS22

Credit: IBM Research – Zurich

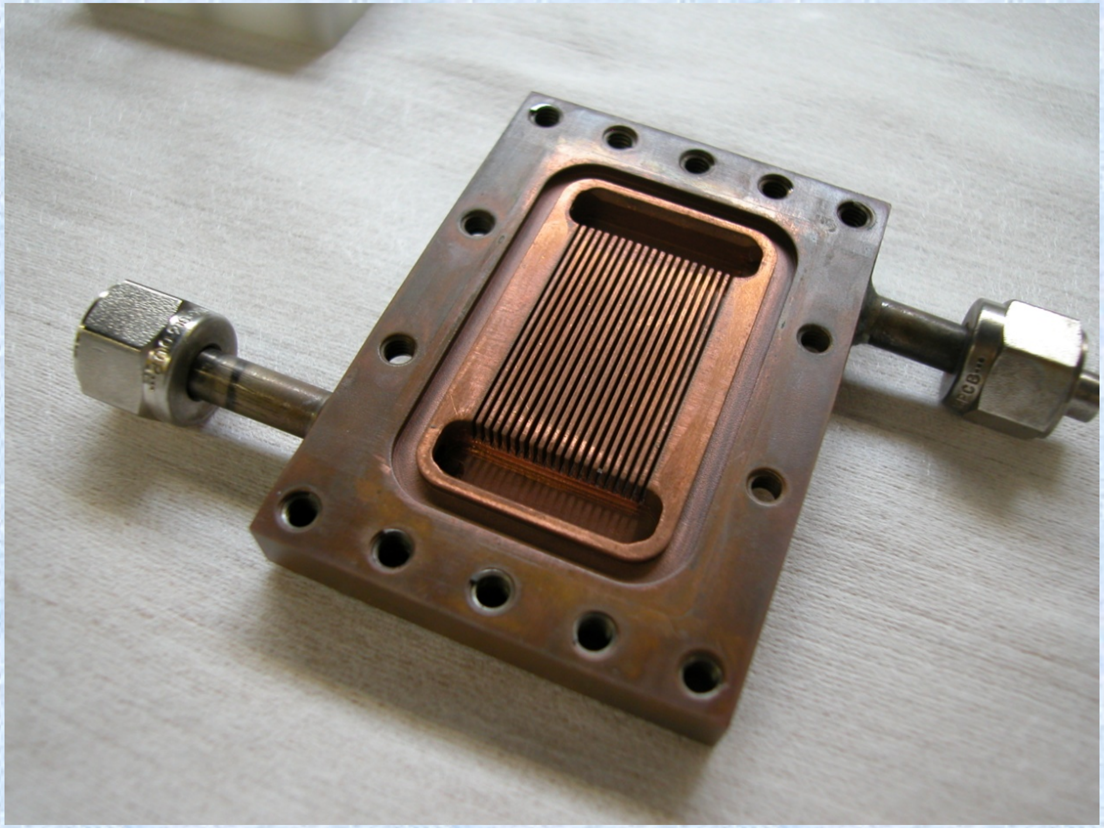
CPU Multi-Microchannel Flow Boiling Test Facility



Tf (°C) -0.3 oC
Mass Flow 33 kg/h
Ppump-diff -686 mbar
Ppump-in 0.86 bar
Tpreh-in -1 oC
T Lauda (°C) 20.5
Preservoir 1.54 bar
Pump Speed (V) 1.0
U pre-h (V) 0.00
P pre-h (W) 0.00
Pevap-diff 93.9 mbar
Tpreh-out 17 oC
Tcond-out -5.6 oC
Pevap-in 1.33 bar
Tmicro 110.9 oC
Tevap-in 15.9 oC
Tevap-out 20.1 oC
U heater (V) 110.00
U heater(V) 109.48
I heater (A) 2.04
q heater (W/cm^2) 55.75
x out 0.10
P heater (W) 223

Flow loop for copper micro-channel array: currently used to measure CHF for R-134a, R-245fa and R-236fa with flow visualization using high speed camera. Diagram of Park (LTCM).

CPU Microchannel Flow Boiling Cooling at LTCM

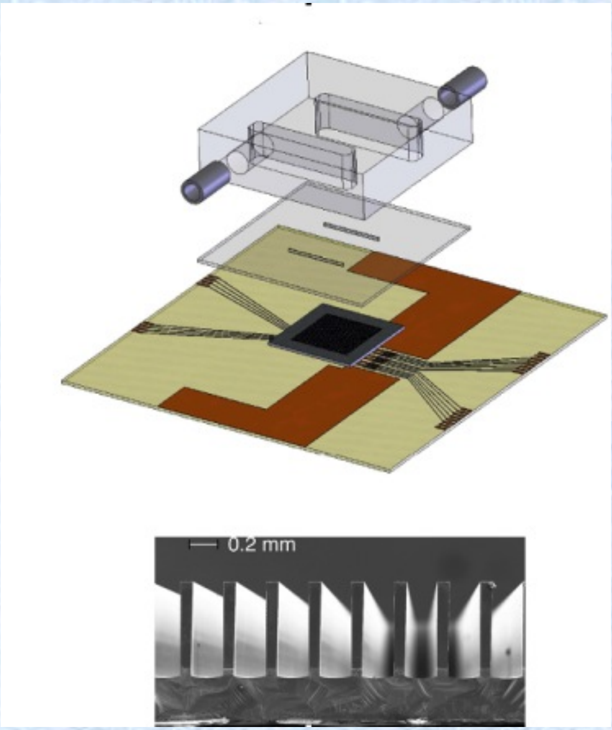


Multi-microchannel evaporator in copper fabricated at LTCM: 20 channels (0.45 x 4.0 mm) and dissipates 340 W/cm^2 with a low pressure refrigerant as coolant (*LTCM PhD thesis of J.E. Park (2008*).

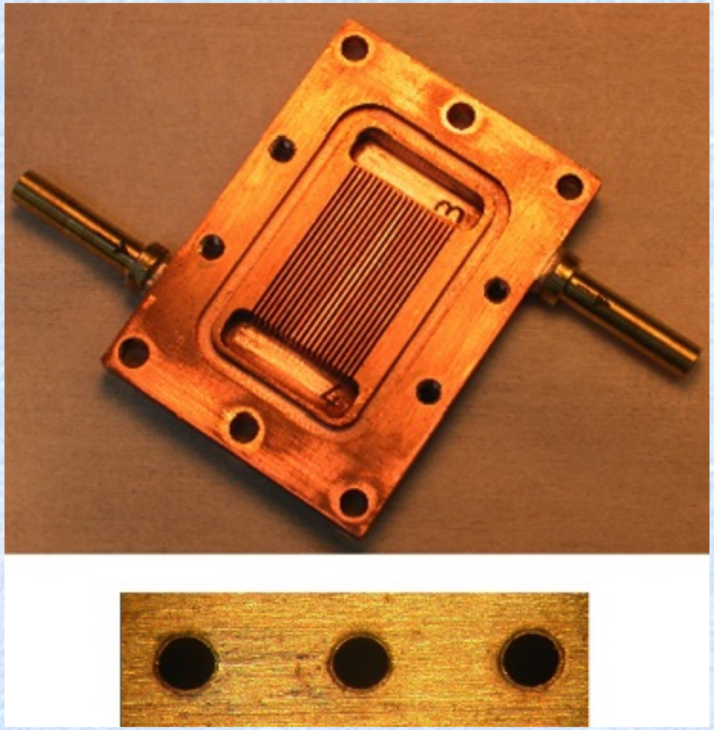
Video at High Heat Flux in Copper: Poor Flow Distribution

Maximum heat flux dissipation possible is only about 115 W/cm^2 (as a result of mal-distribution and back flow, there is over heating in liquid starved/ dry area!). Video of LTCM.

