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Dynamic modeling and Integration of New Generation Datacenter Cooled with On-Chip Two-Phase Cooling System

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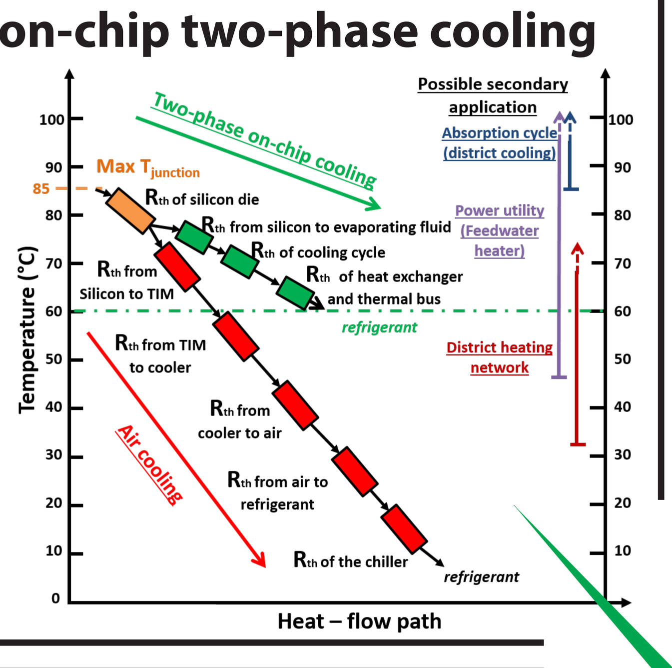
1 - Context and Motivation

From air cooling to on-chip two-phase cooling in datacenters:

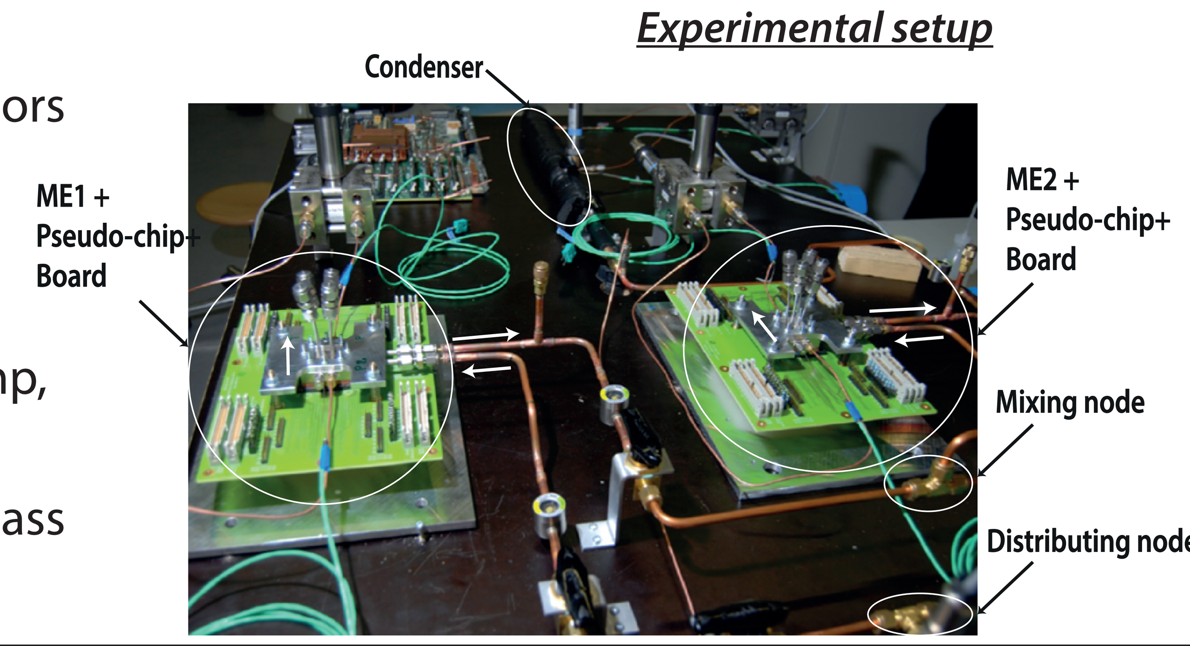
- Better cooling performances
- Reduce the power consumption
- Allow the reuse of the large amount of evacuated heat

