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Two-Phase Cooling of Targets and Electronics for Particle Physics Experiments

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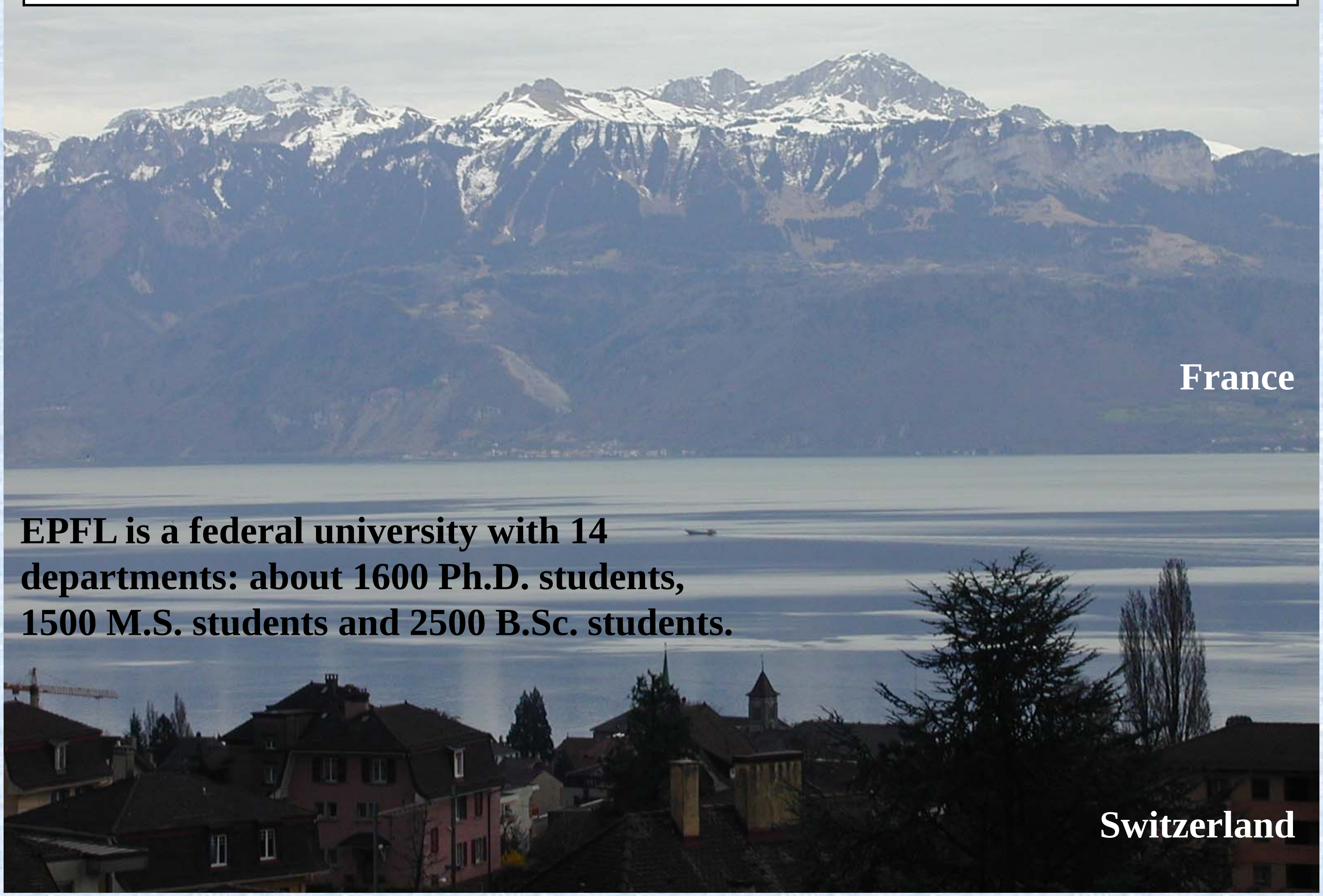
Overview of Lecture, Topics and Sponsors:

Topics to be Addressed:

- **Overview of two-phase cooling of electronics and computer chips.**
- **Videos of boiling in multi-microchannel cooling elements.**
- **Flow patterns in microchannels.**
- **Design considerations to make two-phase cooling work.**
- **Heat transfer in a silicon cooling element with microchannels.**
- **Comparisons of two-phase vs. single-phase cooling of *targets*.**

***Sponsors of Microscale Two-Phase Flow and Heat Transfer at LTCM*:**
Swiss National Science Foundatin, Swiss CTI agency, IBM, ABB, European Madame Curie, European Space Agency, etc.

Lausanne: View of Lake Geneva and Alps



EPFL is a federal university with 14 departments: about 1600 Ph.D. students, 1500 M.S. students and 2500 B.Sc. students.

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Who is the EPFL?: 2009 Shanghai Rankings in Engineering

World Rank	Institution*	Country	Score on HiCi	Score on PUB	Score on TOP	Score on Fund	Total Score
1	Massachusetts Institute of Technology (MIT)		99	78	94	98	100
2	Stanford University		100	65	97	79	92.5
3	University of Illinois at Urbana-Champaign		63	73	89	91	85.8
4	University of California, Berkeley		77	71	90	70	83.6
5	Carnegie Mellon University		53	55	90	100	81.1
6	University of Michigan - Ann Arbor		61	69	90	77	81.0
7	The University of Texas at Austin		73	63	86	71	79.8
8	Georgia Institute of Technology		35	81	86	91	79.7
9	University of California, San Diego		68	58	90	75	78.9
10	Pennsylvania State University - University Park		69	68	84	70	78.8
11	University of Southern California		60	51	91	83	77.4
12	California Institute of Technology		73	53	97	57	75.9
13	University of California, Santa Barbara		80	48	100	50	75.6
14	University of Maryland, College Park		56	60	82	79	75.3
15	Swiss Federal Institute of Technology of Lausanne		55	62	87		73.8
15	University of Cambridge		55	63	86		73.8

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Brief Description of LTCM Laboratory

Staff: (about 21 researchers not counting M.S. students)

- **currently 14 Ph.D. Students and 3 M.S. students.**
- **6 post-doctoral reseachers.**
- **2 technicians available more or less full time from pool.**
- **1 prof. plus 2 secretaries.**

Test facilities: (*all with flow visualization*)

One multi-channel microscale flow boiling test facility;
Second multi-channel microscale flow boiling facility at IBM (CH);
One single-channel microscale flow boiling test facility;
One multi-microchannel condensing test facitity;
Air-water micro-channel and macro-channel test facilities;
One macrochannel flow boiling test facility for macroscale flows;
One falling film boiling and condensation test facility;
One tube bundle boiling test facility;
One micro-PIV test setup to measure velocity profiles in one/two-phase flows;
3 high speed digital cameras (one up to 120k Hz) and 3 IR cameras.

Website of My Free Web e-Book on Heat Transfer:

***Engineering Data Book III*:**

a free e-book at website

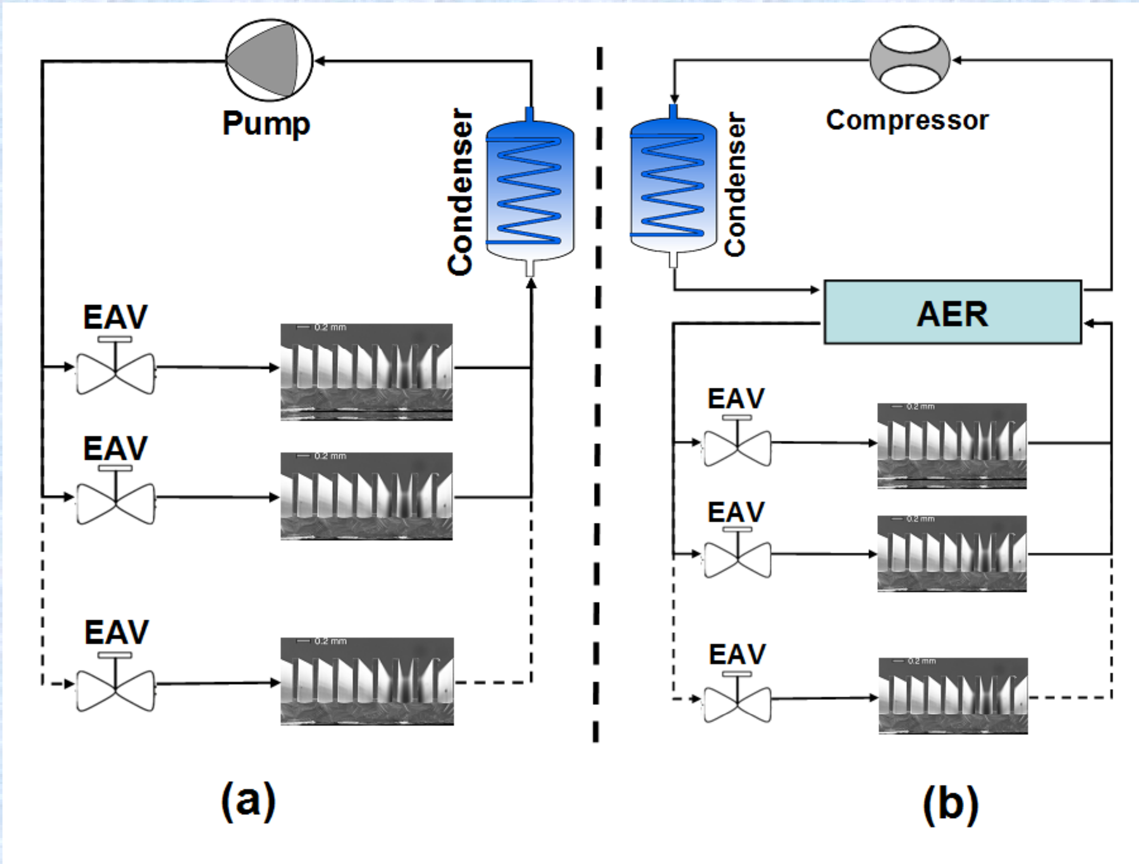
www.wlv.com

Then go to the online book page. It includes 20 chapters on micro and macro scale single-phase and two-phase flow and heat transfer, over 200 videos in Chapter 1, an Excel calculation program, etc.

Desired Attributes of CO2 Two-Phase Target Cooler

- ✓**Low mass cooler (use microchannels in silicon)**
- ✓**Low mass of coolant (two-phase fluid achieves this)**
- ✓**Remove heat effectively (high h.t.c. for boiling fluid)**
- ✓**Temperature uniformity (achievable)**
- ✓**Cool hotspots (achievable)**
- ✓**Stable flow (achievable *but* requires dedicated attention)**
- ✓**Handle transient heat fluxes (okay but requires study)**
- ✓**Handle low temperatures (no problem for CO2)**
- ✓**Work at low pressures (not feasible with CO2)**
- ✓**Use stable non-corrosive fluid with long life (CO2 is fine)**
- ✓**Very thin cooler design (channel heights limited)**

Liquid Pumped & Heat Pumped Two-Phase Systems



Left: Pump-based system; Right: Compressor-based system. EAV refers to electronic actuated valve, AER refers to accumulator, heat exchanger and receiver components.

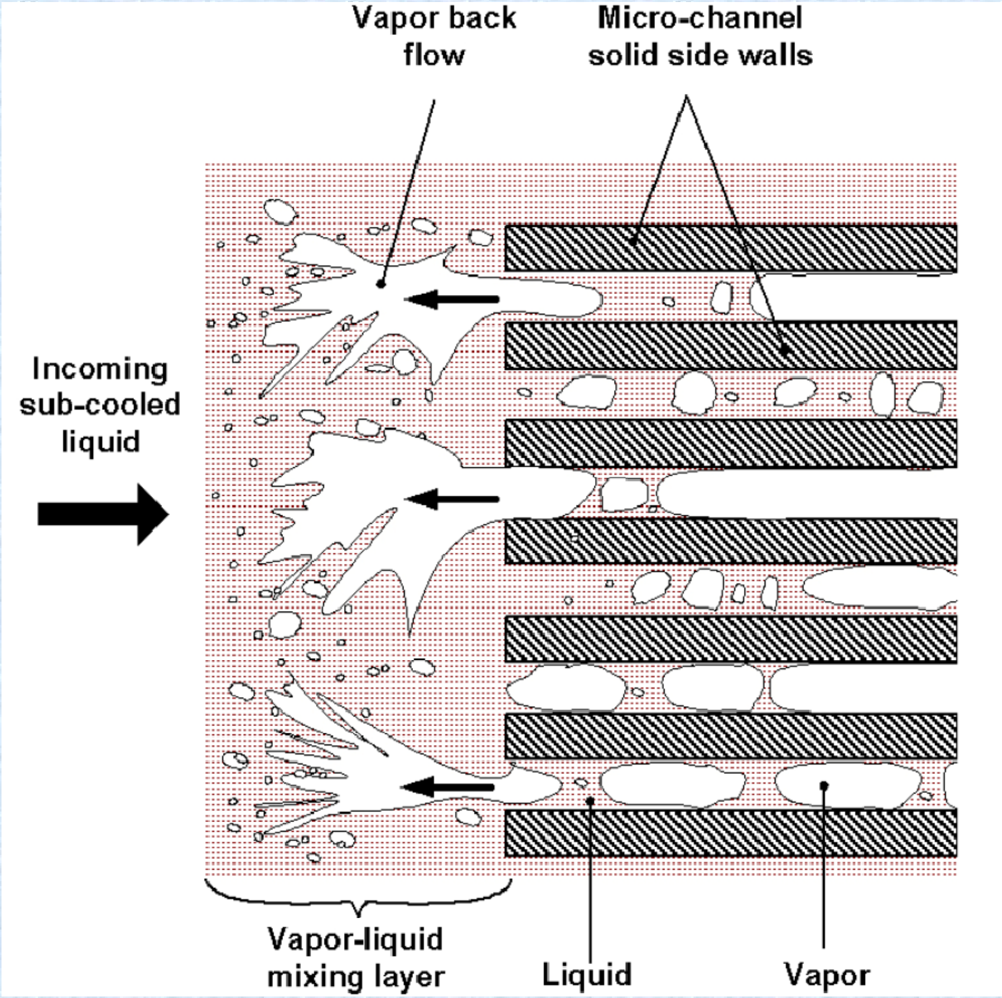
Models Required for Design of Micro-Evaporators

- Flow boiling model and flow pattern map: LTCM has 3-zone model and flow map.
- Two-phase pressure drop and void fraction models for microchannels: Must cover laminar, transition and turbulent regimes for circular and rectangular channel shapes. LTCM has 1-d turbulence model for annular microchannel flows.
- CHF model for circular/non-circular, single and multi-channel heat sinks: LTCM has theoretical and empirical methods and is improving them.
- Stable two-phase flow with large scale instabilities: LTCM has method that stabilizes flow in our test sections with up to 134 parallel channels.
- 3-d numerical modeling of conduction in heat sinks: commercial codes are okay.
- Temperature overshoots at startup: LTCM has limited data and a passive method to avoid overshoot, and has patented an active method to avoid them.
- Numerical model to simulate distribution of single and two-phase flows in the inlet and outlet headers: LTCM is working on this.
- Transient simulation capability and hot spots: LTCM has limited data on first topic; has first method to simulate CHF at hot spots and just now first data too.
- Comprehensive simulation tool has been developed within LTCM.

Backflow/Instability in Parallel Microchannels:

Qu and Mudawar (Purdue) diagram: backflow into inlet header, flow maldistribution and unstable flow.

Needs solution!