Micro-Evaporators: Basic Geometry and Flow Stabilization



(a)



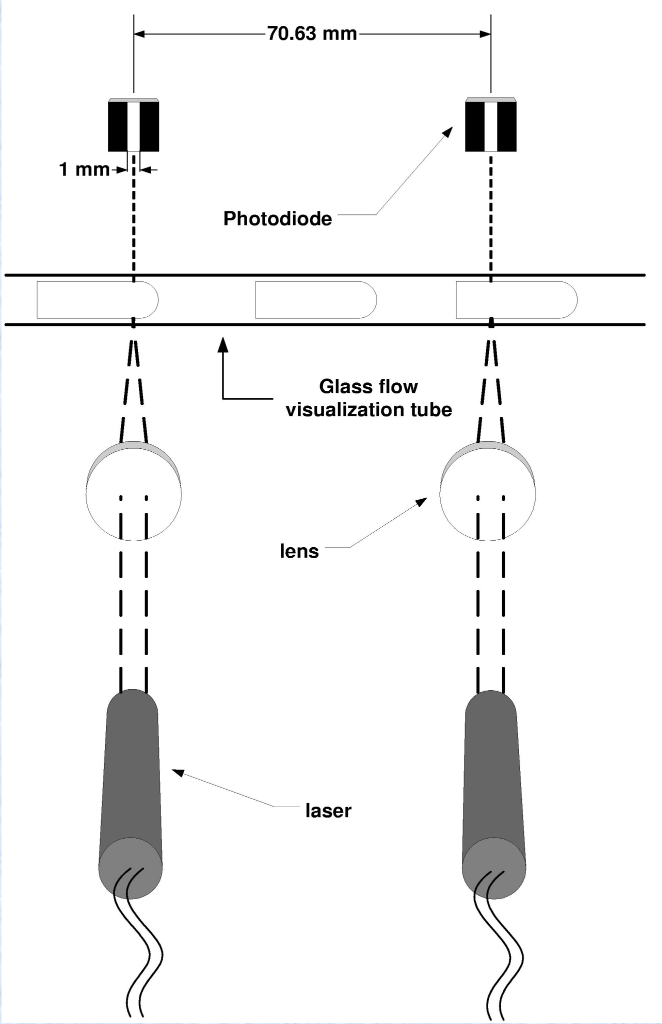
(b)

Examples of (a) silicon micro-evaporator with micro-channels etched on the chip silicon die and (b) copper micro-evaporator test section made by electro-erosion with an inlet orifice insert.

Video at High Heat Flux in Copper: Good Flow Distribution

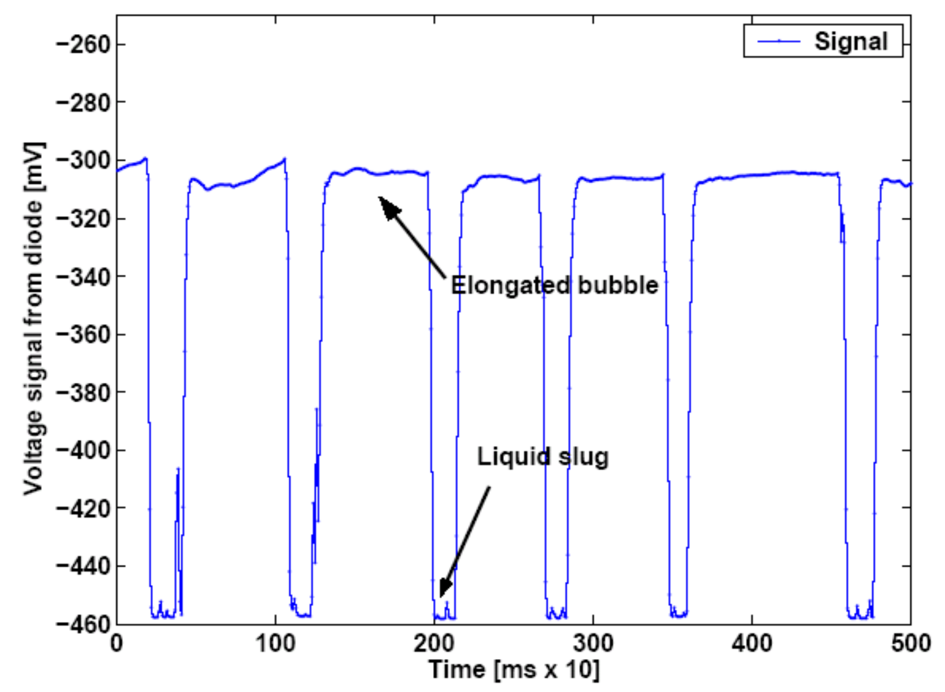
Maximum heat flux dissipation possible is at least 340 W/cm^2 using inlet flow restrictions to prevent back flow and create uniform flow distribution (shown here at 250 W/cm^2 at 2000 images/sec). Video of LTCM.

LTCM Optical Measurement Technique for 2-Phase Flow

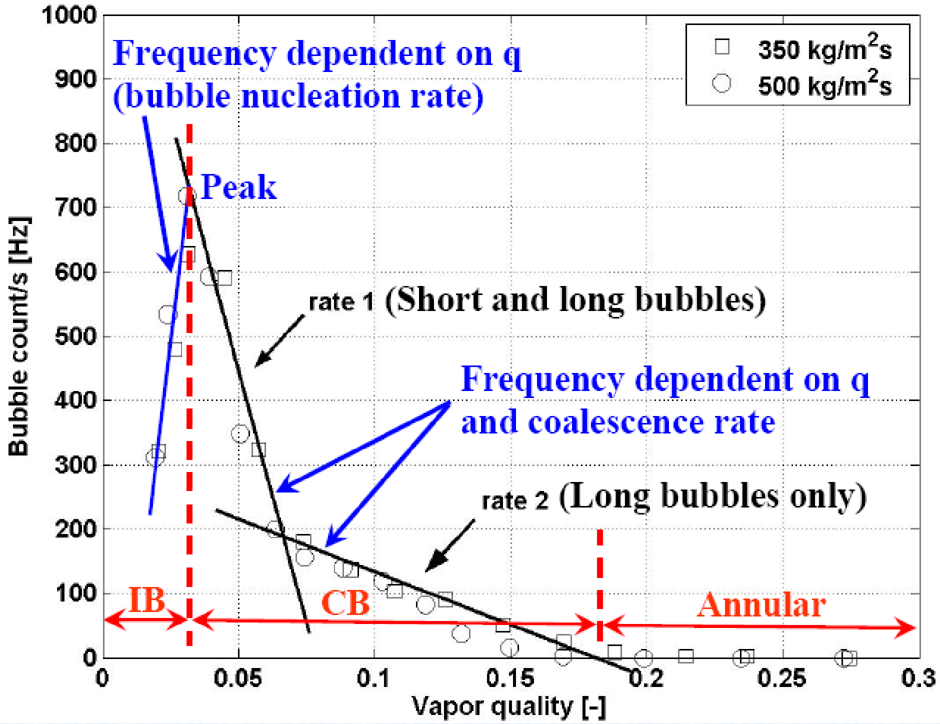


It yields:

- Bubble velocity
- Void fraction
- Bubble length
- Bubble frequency
- Flow pattern



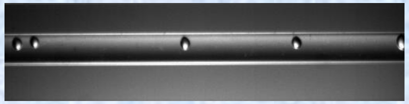
Flow Patterns/Bubble Frequencies in Micro-Channels



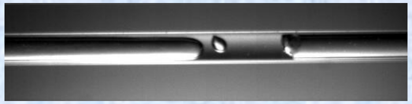
R-134a:
$D = 0.509$ mm
$T_{sat} = 30°C$
$L_h = 50$ mm
$\Delta T_{sub} = 3°C$

Revellin, Thome et al., Int. J. Multiphase Flow, Vol. 32, pp. 755-774, 2006.