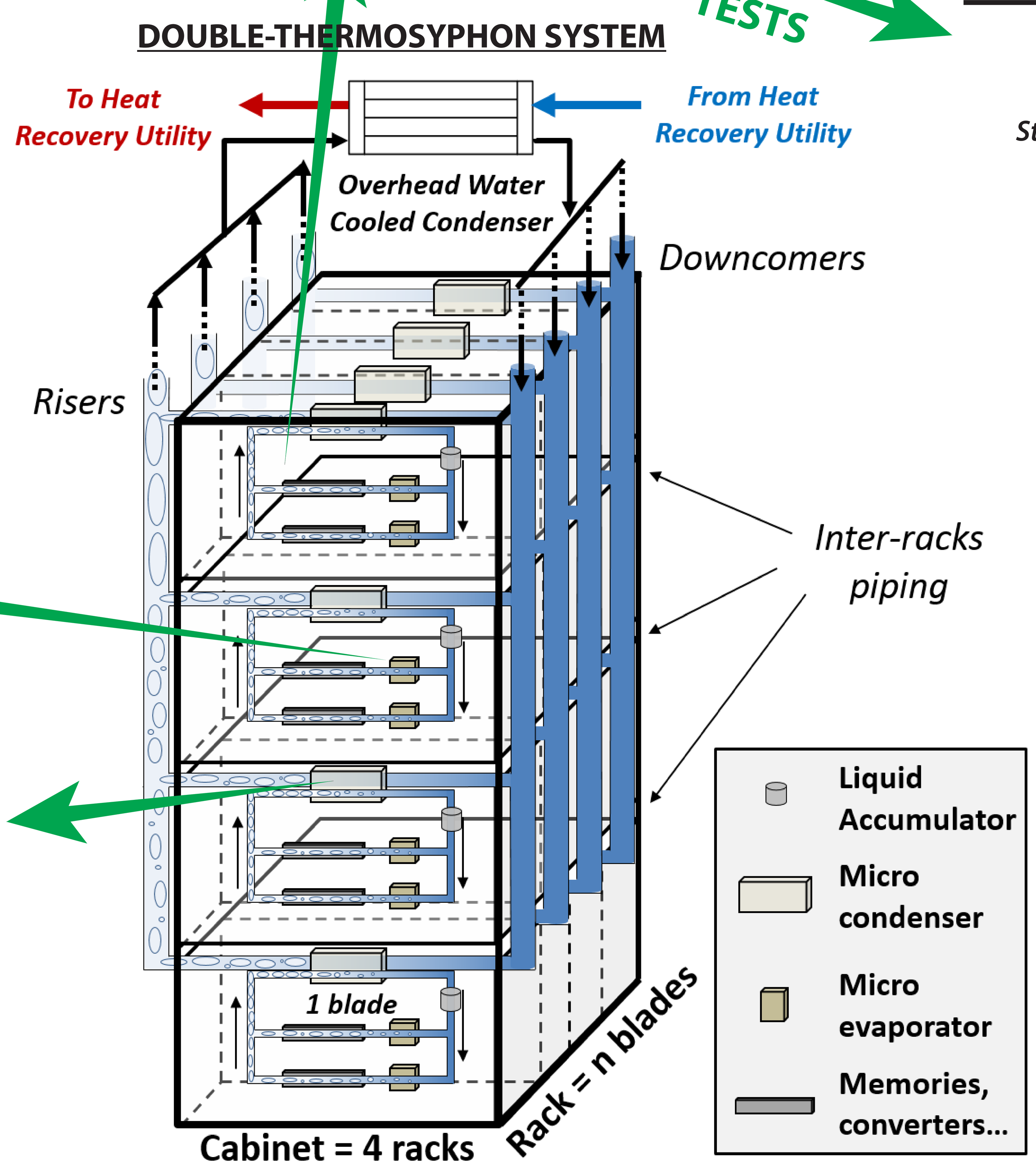


2 - Cooling System Description

2 parallel microevaporators (ME) assembled on microprocessors composed of 35 heaters and temperatures sensors,
a heated pipe to emulate memories and converters,
a condenser (tube-in-tube) for cooling and heat recovery,
a liquid accumulator to ensure that only liquid flow to the pump,
a dry filter,
a liquid pump and **a stepper motor valve** to modulate the mass flow rate.

Experimental setup