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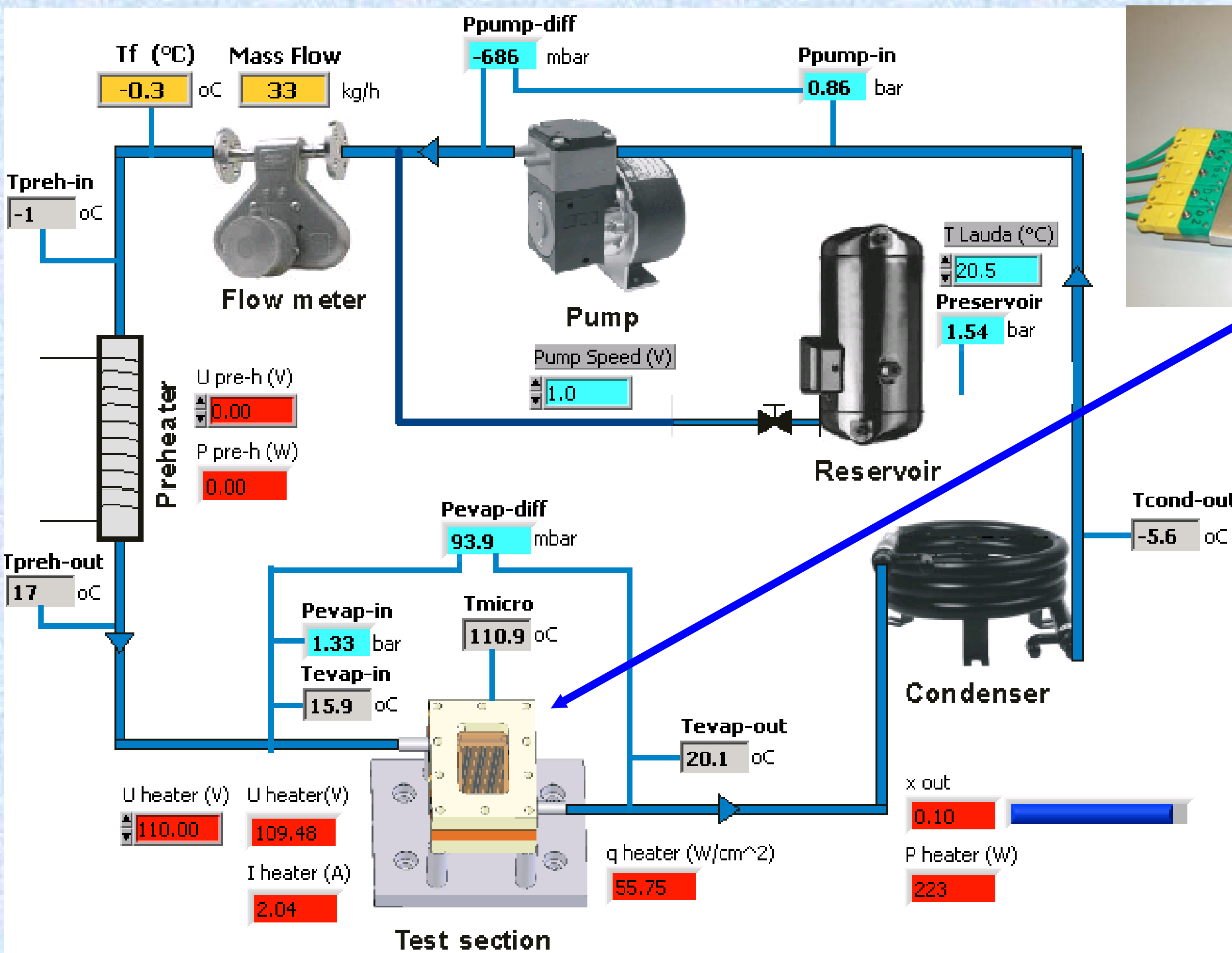
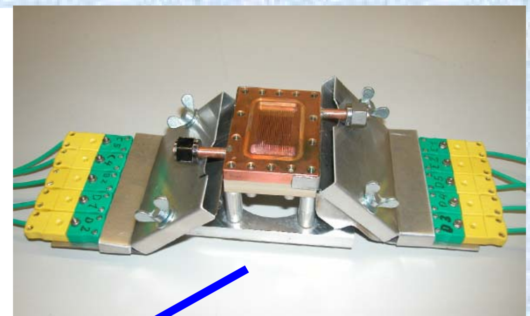
CPU Multi-Microchannel Flow Boiling Test Facility





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).

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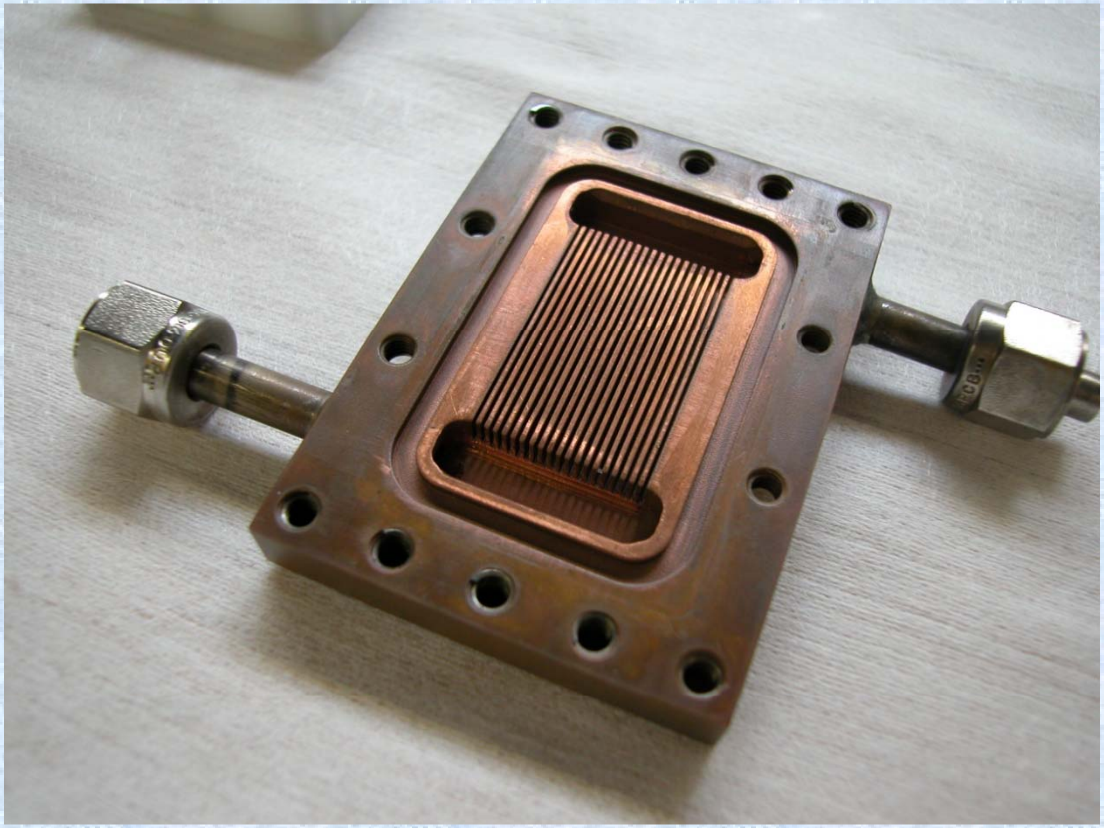
CPU Microchannel Flow Boiling Cooling at LTCM



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*).

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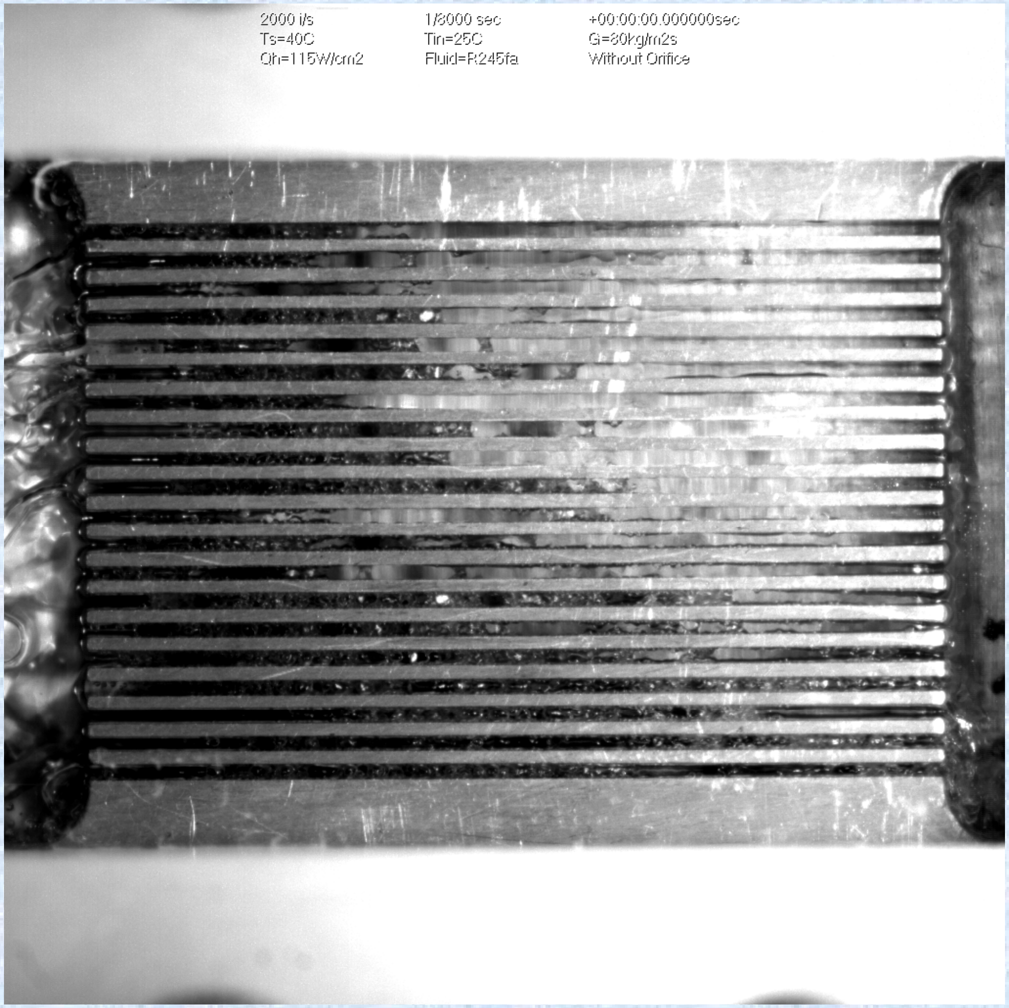
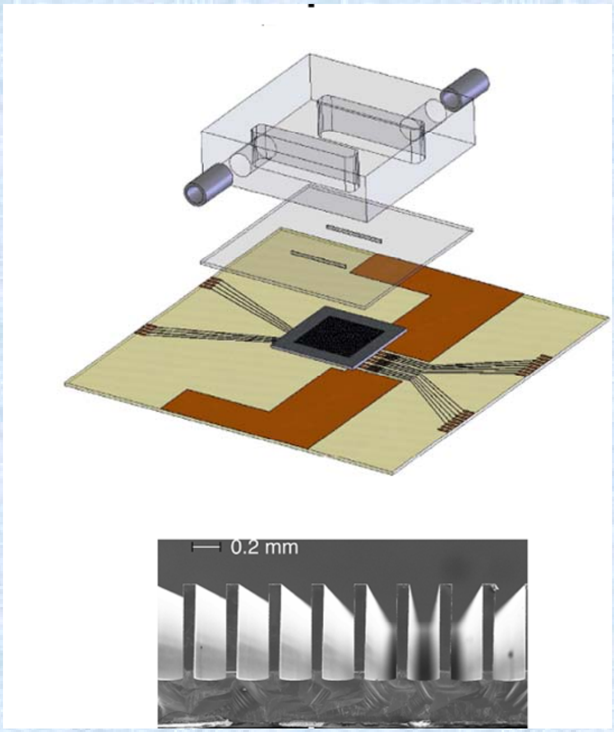
Video at High Heat Flux in Copper: Poor Flow Distribution

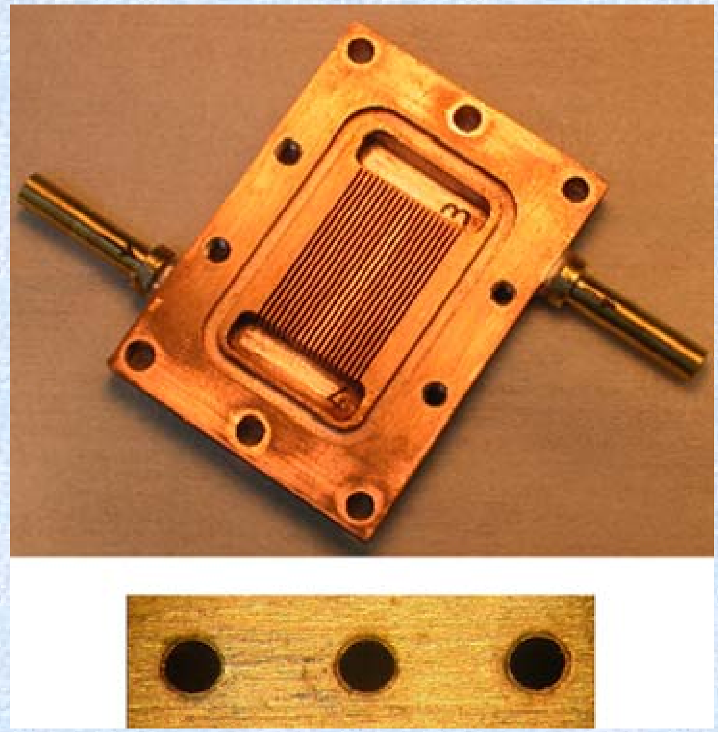


Maximum heat flux dissipation possible is only about 115 W/cm^2 (as a result of mal-distribution and back flow, there is over heating in liquid starved/ dry area!). Video of LTCM.