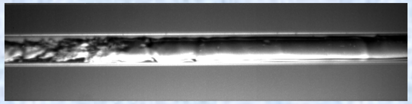
Awarded Eurotherm PhD thesis prize.



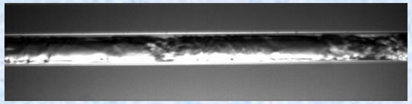
bubbly



slug

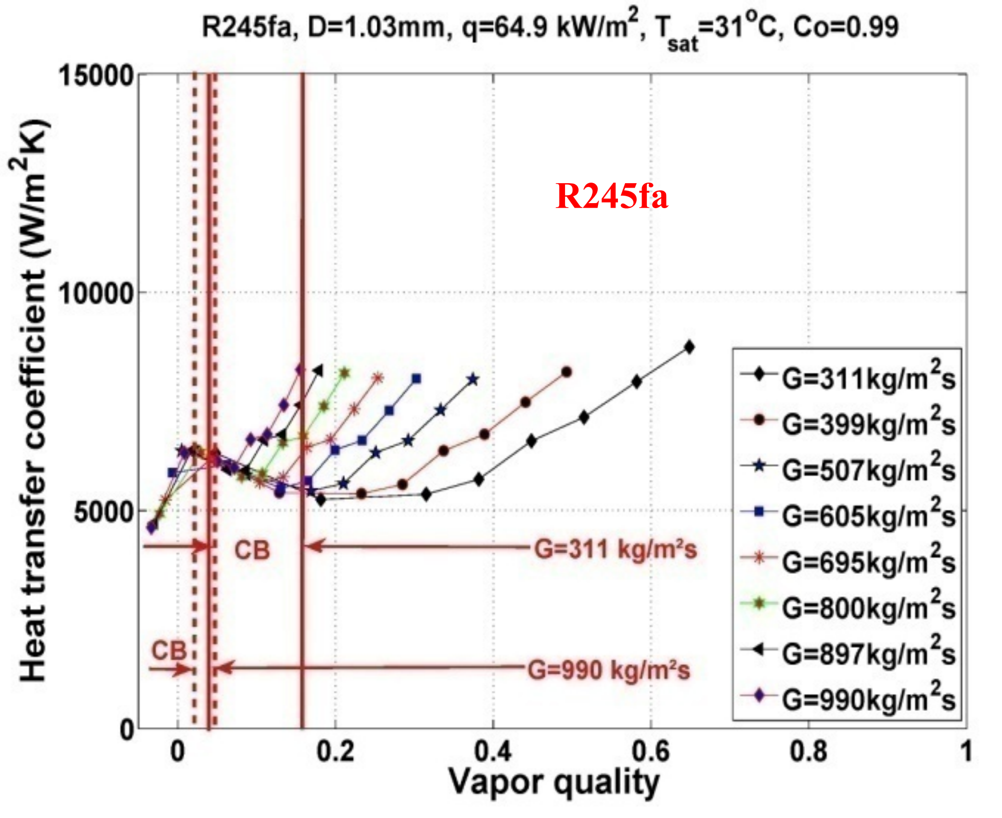


churn – semi-annular



annular

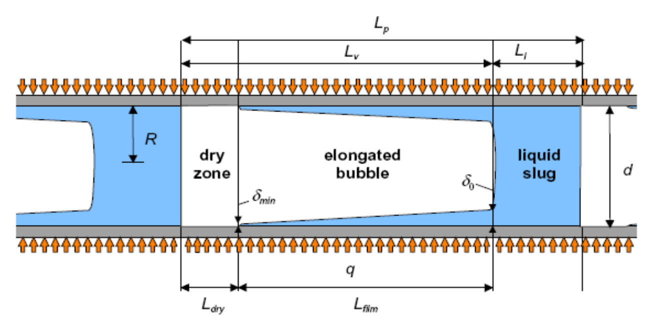
Flow Boiling Heat Transfer: Flow Pattern Effects (Ong)



1. IB/CB flow regime nearly disappears at high mass velocities while the annular flow becomes nearly totally dominant.
2. Heat transfer coefficient rises in the sub-cooled region to the IB region (ONB).
3. Decreasing trend in htc in the CB flow but rising in the annular flow regime.

Flow Boiling HT in CB Zone

Three zone model of Thome et al. (2004) ➡



$$h(z)=\frac{t_{liquid}}{\tau}h_{liquid}(z)+\frac{t_{film}}{\tau}h_{film}(z)+\frac{t_{dry}}{\tau}h_{vapor}(z)$$

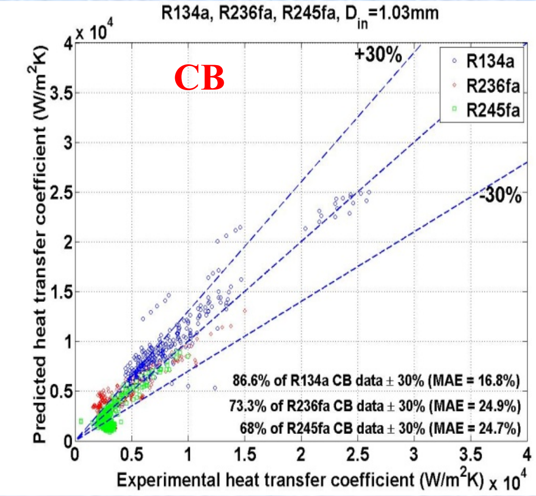
$$f_{opt}=(\frac{q}{q_{ref}})^{nf}$$

$$n_f=1.74, \delta_{\min}=300nm, C_{\delta 0}=0.29$$

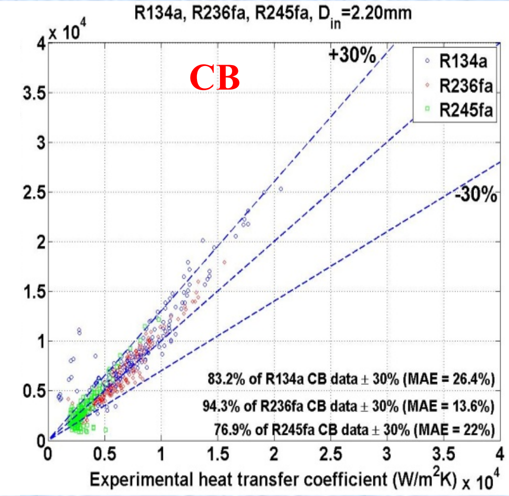
Replacing δmin with actual roughness gives better results

Surface roughness

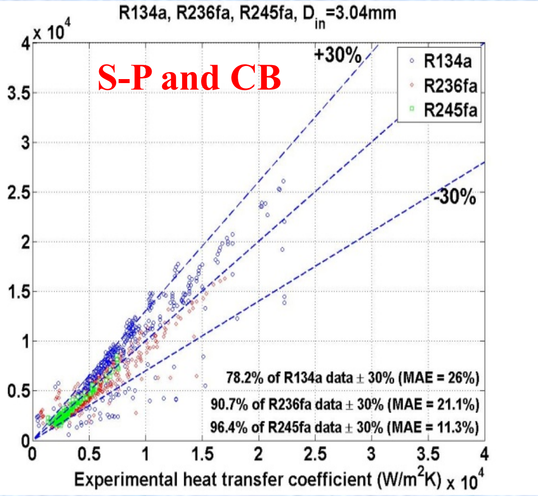
D_{int} (mm)	δ_{min} (nm)
1.03	595.85
2.20	826.99
3.04	796.81