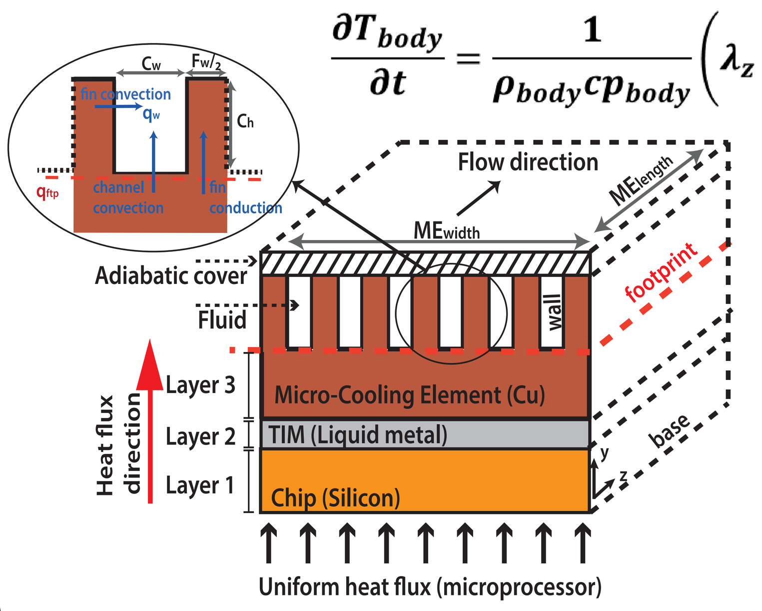




3 - Microevaporator

2D conduction

$$\frac{\partial T_{body}}{\partial t}=\frac{1}{\rho_{body}c p_{body}}\left(\lambda_z\frac{\partial^2 T}{\partial z^2}+\lambda_y\frac{\partial^2 T}{\partial y^2}\right)$$

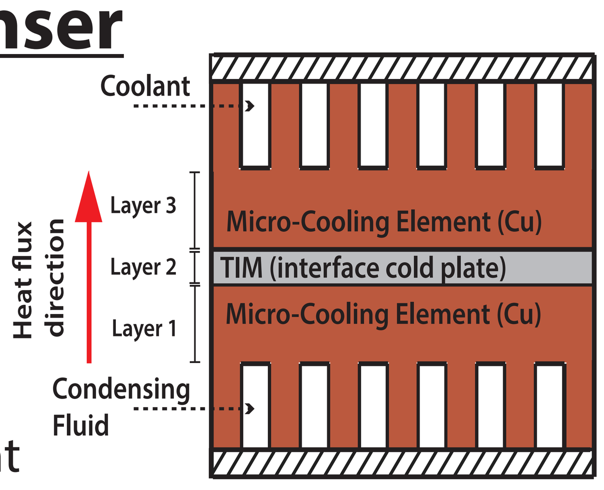


- Local HTC
- Local chip T
- Row Hot Spot

4 - Microcondenser

1D conduction

Condensing refrigerant to Water
OR
Condensing refrigerant to Evaporating refrigerant