Micro-Evaporators: Basic Geometry and Flow Stabilization



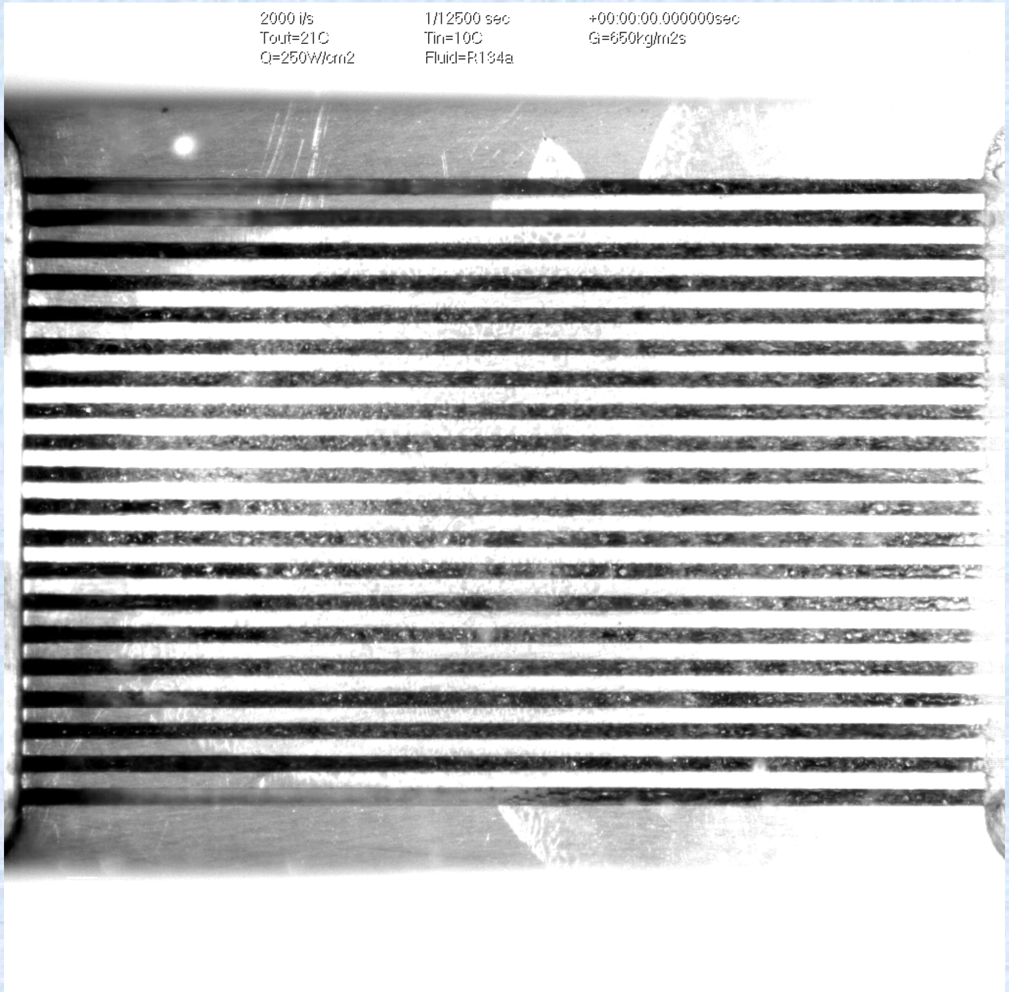
(a)



(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.

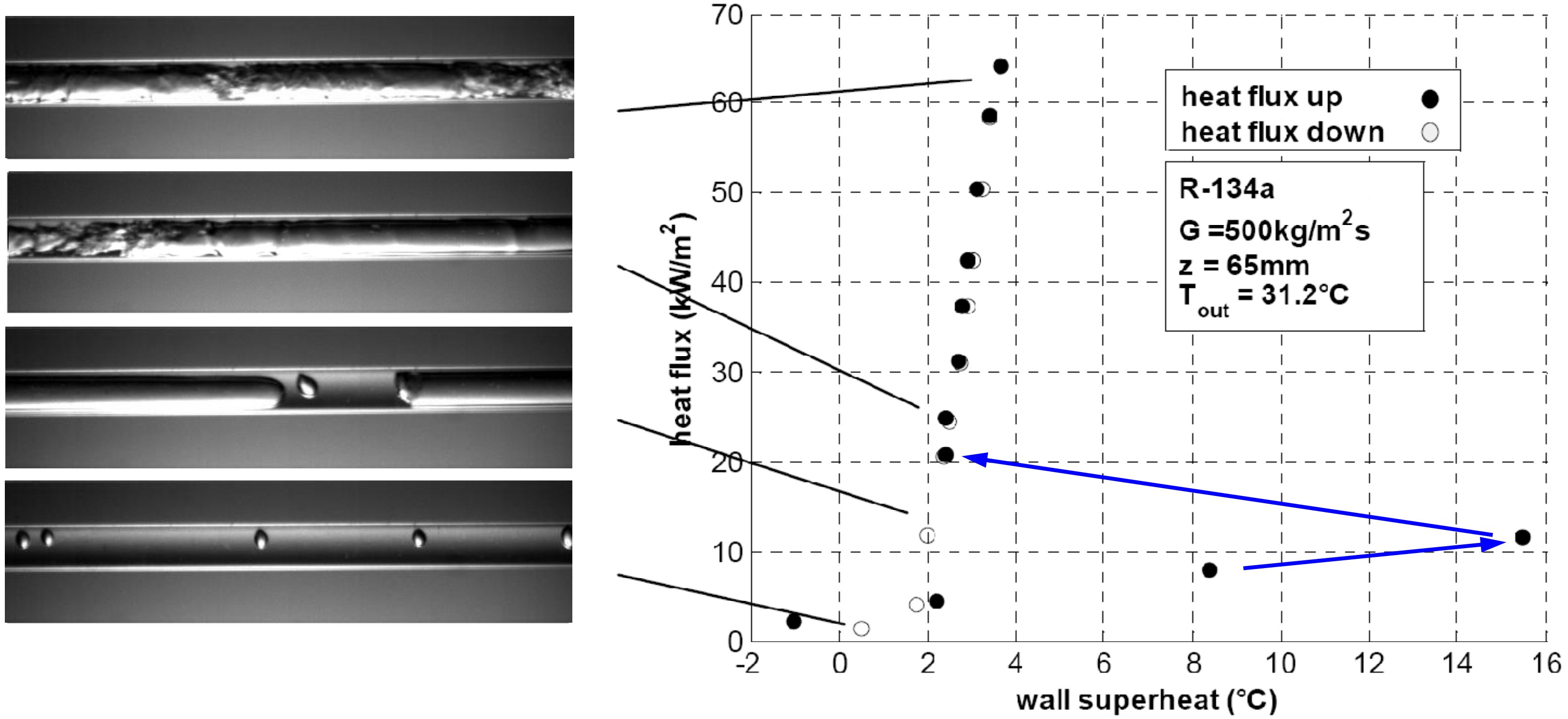
Video at High Heat Flux in Copper: Good Flow Distribution



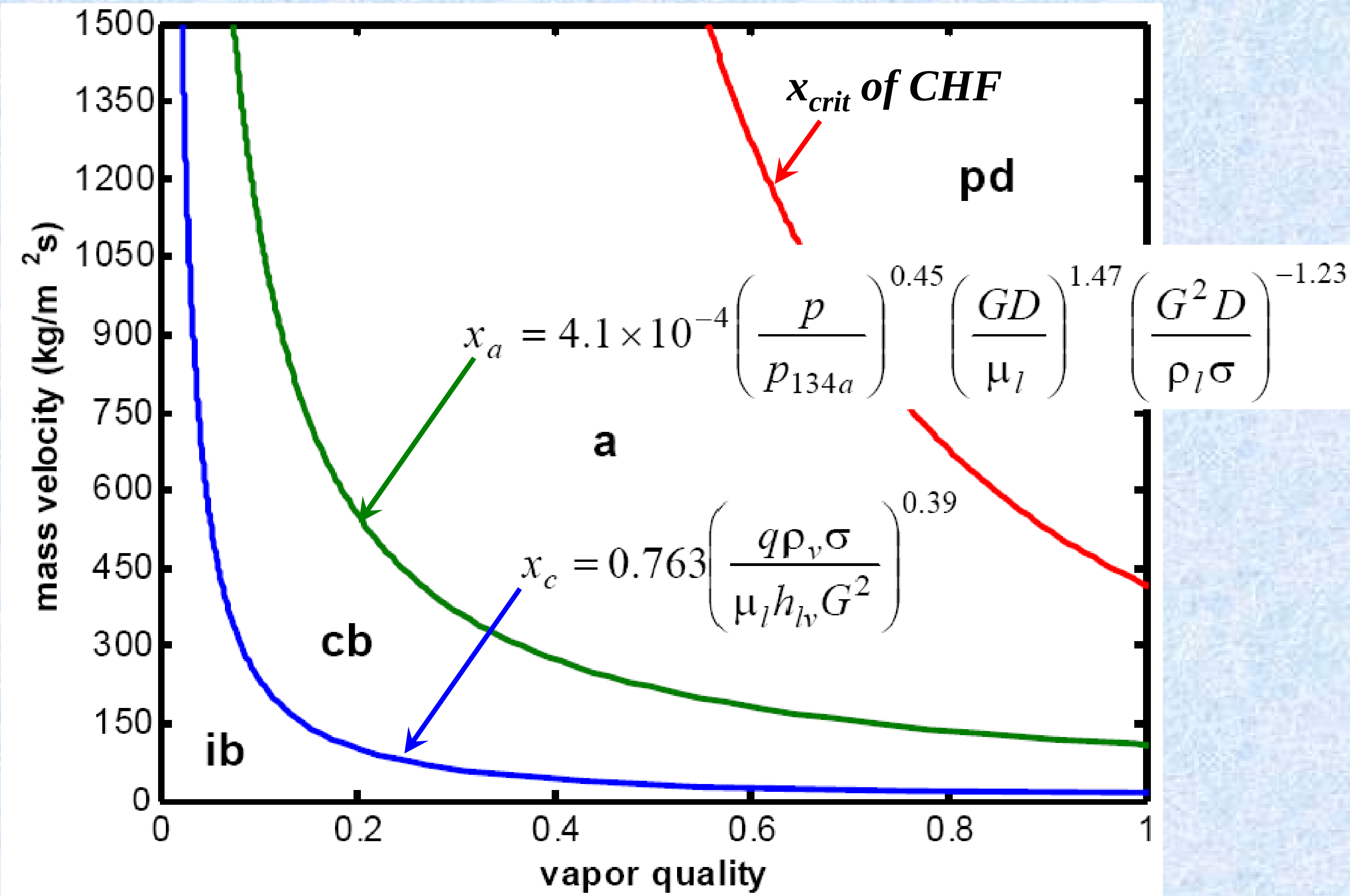
Maximum heat flux dissipation possible is at least 340 W/cm^2 using inlet flow restrictions to prevent back flow and create uniform flow distribution (shown here at 250 W/cm^2 at 2000 images/sec). Video of LTCM.

Microchannel Boiling Curve versus Flow Patterns

Flow Patterns in a 0.5 mm Diameter Channel: Videos at exit of microchannel & boiling data from Consolini Ph.D. thesis at EPFL (2008).



Microscale Map of Ong-Thome-Revellin 2009



Microscale Map of Ong-Thome-Revellin 2009

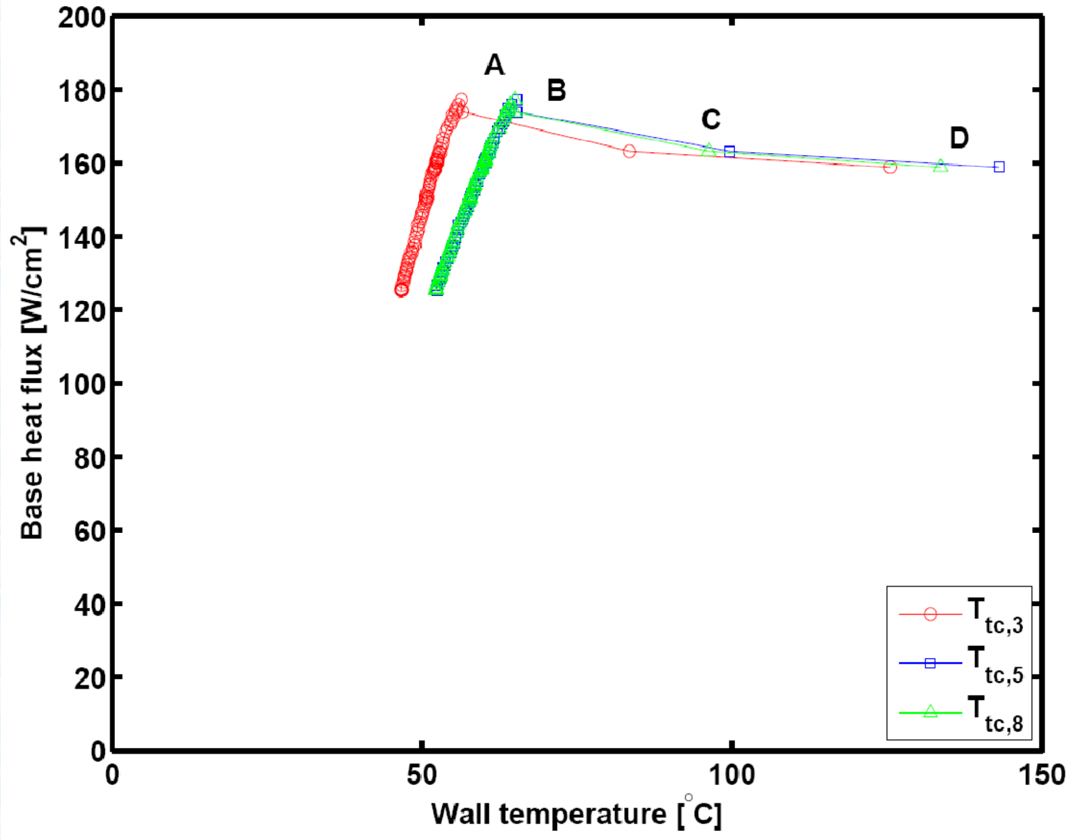
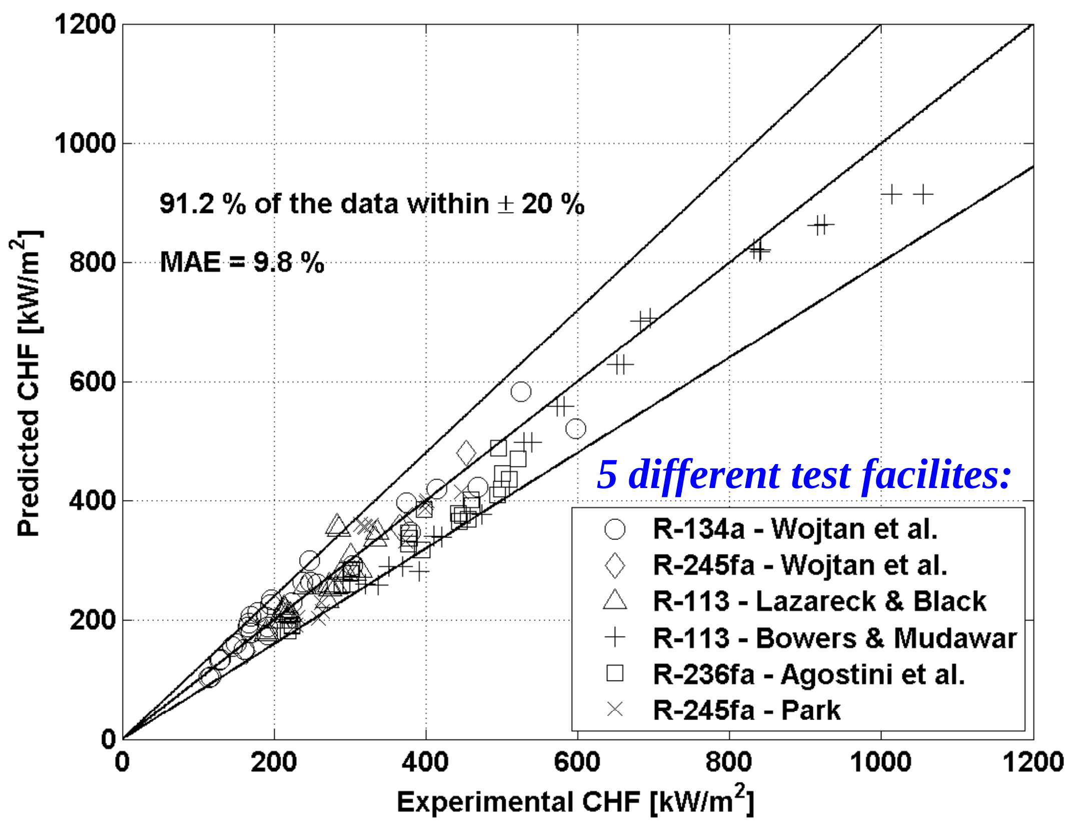
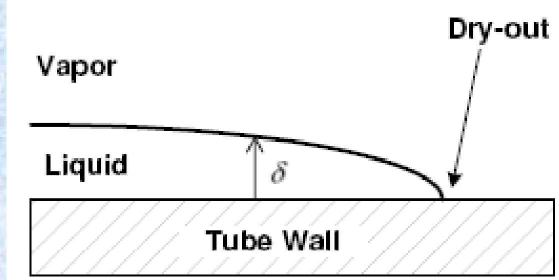


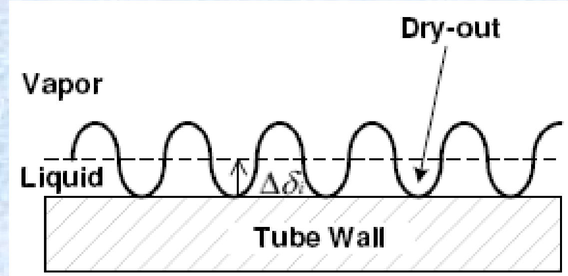
Figure 11: Flow boiling curve measured at three different positions along the channel showing the onset of critical heat flux from Park [13] for R134a.