86.6% of R134a CB data ± 30% (MAE = 16.8%)
73.3% of R236fa CB data ± 30% (MAE = 24.9%)
68% of R245fa CB data ± 30% (MAE = 24.7%)



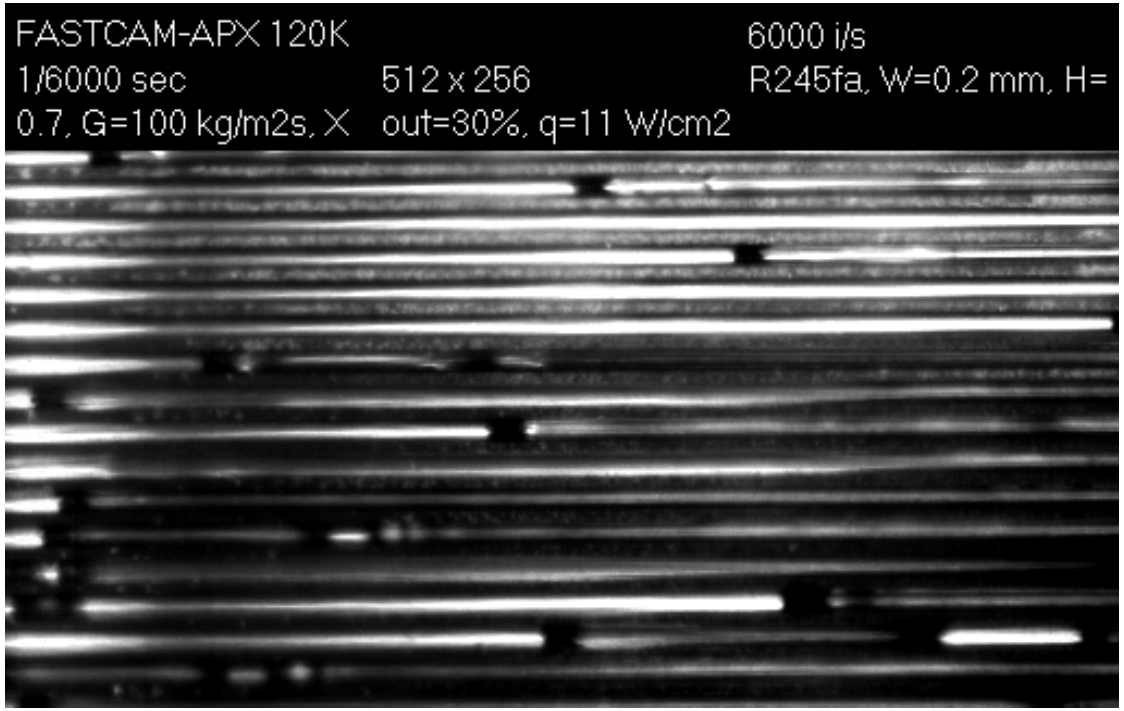
83.2% of R134a CB data ± 30% (MAE = 26.4%)
94.3% of R236fa CB data ± 30% (MAE = 13.6%)
76.9% of R245fa CB data ± 30% (MAE = 22%)



78.2% of R134a data ± 30% (MAE = 26%)
90.7% of R236fa data ± 30% (MAE = 21.1%)
96.4% of R245fa data ± 30% (MAE = 11.3%)

New: importance of surface roughness now found in 3 different LTCM studies!

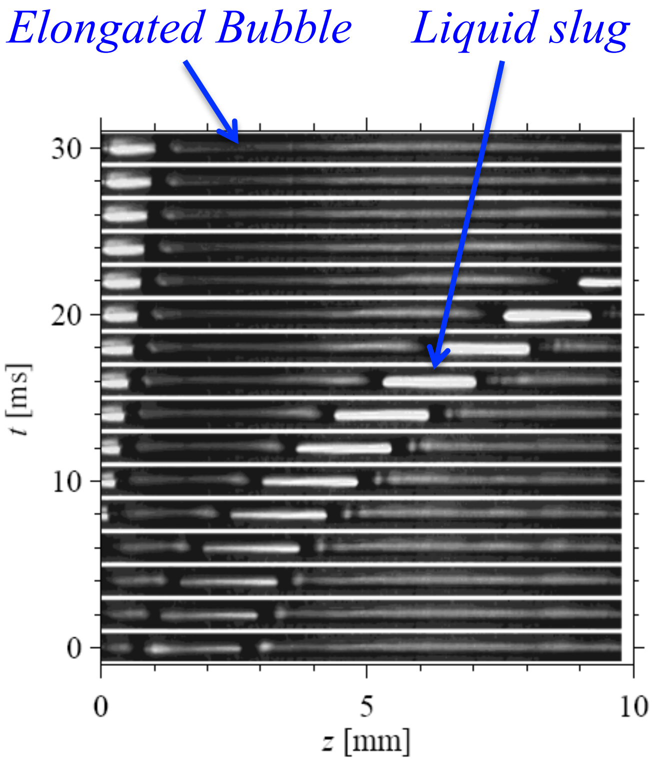
New Time Strip Analysis of Two-Phase Flow



- Photron Fastcam-APX120K CMOS camera at 6 kHz and a frame size of 512×256 pixels.
- Resolution of 1 pixel per 19 μm, resulting in a captured area of size 9.8×6.2 mm just downstream of the inlet plenum.