5 - Mathematical model

PDE and SEMI-IMPLICIT Solver

- Overall Steady State Momentum Balance -

$$\frac{\partial P}{\partial z}+\cancelto{0}{\frac{d}{dt}[(1-\varepsilon)\rho_l u_l+\varepsilon\rho_g u_g]}=-\frac{\partial}{\partial z}[(1-\varepsilon)\rho_l u_l^2+\varepsilon\rho_g u_g^2]-\left(\frac{\partial P}{\partial z}\right)_f-[\rho_g\varepsilon+\rho_l(1-\varepsilon)]g\sin\theta$$

- Transient Energy Balances in ME, piping and condenser

$$[\rho_g\varepsilon+\rho_l(1-\varepsilon)]\frac{dh}{dt}=-\frac{1}{n_c C_w C_h}\frac{\partial(\dot m h)}{\partial z}+\frac{\alpha_{ftp}(T_{ftp}-T_f)*ME_{width}}{C_w C_h}-(UA)_{T_{av}}\frac{(T_{av}-T_{amb})}{n_c C_w C_h ME_{length}}$$

$$\frac{dh}{dt}=\frac{1}{\varepsilon\rho_g+(1-\varepsilon)\rho_l}\left[-\frac{4\dot m}{\pi D_{int}^2}\frac{\partial h}{\partial z}+4\,\alpha_{loss}\frac{D_{int}+2e_{ins}}{D_{int}^2}(T_{amb}-T_f)\right]$$

$$\frac{dh}{dt}=\frac{1}{\varepsilon\rho_v+(1-\varepsilon)\rho_l}\left[-\frac{1}{S_{cond}}\frac{\partial(\dot m h)}{\partial z}-\frac{U*P_{cond}*(T-T_w)}{S_{cond}}\right]$$

The liquid refrigerant flows through the inlet piping, is then split into two pipes feeding the cold plates and exits in separate piping. The flows rejoin to proceed in the outlet pipe.

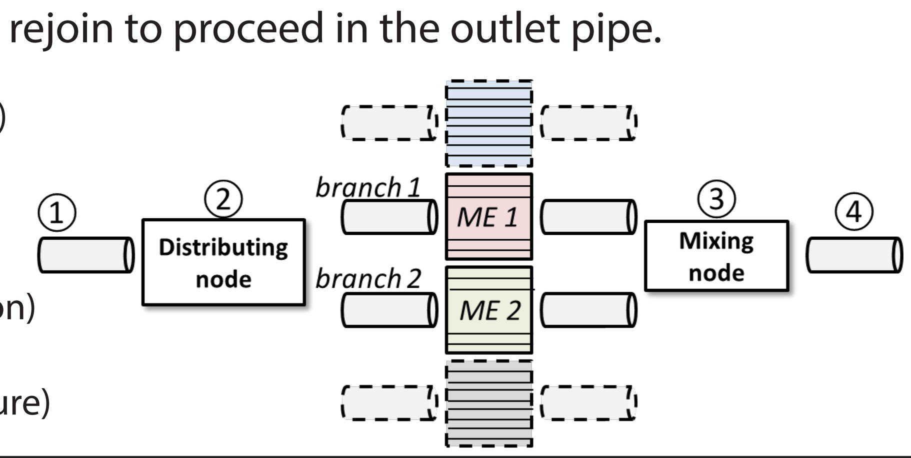
- Controllers

$$\frac{d\dot m}{dt}=\left(K_i\,(x_{mix}-x_{set})+K_c\frac{dx_{mix}}{dt}\right)$$ (Mixing Vapor Quality)

$$\frac{d\dot m_w}{dt}=\left(K_{w,i}\,(h_{out,cond}-h_{set})+K_{w,p}\frac{dh_{out,cond}}{dt}\right)$$ (Subcooling)

$$\frac{d\dot m_i}{dt}=K_{distri}\,(\Delta P_i-\Delta P_{i+1})$$ (Mass Flow Distribution)