Revellin-Thome CHF Model for Microchannels: IJHMT'2007



Solving 1-d conservation equations for an annular flow and expression for wave height, solution gives location of CHF:



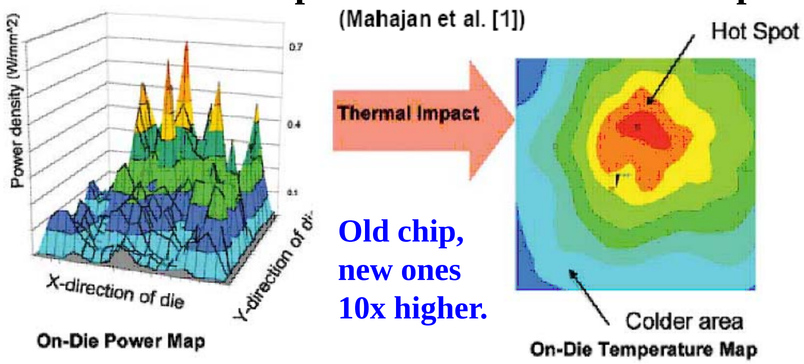


$$\frac{\Delta\delta_i}{R} = 0.088\left(\frac{u_V}{u_L}\right)^{-3/5}\left(\frac{(\rho_L-\rho_V)\,g\delta^2}{\sigma}\right)^{-1/5}$$

$$\Delta\delta_i = \delta$$

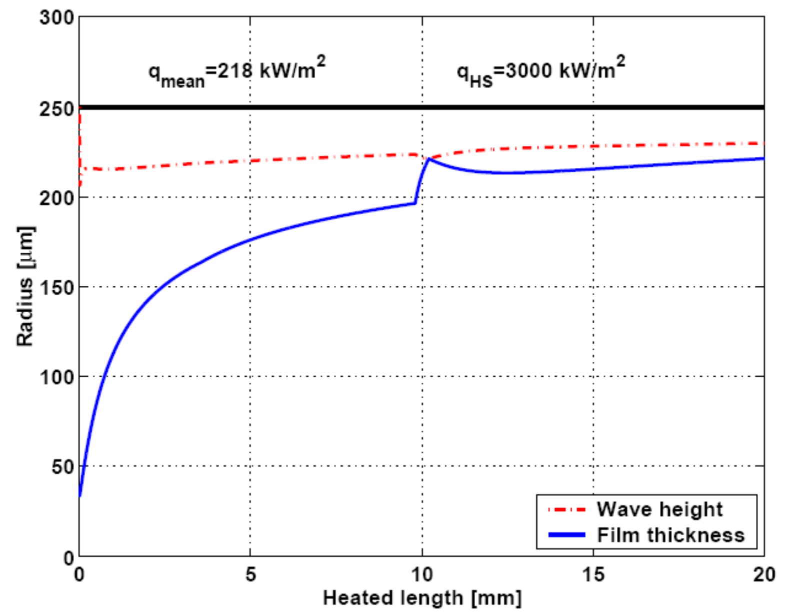
Analysis of CHF of Hotspots on Computer Chips

Heat flux/ temperature distribution on chip.



Old chip, new ones 10x higher.

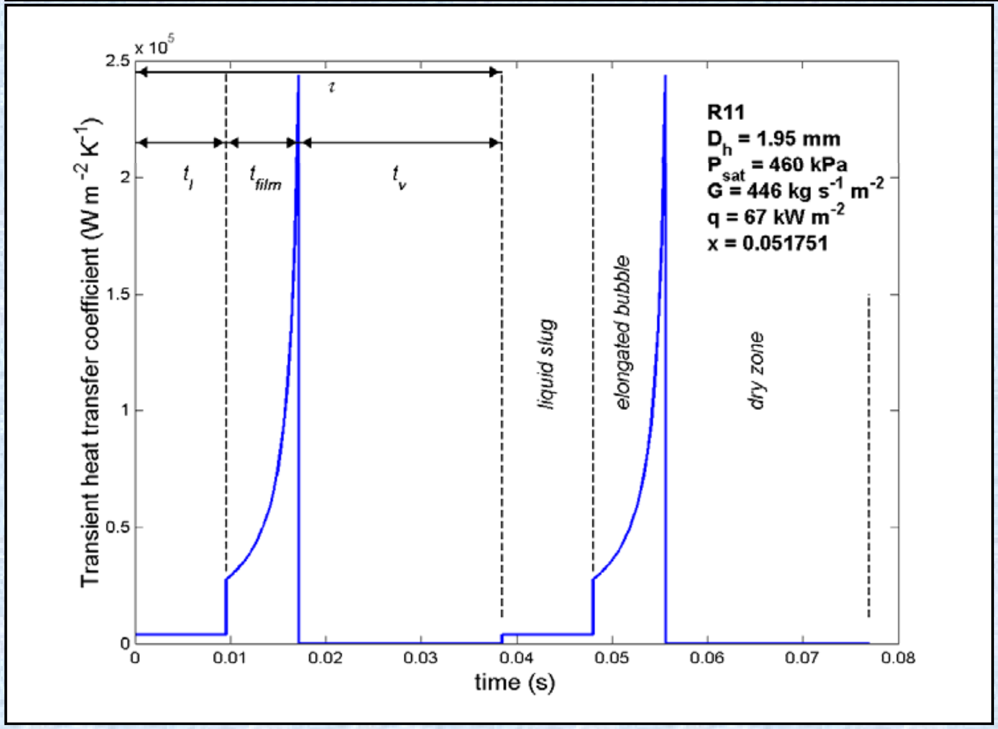
Revellin-Thome (2007): 1-d numerical model applied to prediction of local CHF at hotspots in micro-channels with micro-scale boiling.



(e) $q_{HS} = q_{HS,\,max} = 3000\ \mathrm{kW/m^2}$. Dryout occurs at the hot spot location.

Hot spot heat flux as a function of the hot spot size located at the midpoint along the circular microchannel for D=0.5 mm, G=500 kg/m^{2}s, T_{sat}=30°C, L_{MEV}=20 mm and the local hot spot situated at the midpoint along the microchannel.

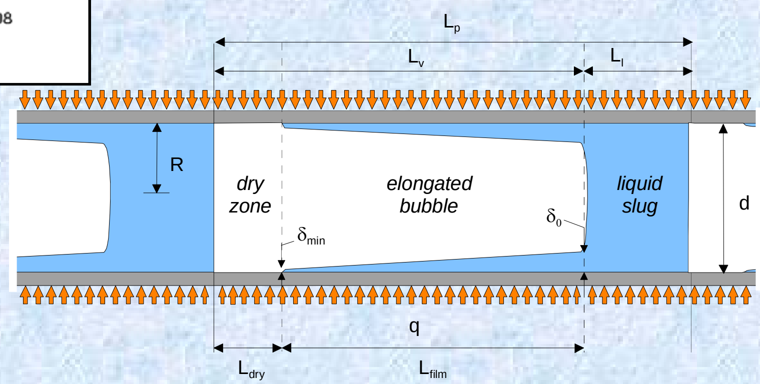
Local time averaged heat transfer flow boiling model



Three-zone flow boiling model of Thome, Jacobi and Dupont: time averaging of dynamic heat transfer coefficients gives local heat transfer coefficient (7 fluids from 7 labs in original data base, now 5 more fluids).

(in Int. J. Heat Mass Transfer, 2004)

$$h(z) = \frac{t_l}{\tau} h_l(z) + \frac{t_{film}}{\tau} h_{film}(z) + \frac{t_{dry}}{\tau} h_v(z)$$



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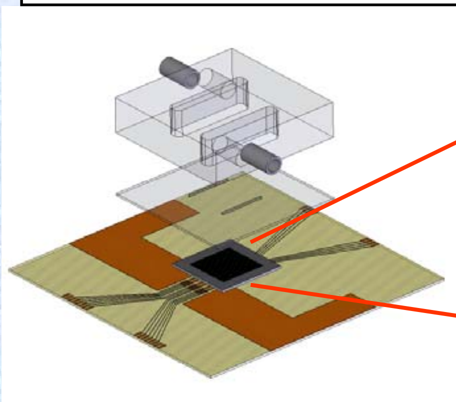
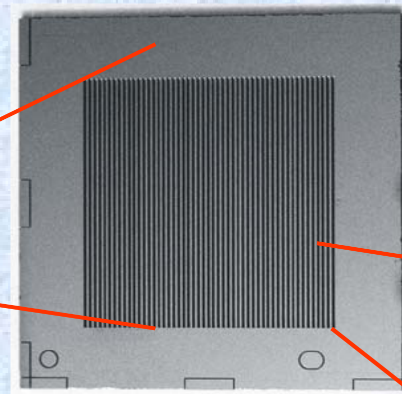
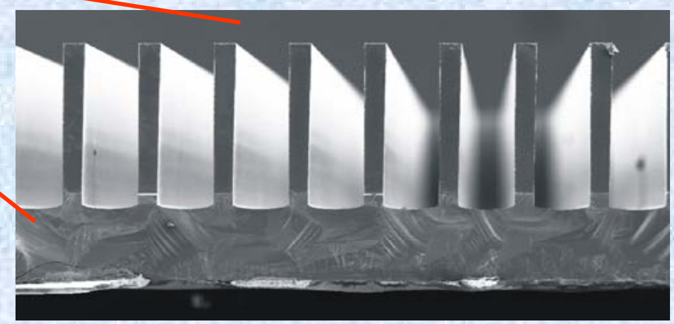
LTCM/IBM Micro-Evaporator Test Section in Silicon

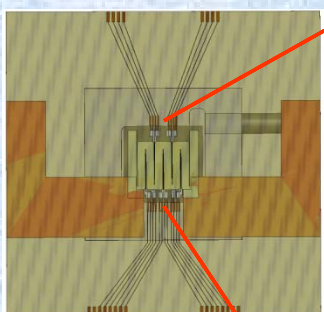


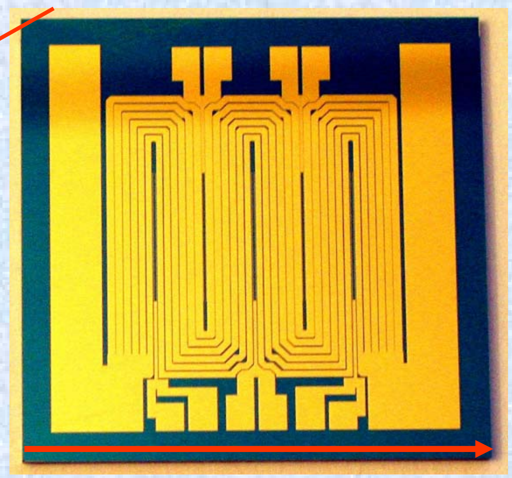


Si microchannel evaporator:

- Channel widths: 200, 100, and 50 microns
- Manifolds: One inlet/one outlet or one inlet/two outlets
- Slit inlet avoids instabilities and generates bubbles to avoid temperature overshoot
- Can be bonded to top of microprocessor





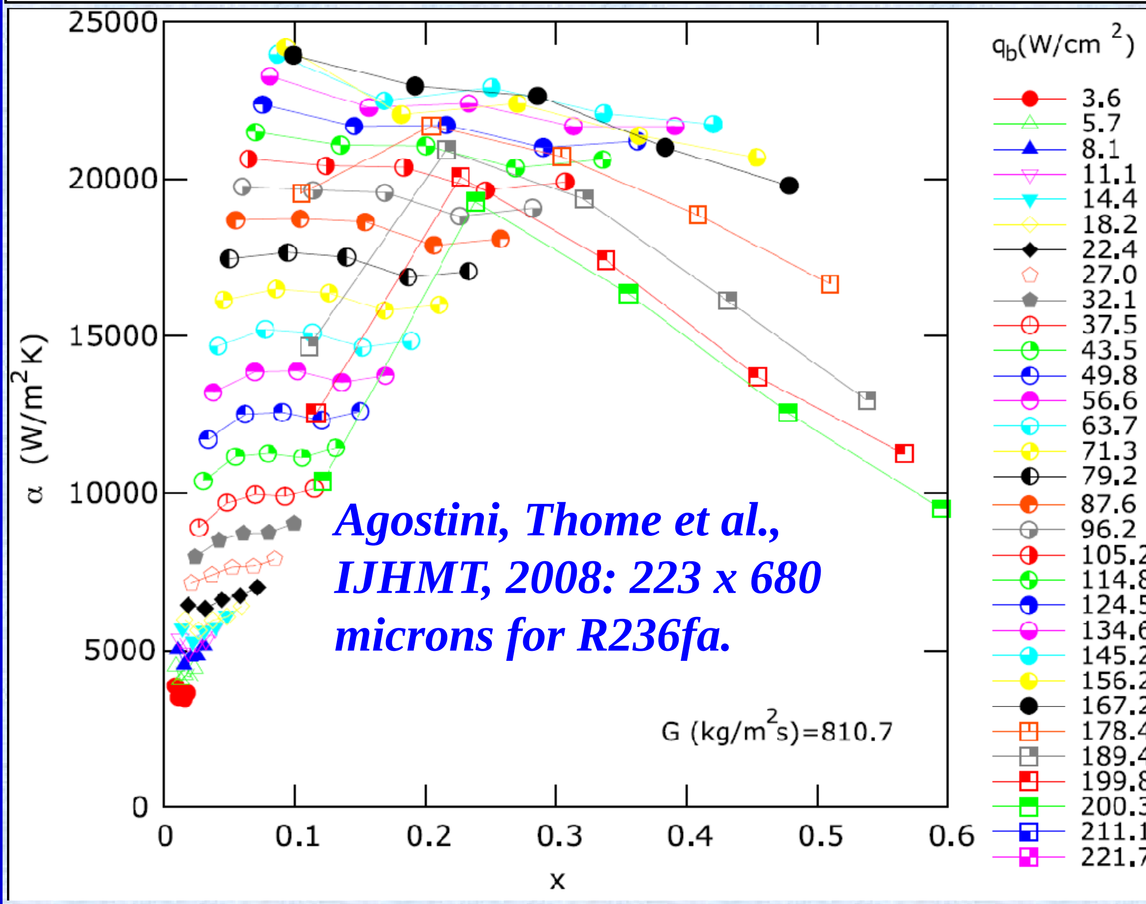


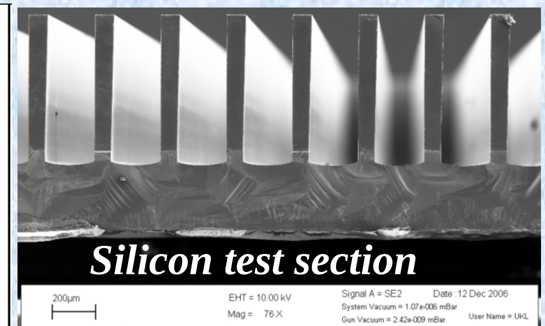
(red arrow) Channel Orientation on backside of chip