New Time Strip Analysis of Two-Phase Flow

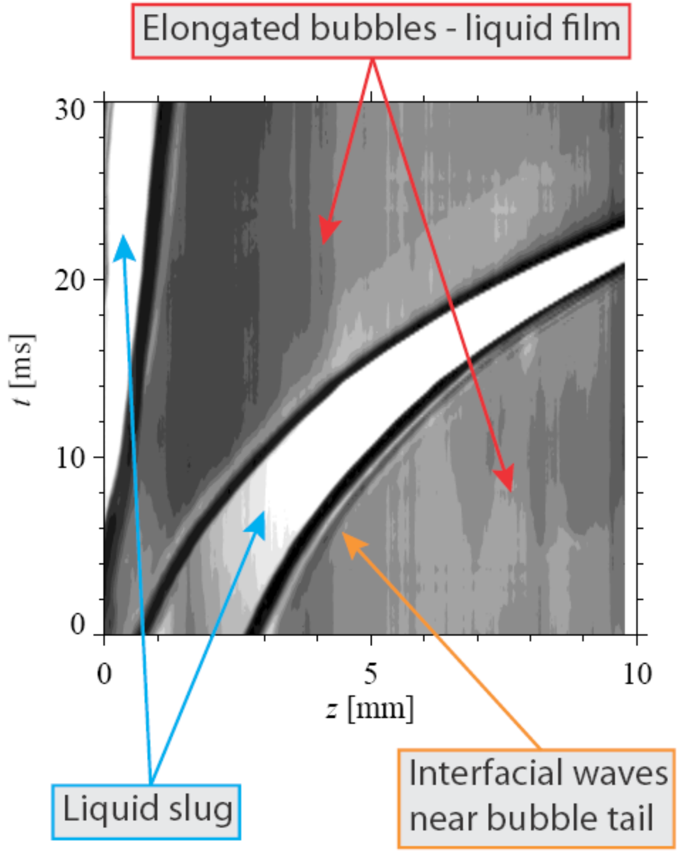
Channel frame sequence



Elongated Bubble

Liquid slug

Channel time strip



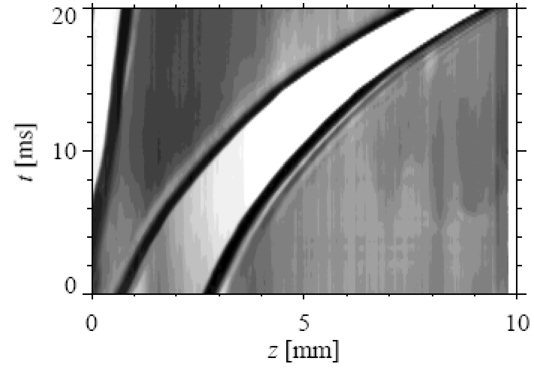
Elongated bubbles - liquid film

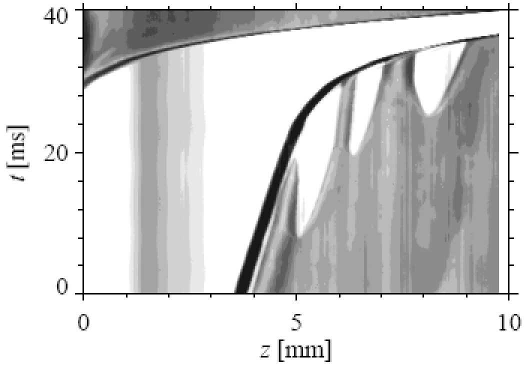
Liquid slug

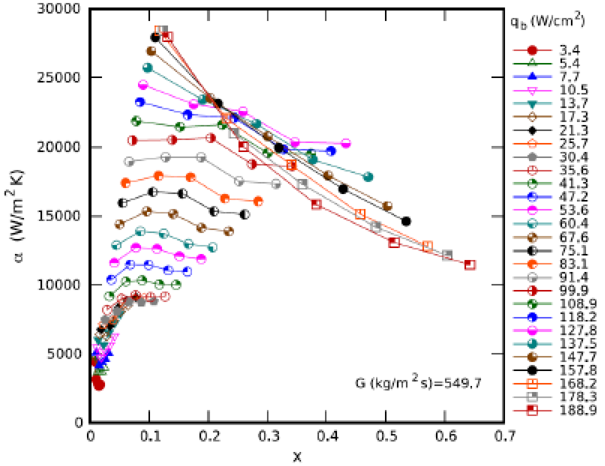
Interfacial waves
near bubble tail

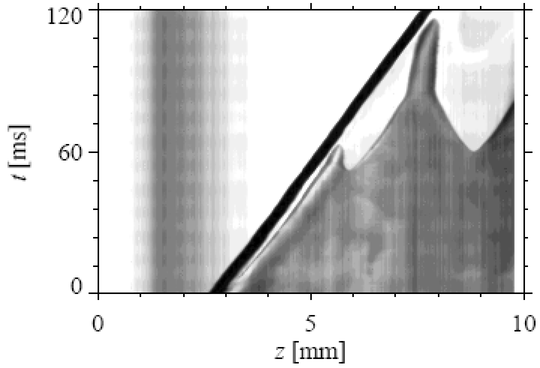
Borhani-Agostini-Thome
in *IJHMT*'2010

New Time Strip Analysis of Two-Phase Flow









- Intermittent dewetting-dryout-rewetting affects the gradient of the heat transfer coefficient - vapour quality trend.

Simulations of Cheng-Thome Heat Transfer Model and Map for CO2

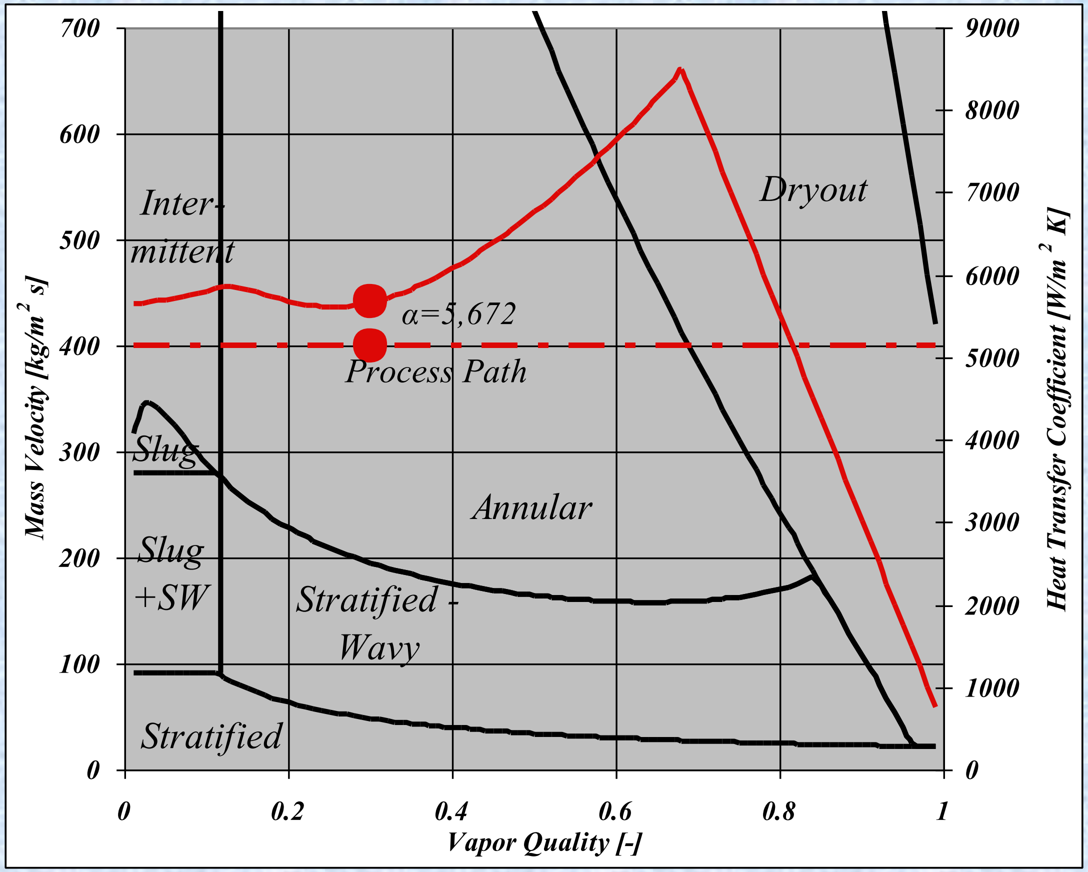


Figure 6. Simulation for 7 mm channel at following conditions: q = 10 kW/m^2, T_{sat} at -20°C and G = 400 kg/m^{2}s with indicated value at x = 0.30.