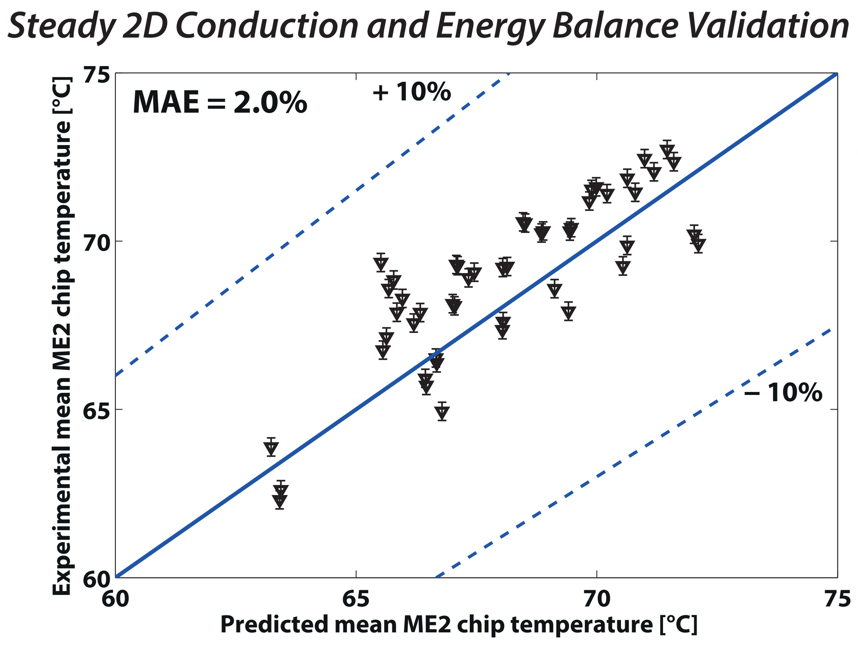
$$\frac{dP}{dt}=K_{pressure}\,(m_{calc}-m_{init})$$ (Overall System Pressure)