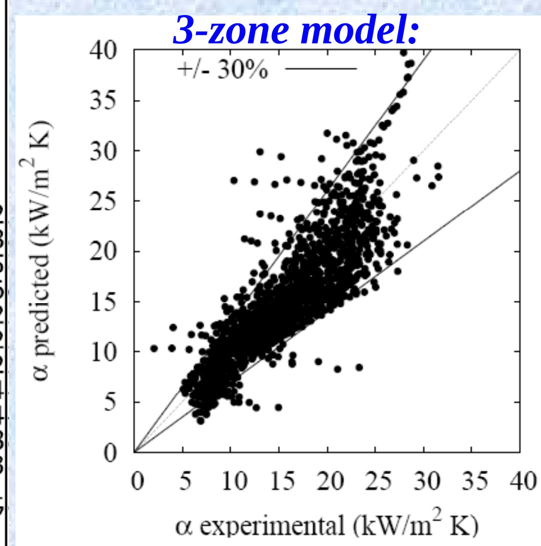
Cobra Heater on backside of silicon chip

- Simulates heat dissipated by microprocessor or electronics
- Better measurement accuracy
- Lower thermal resistance to evaporation surface
- 5 RTD sensors along channel length, span across 1/3rd of width

LTCM/IBM Silicon Test Section: Results/3-Zone Model







Above graph shows some local heat transfer data based on effective area plotted with heat flux based on footprint area indicated (up to 2.11 MW/m^2)…footprint based boiling heat transfer coefficients go over 100'000 W/m^{2}k using a *refrigerant,* not *water.*

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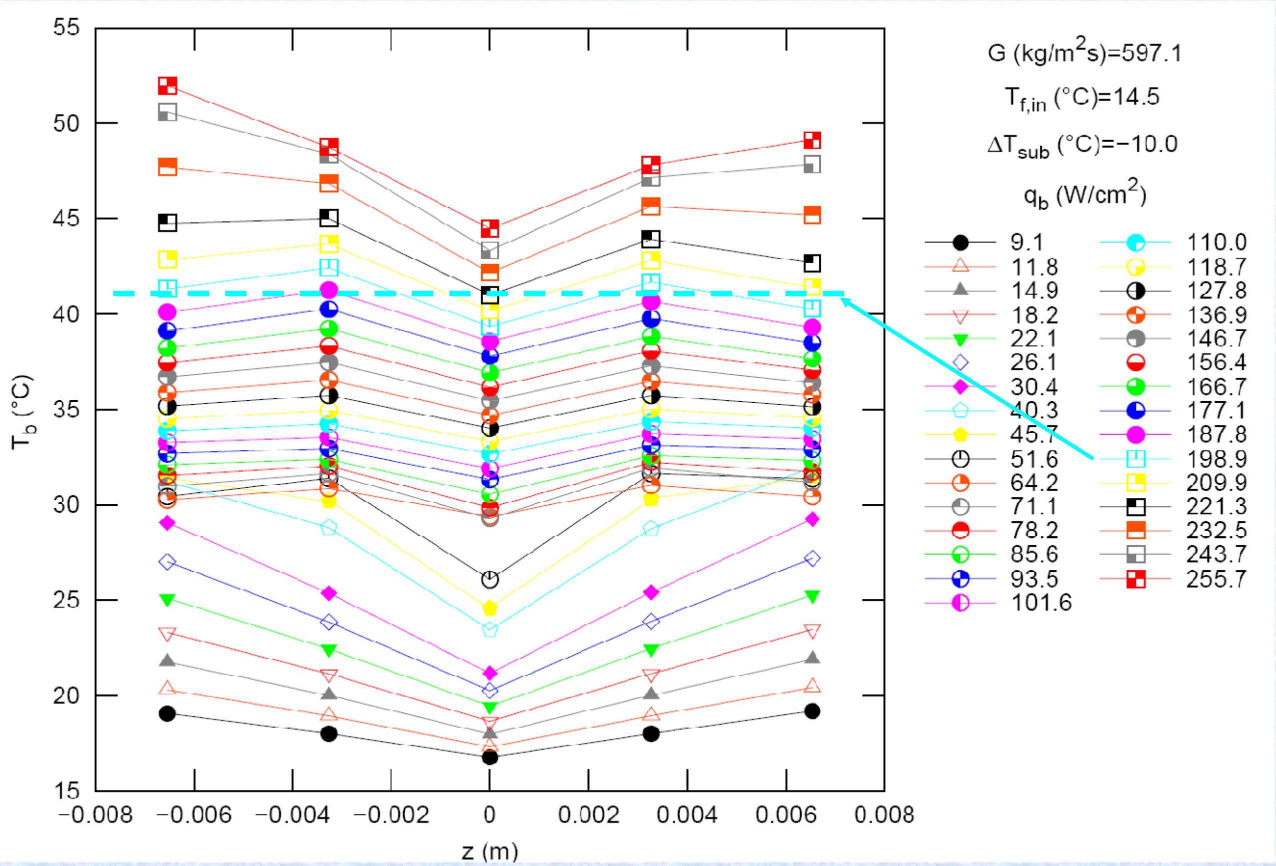
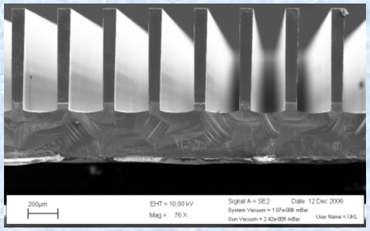
LTCM/IBM Silicon Test Section: Temperatures





***IEEE Trans. on Components and Packaging Technologies*, 2008: featured on cover of the journal.**

Above graph shows some local base temperatures at various heat fluxes with one inlet and two outlets (up to 256 W/cm^2). CHF not reached with this test section with 134 channels. Notice the nearly uniform, low temperatures that can be achieved.

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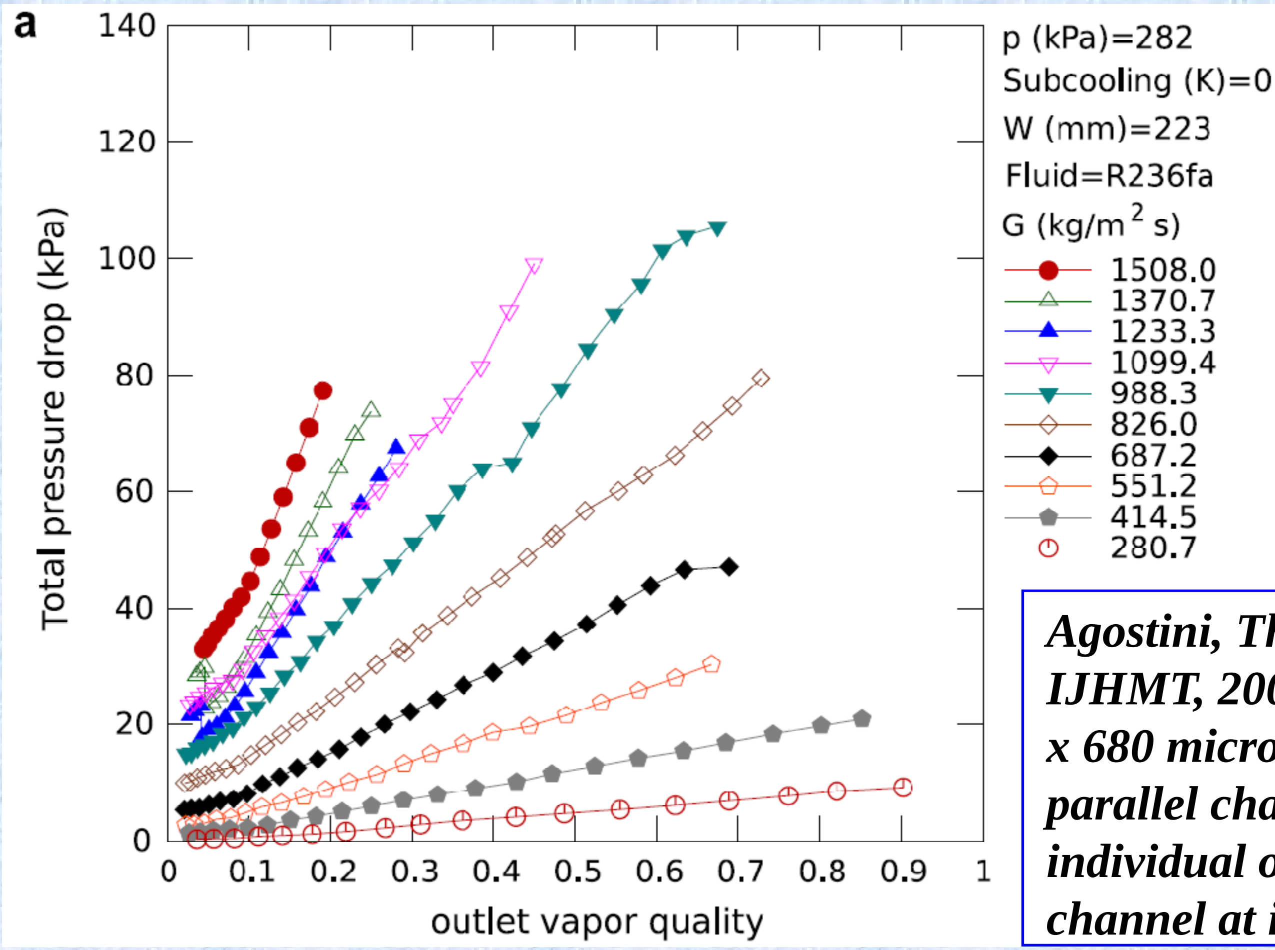
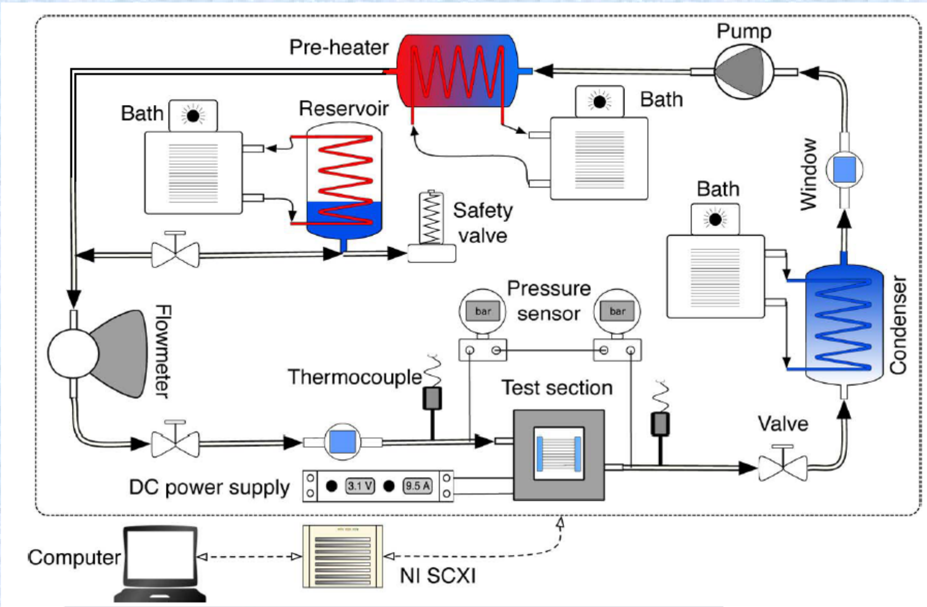
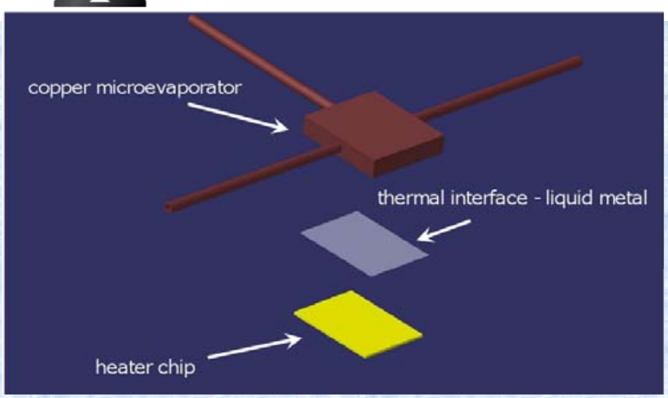
Two-Phase Pressure Drops in Parallel Channels



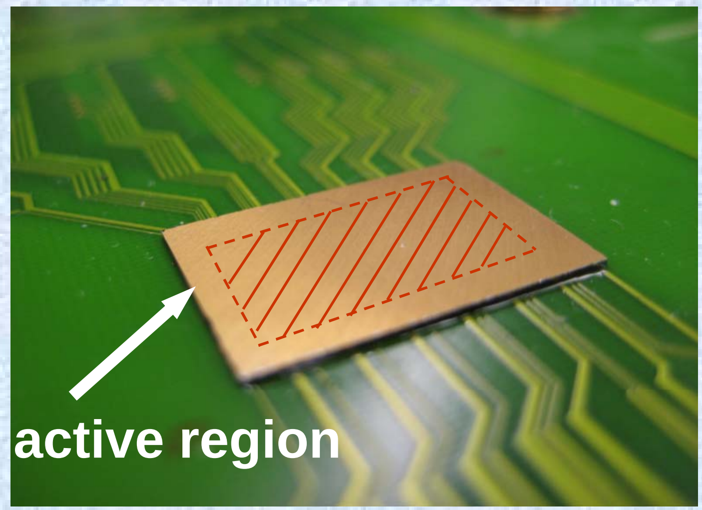
Agostini, Thome et al., IJHMT, 2008, Part 3: 223 x 680 micron channels (67 parallel channels) with individual orifices for each channel at inlet and outlet.