Simulations of Cheng-Thome Heat Transfer Model and Map for CO2

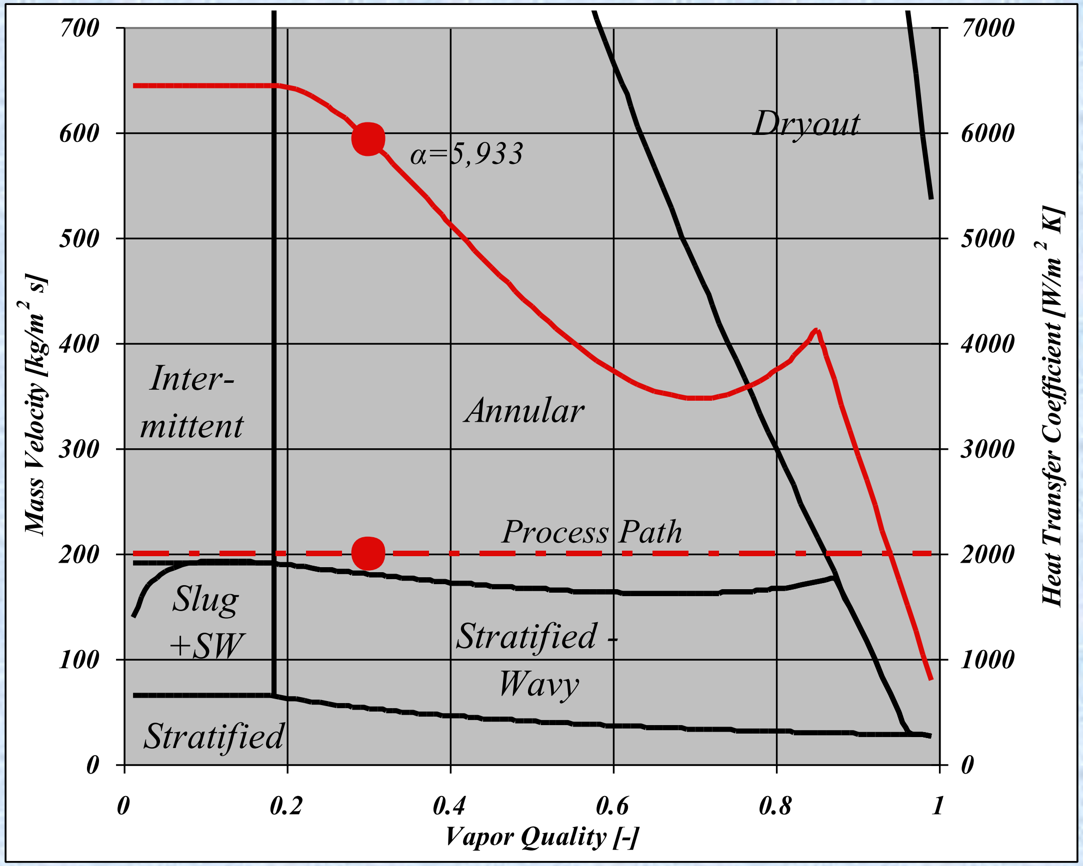
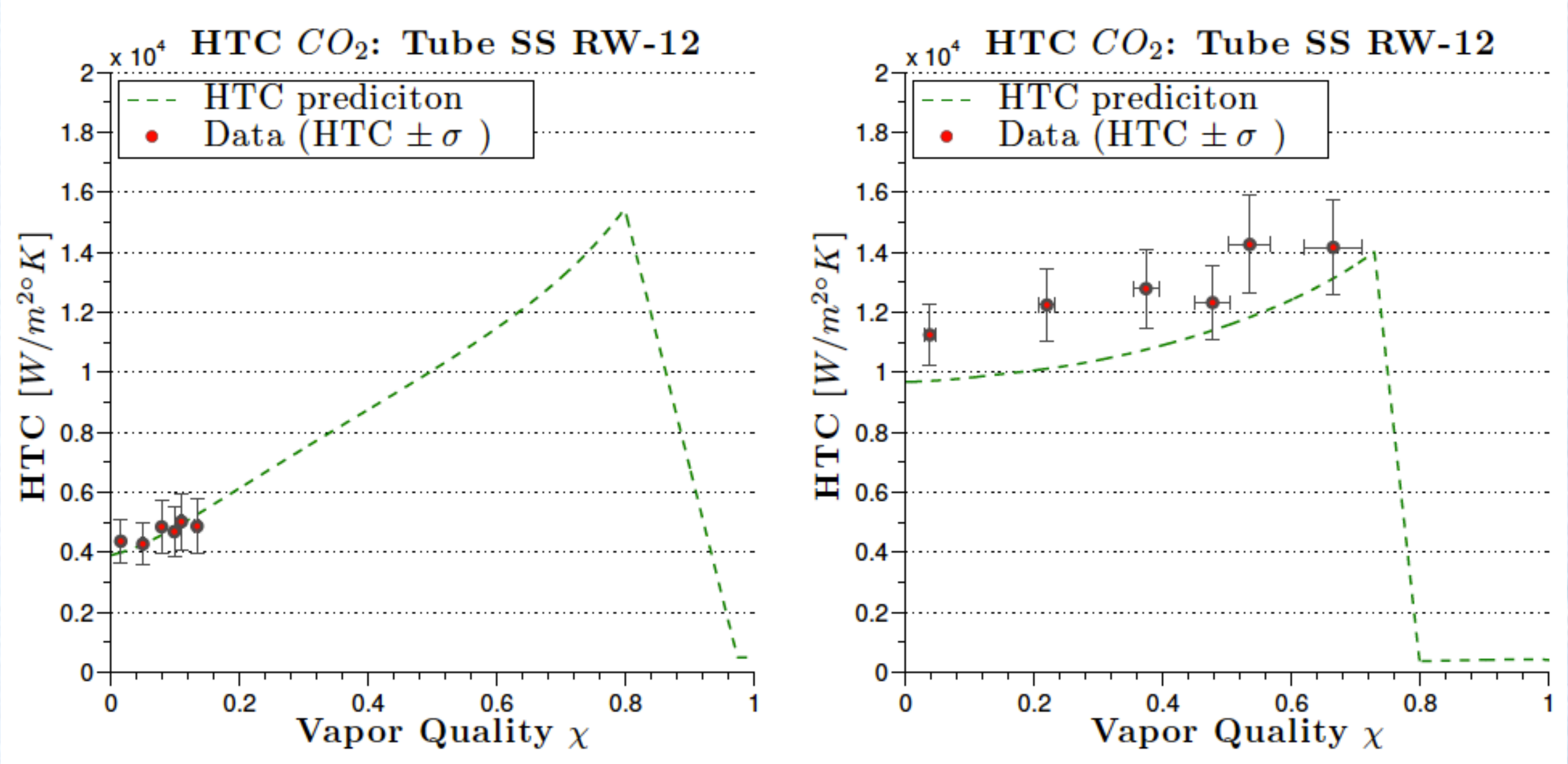
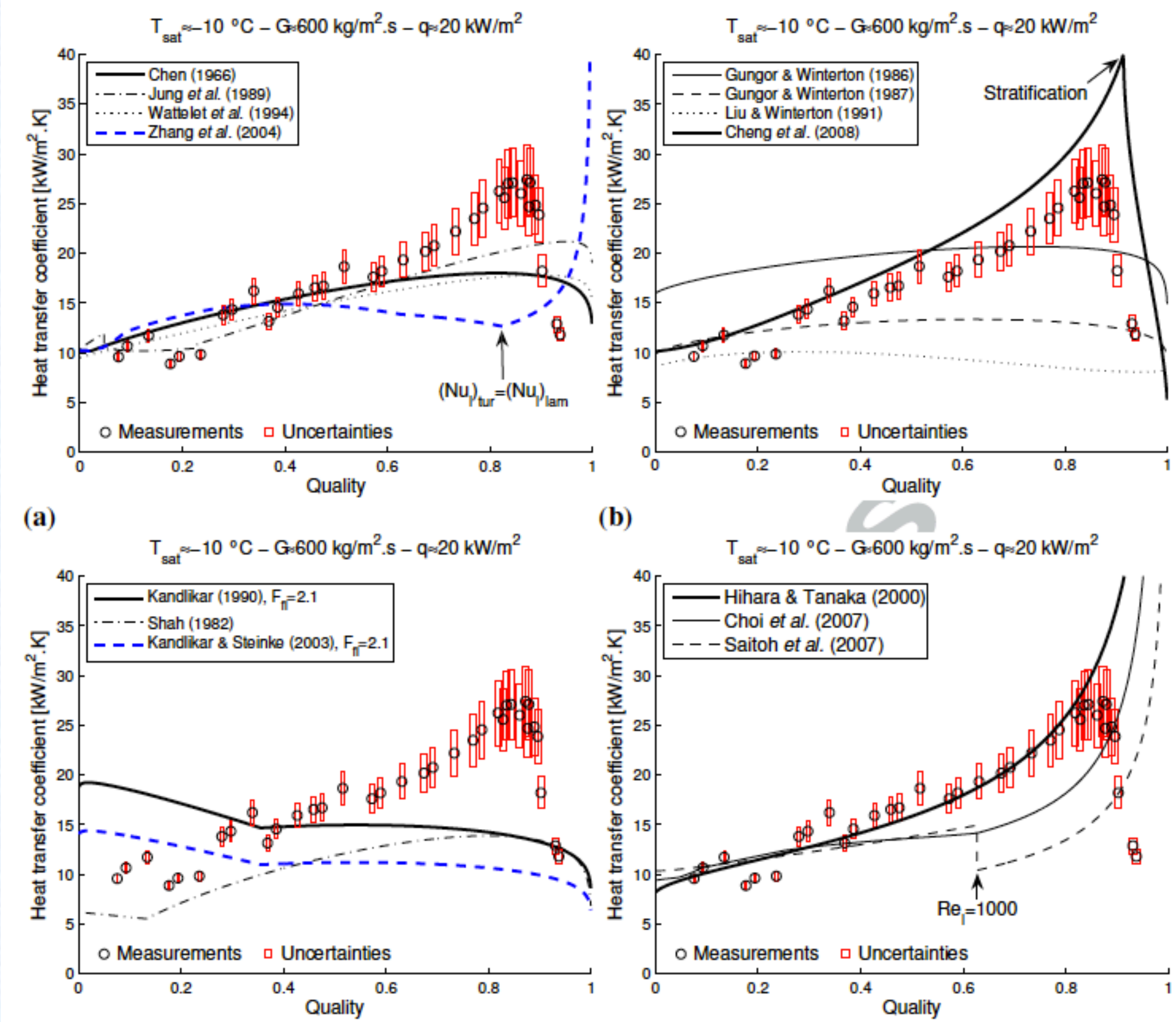


Figure 7. Simulation for 7 mm channel at following conditions: 5 kW/m^2, T$_{sat}$ at 10°C and G = 200 kg/m^{2}s with indicated value at x = 0.30.

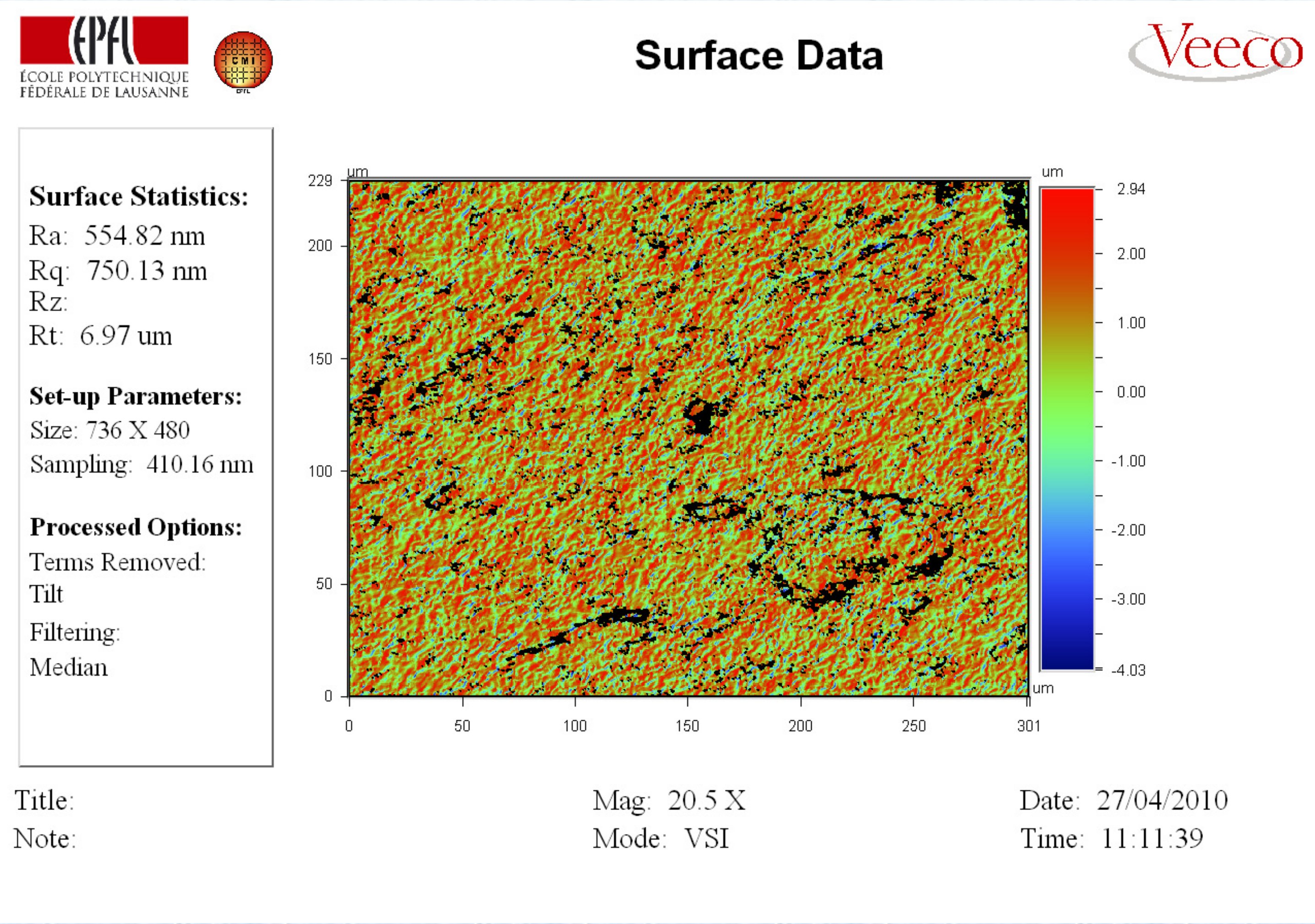
SLAC: CO2 Flow Boiling Tests for IBL prototype from Hemink thesis





CO2 Flow Boiling Tests from Ducoulombier et al. in Expermental Thermal and Fluid Sciences for 0.529 mm SS tube

CERN: CO2 Flow Boiling Test Section Surface Roughness Value



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Surface Data

Surface Statistics:

Ra: 554.82 nm

Rq: 750.13 nm

Rz:

Rt: 6.97 um

Set-up Parameters:

Size: 736 X 480

Sampling: 410.16 nm

Processed Options:

Terms Removed:

Tilt

Filtering:

Median

Title:

Note:

Mag: 20.5 X

Mode: VSI

Date: 27/04/2010

Time: 11:11:39

CO2 Questions:

Is CO_2 a special "maverick" fluid that requires its own special prediction methods to explain its unusual experimental trends and poor comparison to conventional methods *or* not?

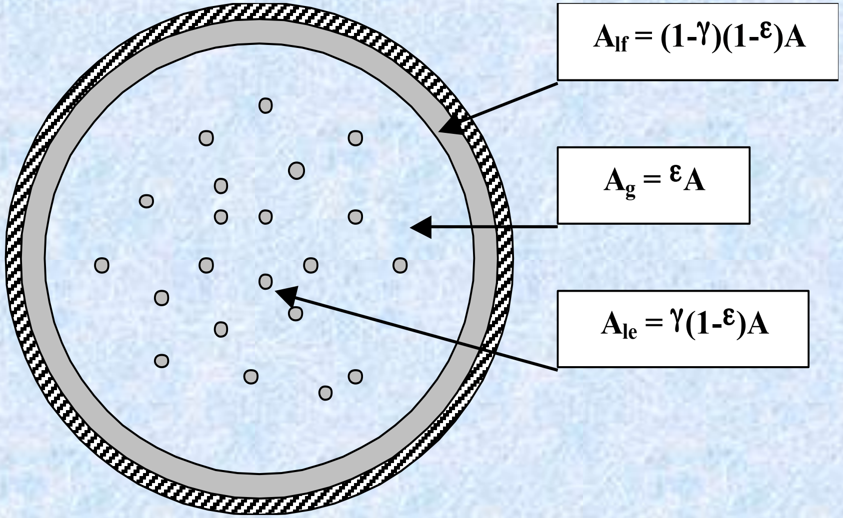
1. **…I think NOT! It is just beyond the range of reasonable extrapolation of conventional methods;**
2. **So, for now, we make special methods only applicable to CO_2;**
3. **In the future, high pressure data are required for other fluids in order to make one general method covering entire range of reduced pressures…we are getting high pressure data for R410A!**

Biggest challenge? Predicting onset of dryout more accurately.