LTCM M.S. Thesis of Madhour: Test Section & Results

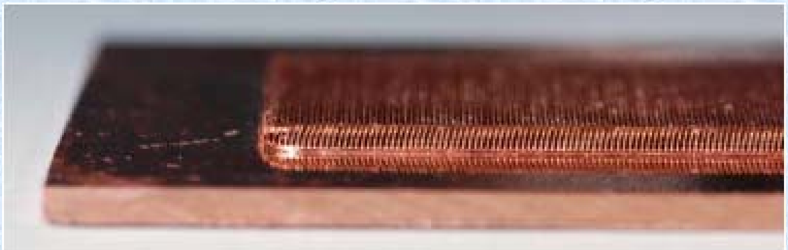


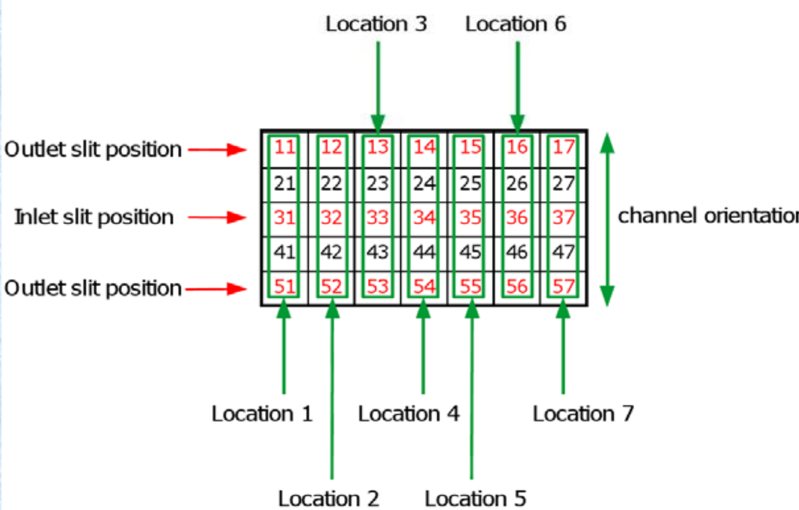


M.S. thesis work and test facility to be used for new PhD thesis work at IBM

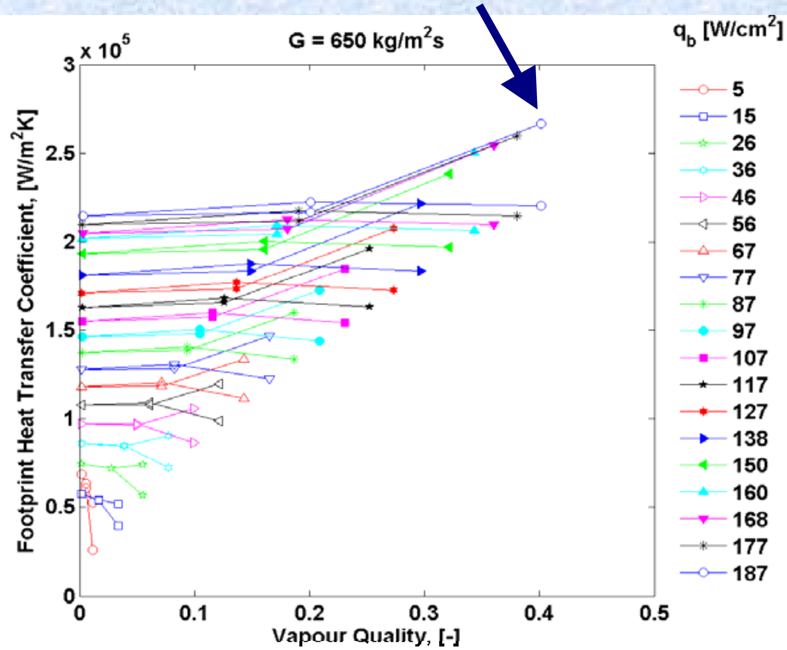


M.S. Thesis of Madhour: Test Section & Results: 35 local heaters and 35 temperature sensors

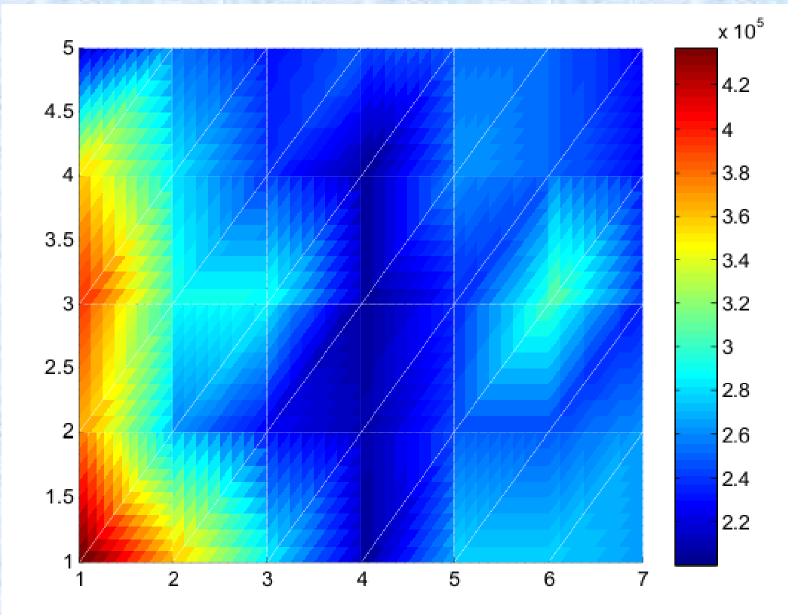




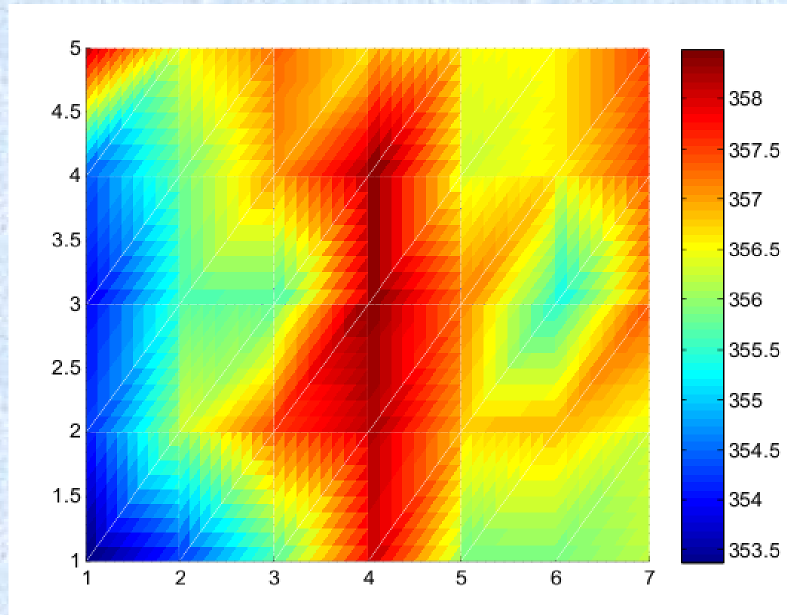
Footprint h.t.c.'s up to 270'000 W/m²K for high aspect microchannels and h.t.c.'s increase with heat flux



M.S. Thesis of Madhour: Test Section & Results



Footprint heat transfer coefficient map [W/m2K]. Mass velocity of 1000 kg/m^{2}s, qb = 184 W/cm^2.



Heater chip surface temperature map [K]. Mass velocity of 900 kg/m^{2}s, qb = 182 W/cm^2 .

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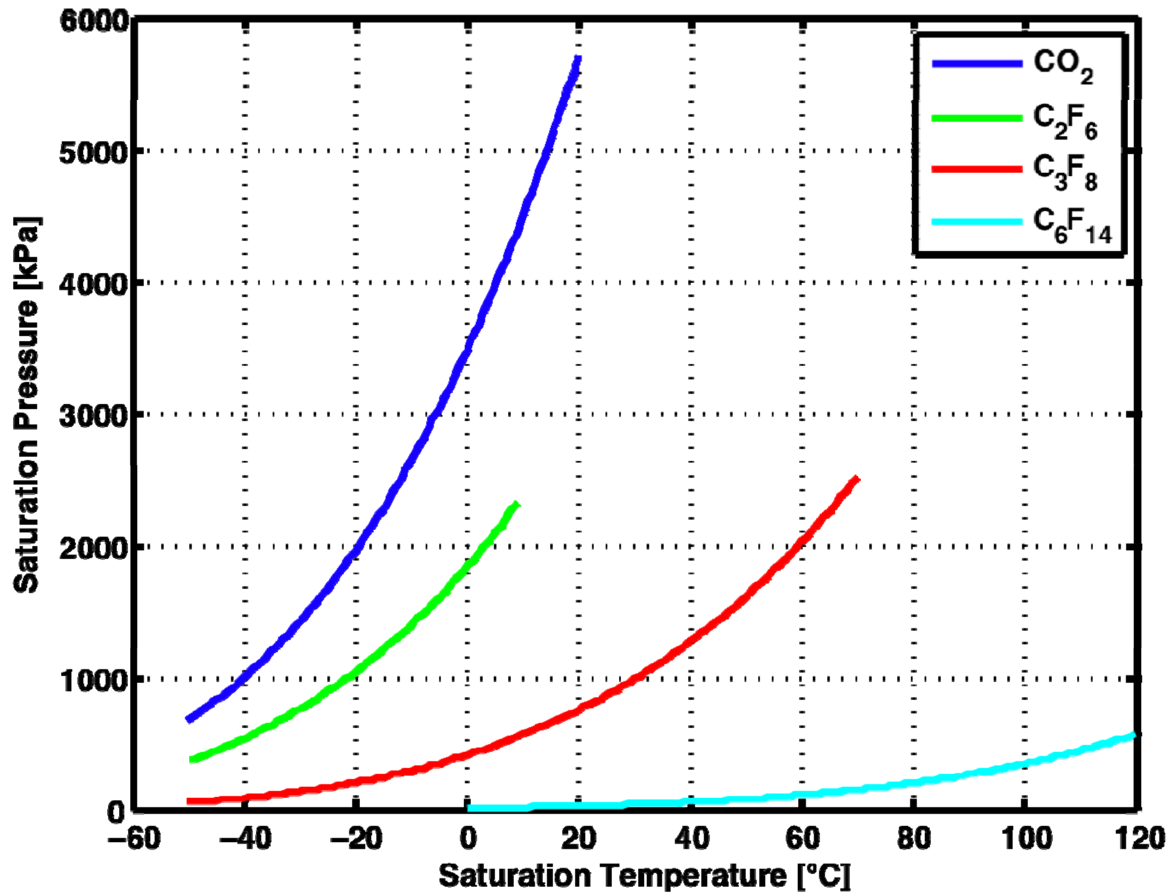
Saturation Pressure Curves of Radiation Hard Fluids



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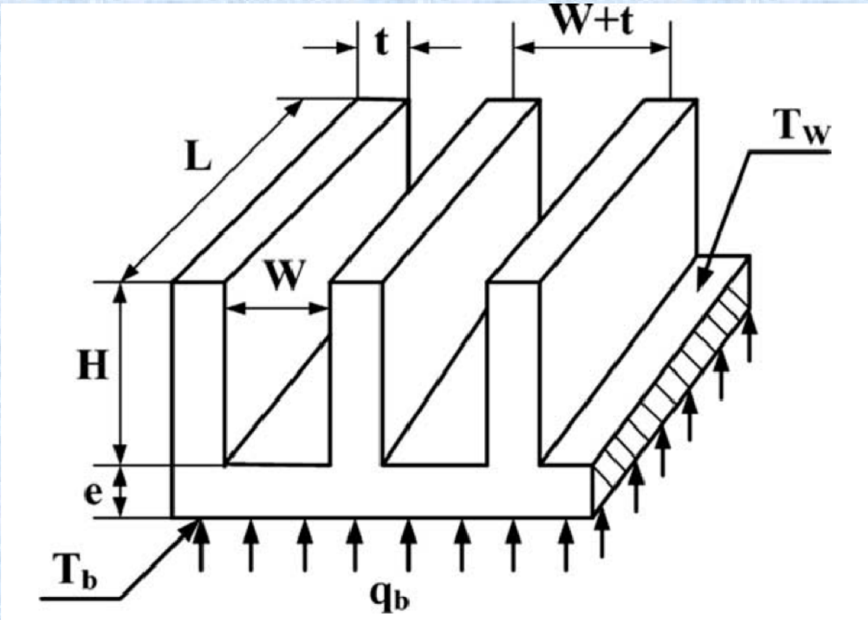
Simulation of Micro-Evaporator Performance of CERN GigaTracKer: Geometry and Dimensions



Parametric study

In all cases, the base thickness, *e*, will be zero, thus showing a best-case scenario as any additional material added can be accounted for in separate calculations.

The GTK should not see a temperature difference along its length of more than 5˚C while being kept as cold as possible (~ -30˚C).

Assumptions made for the present simulations are: (*1*) the evaporator is uniformly heated from the bottom with a base heat flux of q_b, (*2*) the flow through the cooler is uniformly distributed between all the channels, (*3*) the top of the cooler is adiabatic and (*4*) for two-phase flow, no inlet subcooling is used. Cooler is 60mm by 30mm long.

Simulations for Development of CERN GigaTracKer

The models used for single-phase heat transfer and pressure drop are those from Shah and London, while the three-zone model and homogeneous model were used for the two-phase heat transfer and pressure drop, respectively.

The fluids to be simulated are radiation-hard fluorocarbons and CO_2:

•For temperatures below -10˚C, the best choice of fluid would be between CO_2 and C_2F_6 but possibly also C_3F_8.

•The most common cooling fluid used at CERN is C_6F_{14} and is used in single-phase flows only. This fluid is not ideal for two-phase cooling as it is a low-pressure fluid, having a saturation temperature of 56˚C at atmospheric pressure, implying that the system would need to be under vacuum for lower temperatures. This has the disadvantage that one is limited by the allowable pressure drop within the cooling device, implying that channels should be relatively large. The potential of air also leaking into the system becomes greater.

*** Thus, for two-phase cooling: CO_2, C_2F_6 and C_3F_8 will be compared.**

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Effect of Dimensions on Single-Phase Cooler

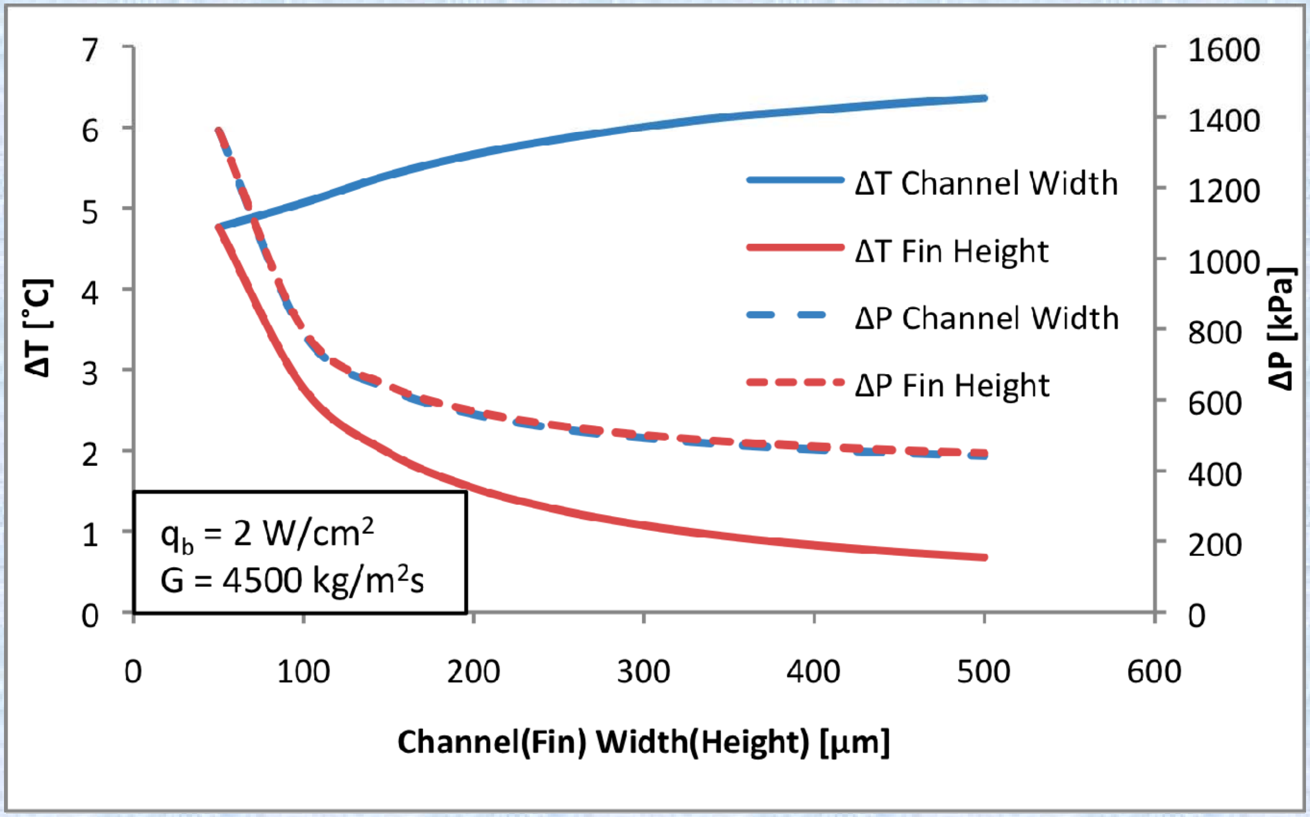

Figure 7: Effect of *channel width* and *fin height* on *maximum base temperature difference relative to the inlet* and on *pressure drop* for single-phase flow using C_6F_{14} relative to 50 microns width or height for fixed fin thickness of 25 microns.