2nd challenge? Roughness effect on CO_2 boiling in microchannels.

VAPOR CORE EQS: OUR UNIFIED ANNULAR FLOW MODEL

Once the average liquid film thickness t is known, the core flow diameter is simply calculated as $d_c=d-2t$, while the void fraction ε and the liquid droplet hold-up γ can be calculated from the following relations:



$A_{lf} = (1-\gamma)(1-\varepsilon)A$

$A_g = \varepsilon A$

$A_{le} = \gamma(1-\varepsilon)A$

$$(1-\varepsilon)(1-\gamma) = \frac{t(2R-t)}{R^2}$$

$$\gamma\frac{1-\varepsilon}{\varepsilon} = e\frac{1-x}{x}\frac{\rho_g}{\rho_l}$$

The density ρ_c and the viscosity μ_c of the droplet-laden gas core are calculated as follows (ε_c is the droplet laden gas core void fraction):

$$\rho_c = (1-\varepsilon_c)\rho_l + \varepsilon_c\rho_g; \quad \mu_c = (1-\varepsilon_c)\mu_l + \varepsilon_c\mu_g \quad \varepsilon_c = \frac{\varepsilon}{\varepsilon + \gamma(1-\varepsilon)}$$

OUR UNIFIED MODEL: *NEW* CONVECTIVE BOILING

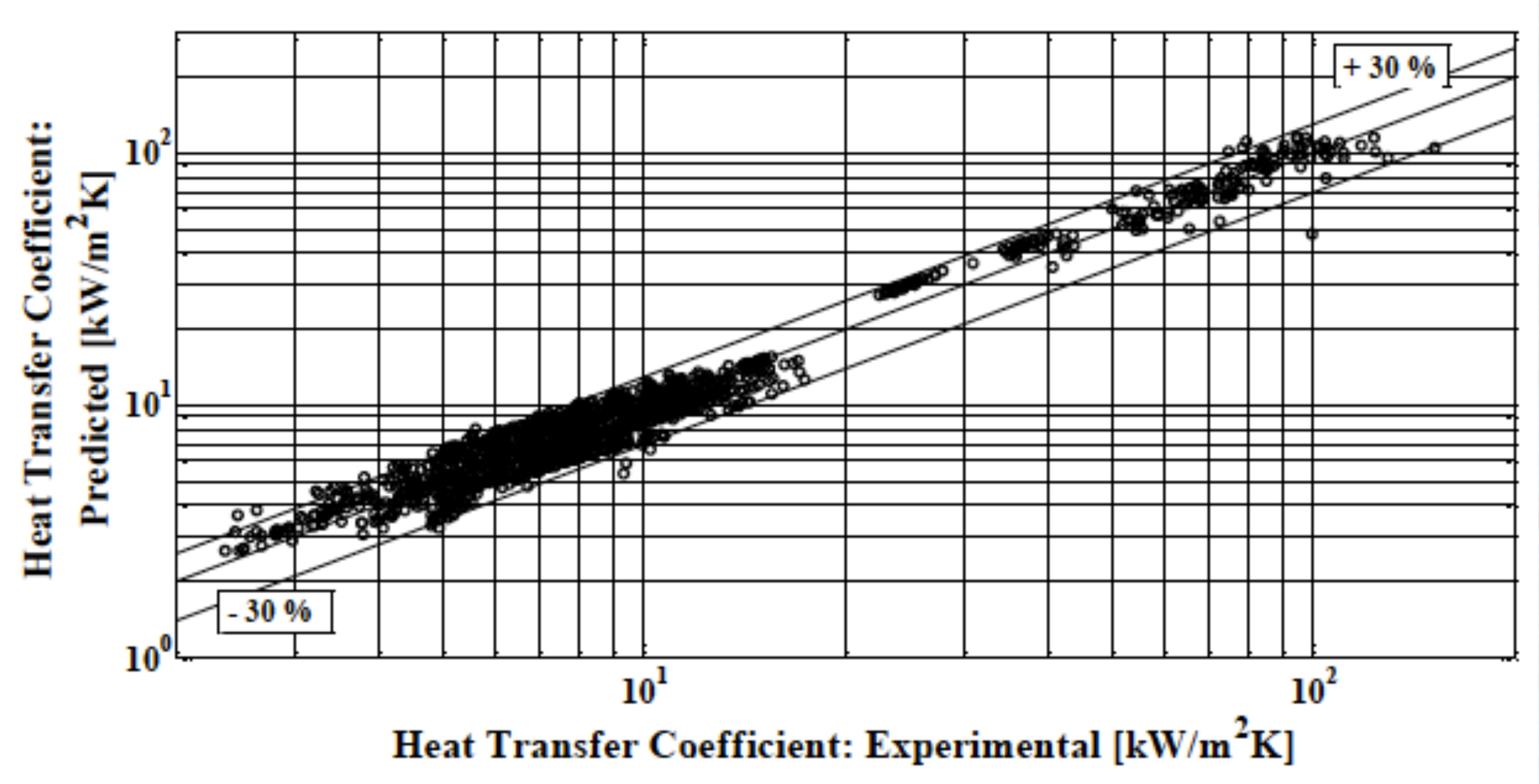
$$1+\alpha_t^+ = \frac{h\,t}{k_l} = Nu = 77.6\cdot 10^{-3}\, t^{+\,0.90}\,\Pr_l^{0.52};\quad 10 \le t^+ \le 800;\quad 0.86 \le \Pr_l \le 6.1 \qquad (27)$$

where h is the convective boiling heat transfer coefficient and Nu is a Nusselt number based on the average liquid film thickness t. As can be seen, the turbulent eddy diffusivity α_t^+ as modeled in Eq. (24) can be interpreted as a Nusselt number for the evaporating liquid film, thus providing a simple and explicit estimate of the heat transfer coefficient. Besides, as the dimensionless liquid film thickness t^+ can be interpreted as a Reynolds number for the liquid film, with the velocity wall scale V^* as characteristic velocity and the average liquid film thickness t as characteristic dimension, Eq. (27) is formally analogous to a Dittus-Boelter like heat transfer correlation. It is worth emphasizing that this method has been developed assuming no nucleate boiling occurs in the annular liquid film.

$$t^+ = \max\left(\sqrt{\frac{2\,\Gamma_{lf}^+}{R^+}},\, 0.066\,\frac{\Gamma_{lf}^+}{R^+}\right);\quad \frac{\Gamma_{lf}^+}{R^+} = \frac{(1-e)(1-x)\,\Gamma}{2\,\pi\,\mu_l\,R} = (1-e)(1-x)\,\frac{G\,d}{4\,\mu_l}$$

OUR UNIFIED MODEL: CONVECTIVE BOILING MODEL

Convective evaporation in annular flow: comparison to database shows no evidence of a macro-to-microchannel transition in the predictions!



OUR UNIFIED MODEL: CONVECTIVE BOILING MODEL

Convective evaporation in annular flow: simulations to illustrate unified model