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Effect of Fin Height on Two-Phase Cooler

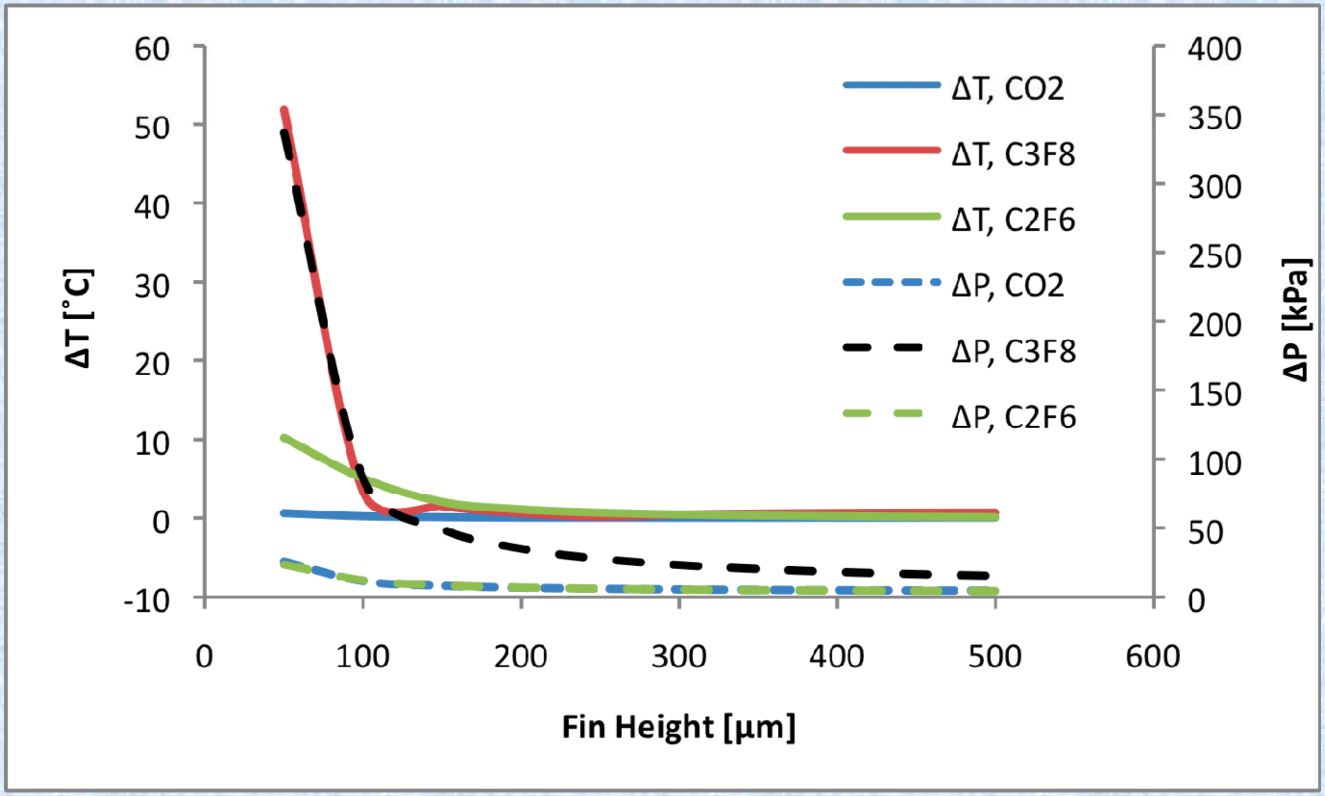

Figure 9: Effect of *fin height* on *maximum base temperature difference relative to inlet* and on *pressure drop* for two-phase flow for channel width of 50 microns and fin thickness of 25 microns. Simulation shows that CO_2 is the best candidate.

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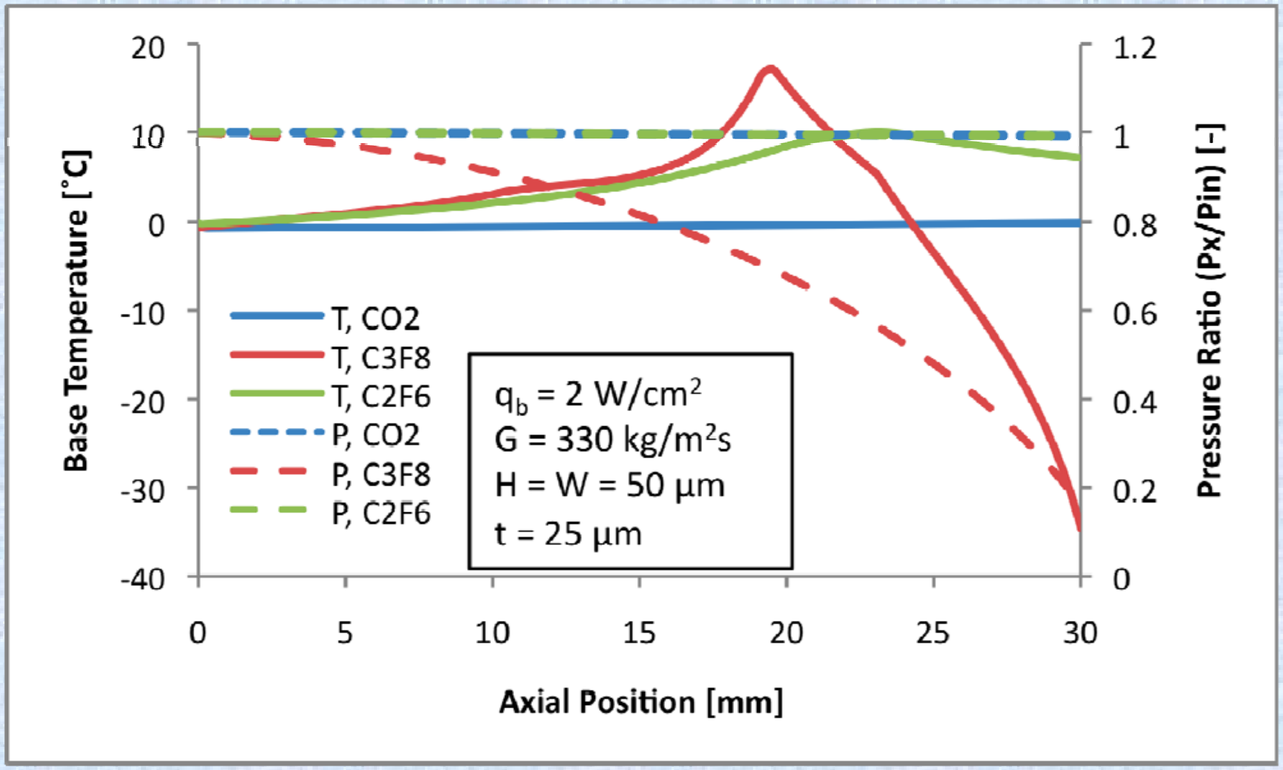
Temperature/Pressure Profiles in Two-Phase Cooler



The pressures are shown in terms of the ratio of the local pressure to the inlet pressure. The actual base temperature varies depending on the heat transfer/pressure drop/vapor pressure curve of the fluid. Smallest temp. variation is for CO_2. Pressure drops are also significantly less for CO_2 and C_2F_6 since their viscosities are about half that of C_3F_8.

Comparison of Single-Phase to Two-Phase Cooler

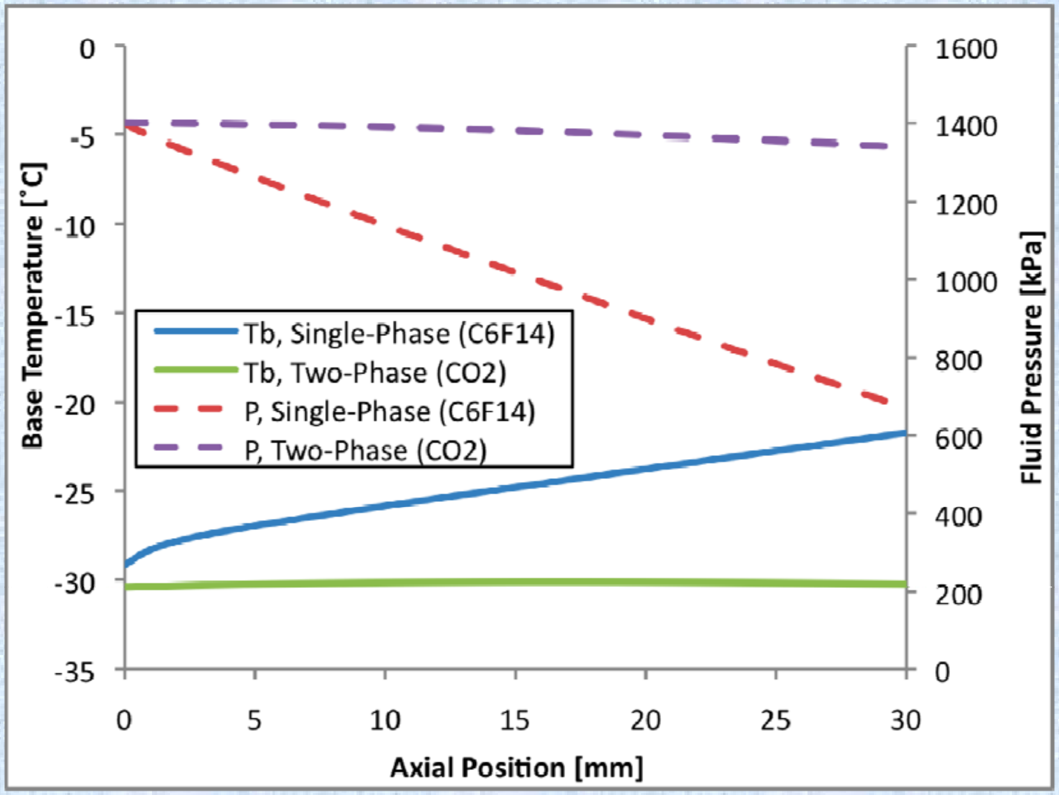


Figure 10 shows a comparison of single-phase to two-phase cooling. Both single-phase C_6F_{14} and two-phase fluid CO_2 have an inlet temperature of -30˚C. The fin height and channel width were 50 µm, while the fin thickness was 25 µm. A base heat flux of 2 W/cm^2 was applied. The actual junction/base temperature and fluid pressure along the channel are shown.

Comparison of Single-Phase to Two-Phase Cooler

For both the single-phase and two-phase results, the axial temperature difference is below 5K, although the increase in temperature for the two-phase fluid is much less than for the single-phase fluid (0.14K vs. 4.7K).

The difference in the fluids' pressure drops is even more significant:

*** The single-phase fluid requires a mass flux of 4500 kg/m^2s to obtain a temperature difference below 5K with a pressure drop of about 700 kPa!**

*** The two-phase fluid only required a mass flux of 250 kg/m^2s that resulted in a pressure drop of 60 kPa.**

The power required to move the two fluids is 1984 mW and 28 mW, respectively.

Simulation implies that CO2 two-phase cooling relative to C6F14 single-phase cooling yields much lower axial temperature gradients in the GTK, lower pressure drops and pumping power consumption, and very high heat transfer coefficients but is more complex to implement.

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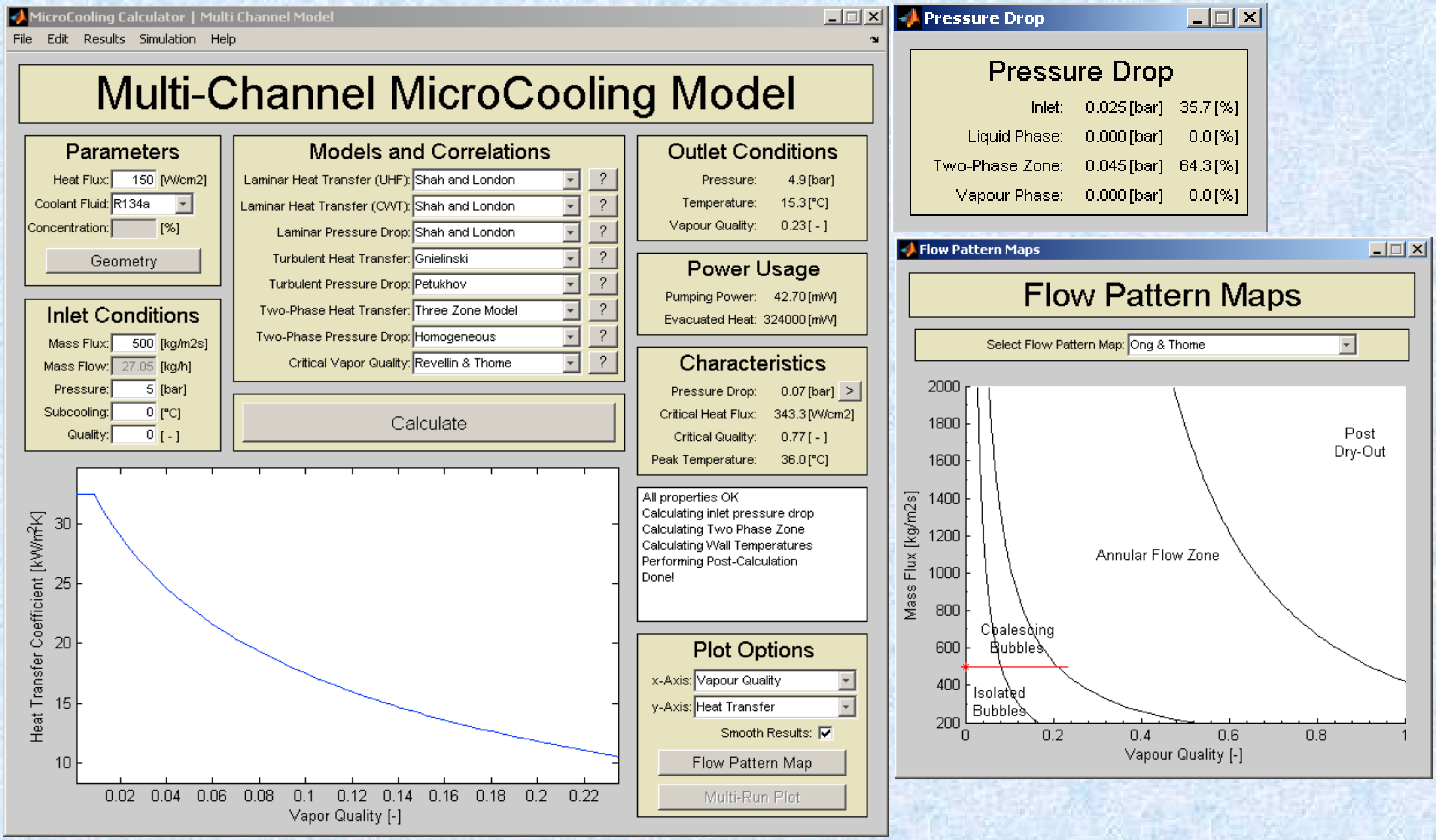
LTCM Lab Internal Cooling Simulation Code



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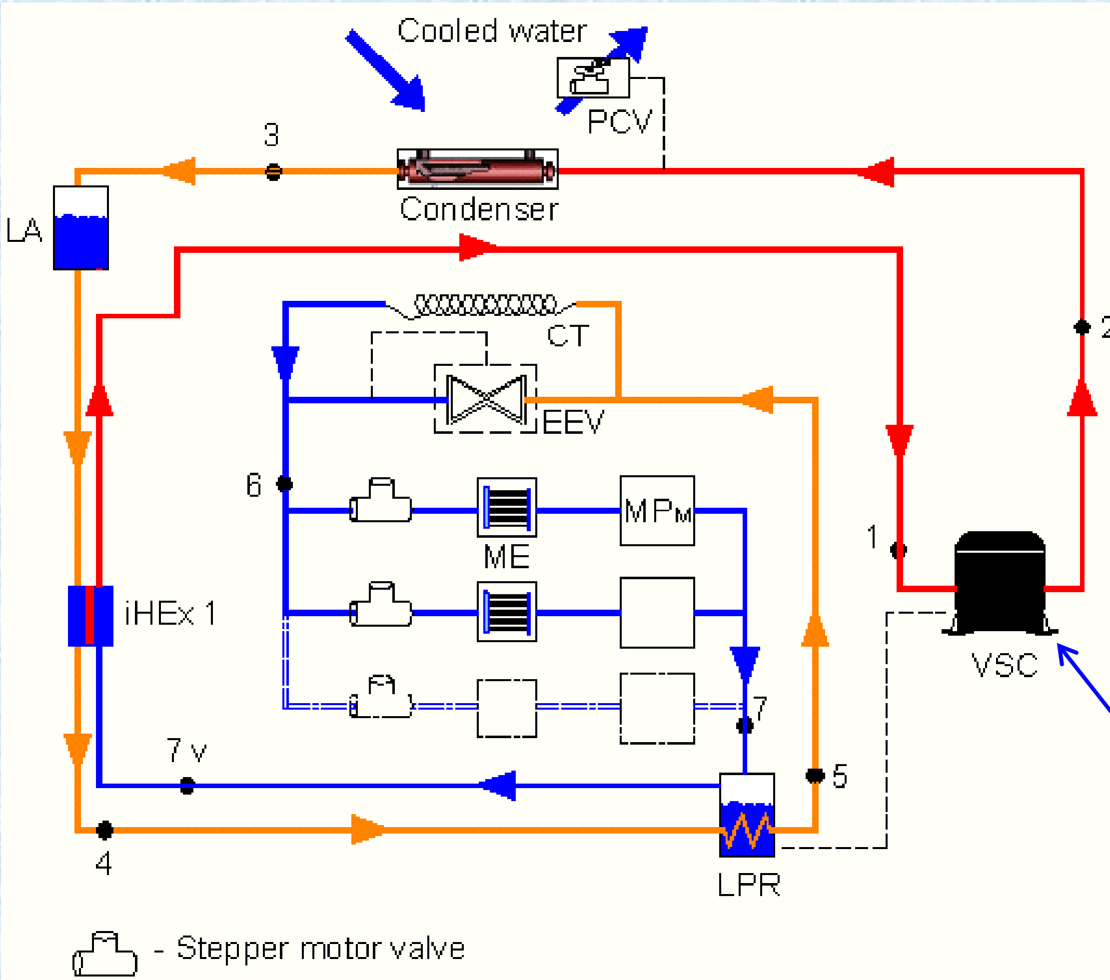
Our Two-Phase System for IBM Blade Server



Oil-free compressor

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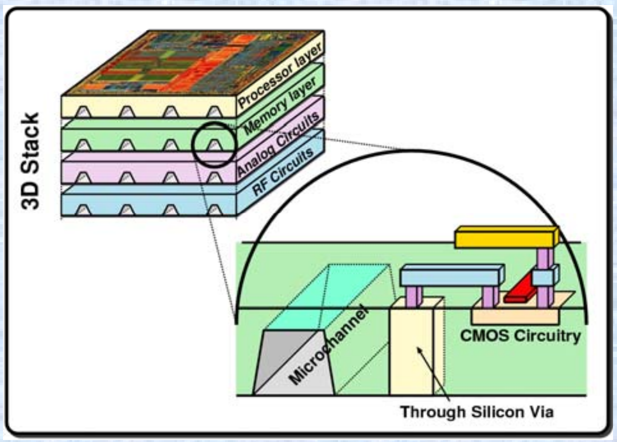
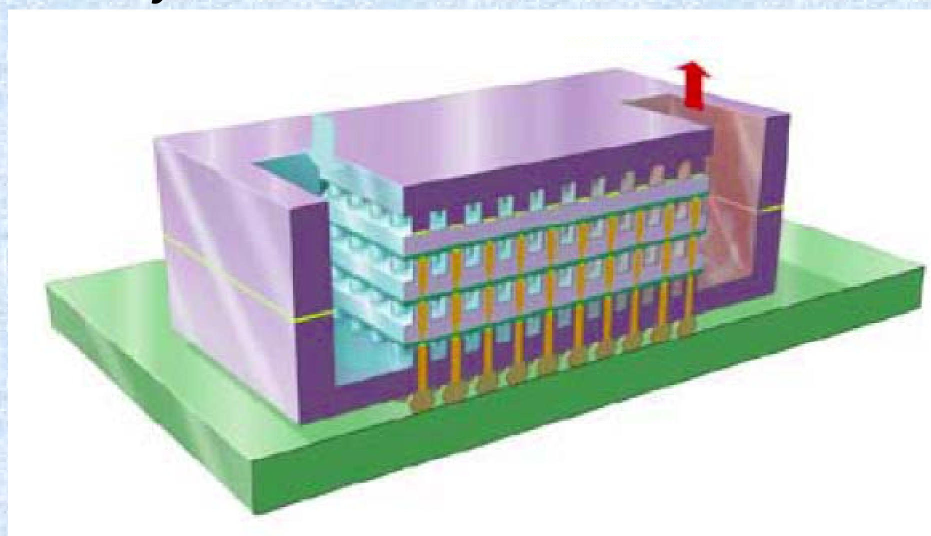
CMOSAIC: 3D-IC Thermal Performance with Microscale Liquid/Evaporative Cooling

- **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***





A new $4.3million Swiss consortium project lead by Prof. Thome

Summary and Advantages:

Flow boiling in micro-evaporator elements is a convincing solution for cooling high energy physics targets and electronics rather than a viscous liquid because:

- **It yields much larger heat transfer coefficients,**
- **It makes low temperature difference operation possible,**
- **It has high critical heat fluxes for high W/cm^2 operation,**
- **It provides a near uniform temperature of cooled element,**
- **Hot spot cooling is self-compensated by boiling itself,**
- **It has lower pumping power vs. single-phase cooling,**
- **Evaporation at -20°C to -30°C is not a problem,**
- **But two-phase cooling is more complex to implement *but* we have significant experience with it.**

Two-Phase Flow in T-Junction:

1. VOF (step one)

2. VOF with level set (step two)

3. Other improvements (step three)

4. Validation

This is an ongoing Ph.D. thesis and hence are preliminary results. Written within *Fluent*.

t_junction_20_10_R134a_2bubbles_D12_d6_g1500.avi

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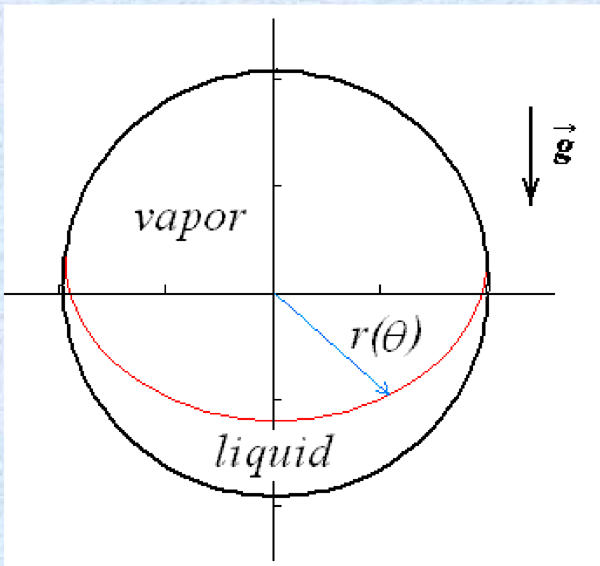
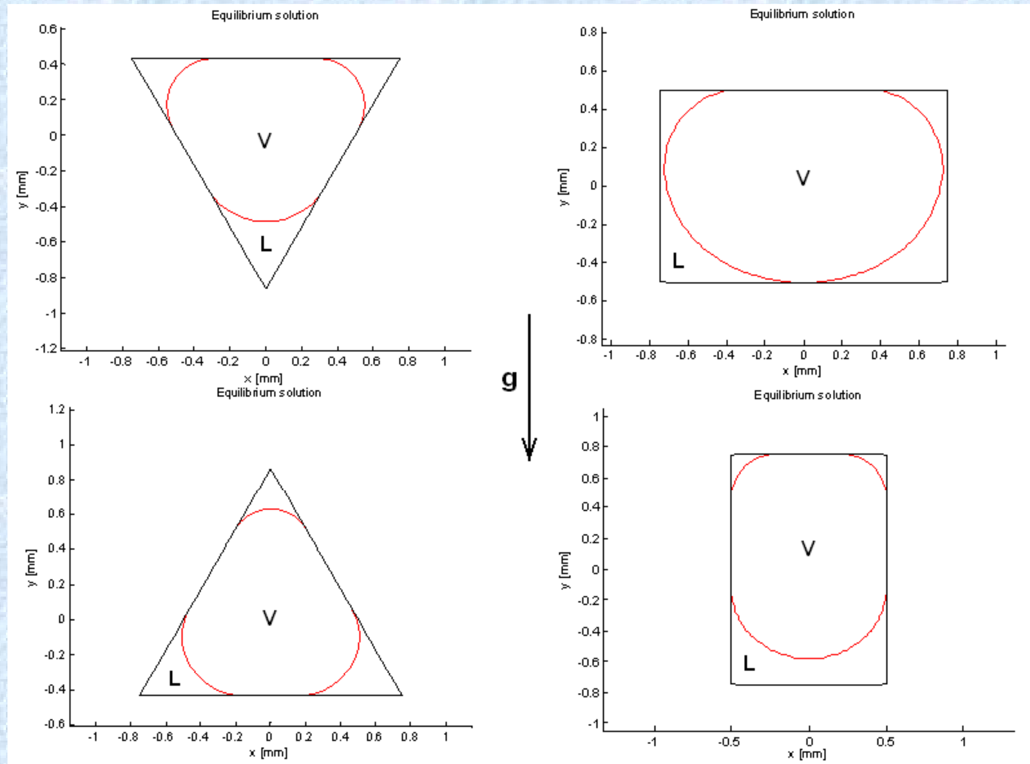
Film Condensation: Microchannel without Vapor Shear

Minimum potential energy of the system:

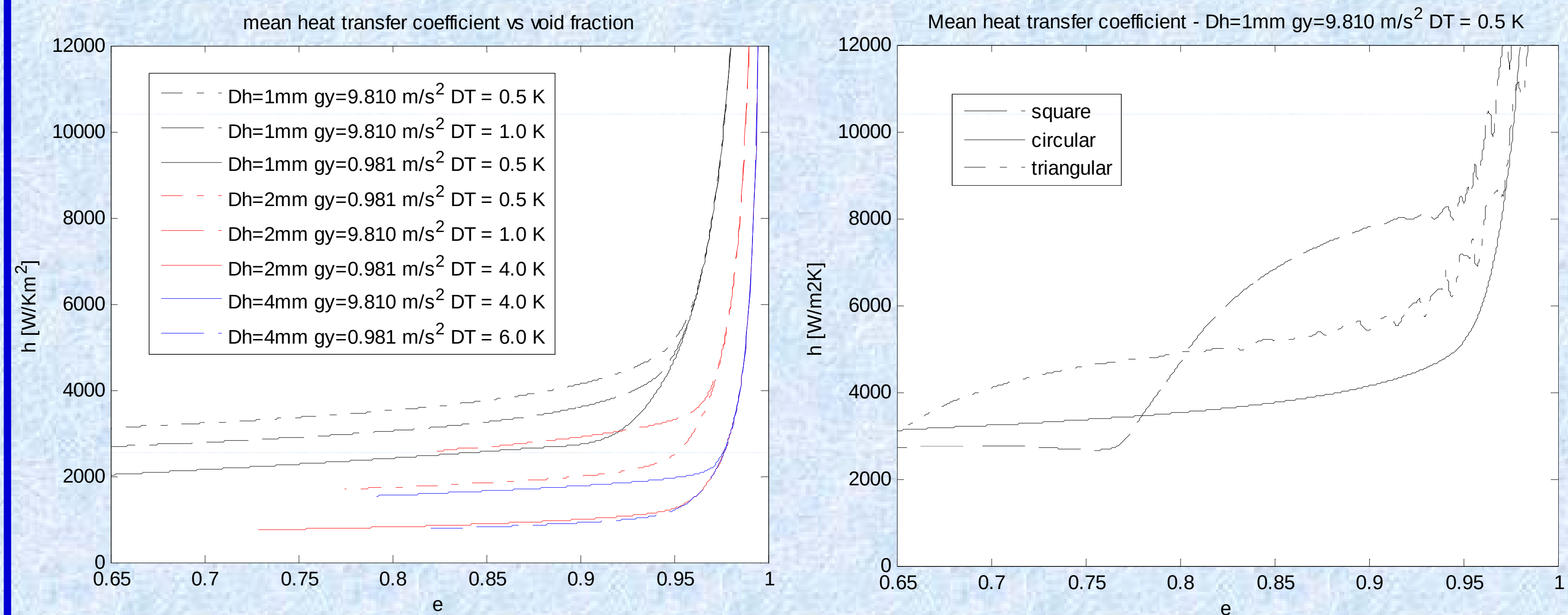
$$e_P = \iint_A g\rho(x,y)h(x,y)dA + \int_{\partial A} \sigma dl$$





Static conditions without vapor shear. Left: reference system and nomenclature; Right: example of solutions obtained for equilateral triangle and rectangle with R-22 fluid, saturation temperature T_{sat} = 30°C, cross sectional void fraction ε=0.8, gravity acceleration g=9.81 m/s^2.

Film Condensation: Microchannel without Vapor Shear



Annular flow without vapor shear. Left: mean heat transfer coefficient (h) versus cross sectional void fraction (e) for circular channels with different hydraulic diameters, different imposed ΔT at the wall and different levels of gravity; Right: mean heat transfer coefficient for different test section shapes with hydraulic diameter of 1mm, ΔT = 0.5 K, g=9.81 m/s^2; the test fluid is HFE7100 in all the cases.

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Microscale Flow and Heat Transfer Course:

FUNDAMENTALS OF MICROSCALE HEAT TRANSFER: BOILING, CONDENSATION, SINGLE- AND TWO-PHASE FLOWS

Date: June 7-11, 2010 at EPFL in Lausanne.

Contact: john.thome@epfl.ch

***Lecturers*: Thome (EPFL), Michel (IBM Research), Celata (ENEA), Zun (Univ. of Ljubljana), Jacobi (Univ. of Illinois).**