6 - Validations

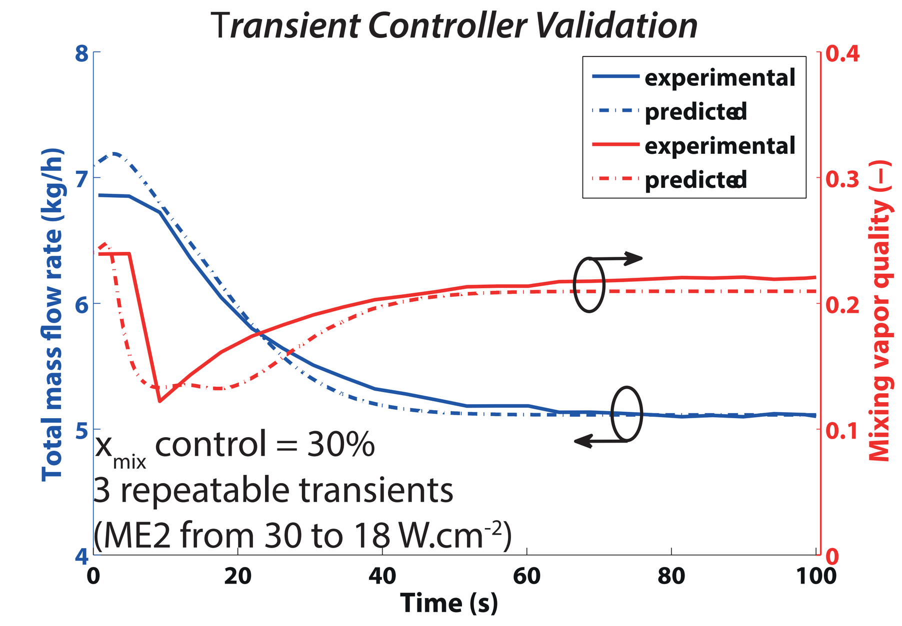
Fluid HFC134a

Steady 2D Conduction and Energy Balance Validation



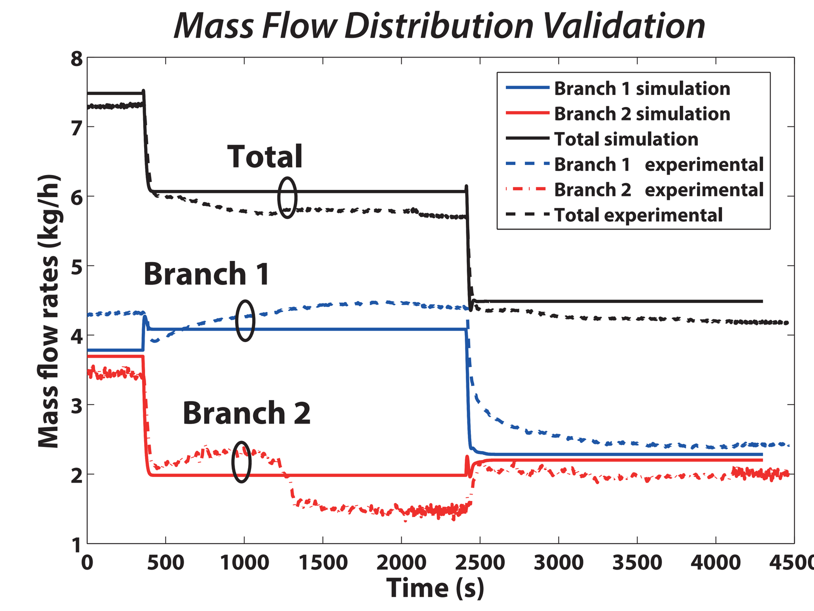
50 steady states
q: 8 to 30 W.cm^{-2}
P:16 to 18 bar
m: 4 and 9 kg/h

Transient Controller Validation



x_{mix} control = 30%
3 repeatable transients
(ME2 from 30 to 18 W.cm^{-2})

Mass Flow Distribution Validation



x_{mix} control = 30%
Step1: ME1 reduced
Step2: ME2 reduced
Backed out individual mass flow rates

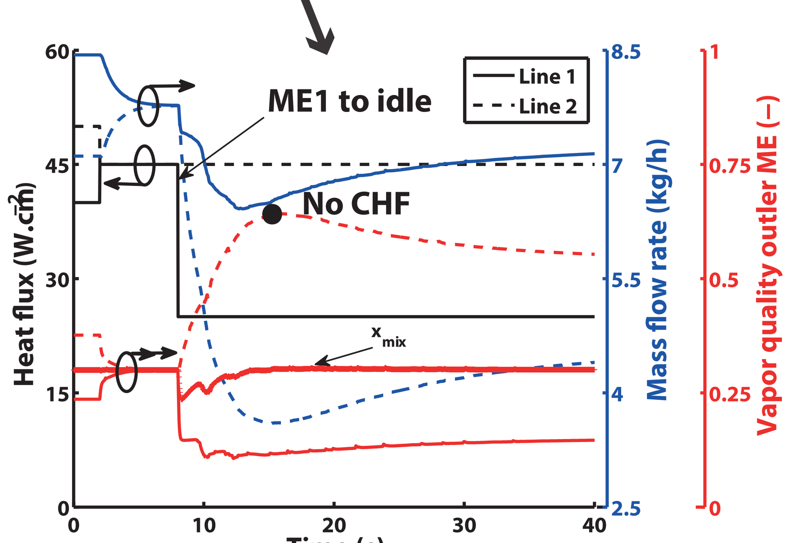
7 - Results

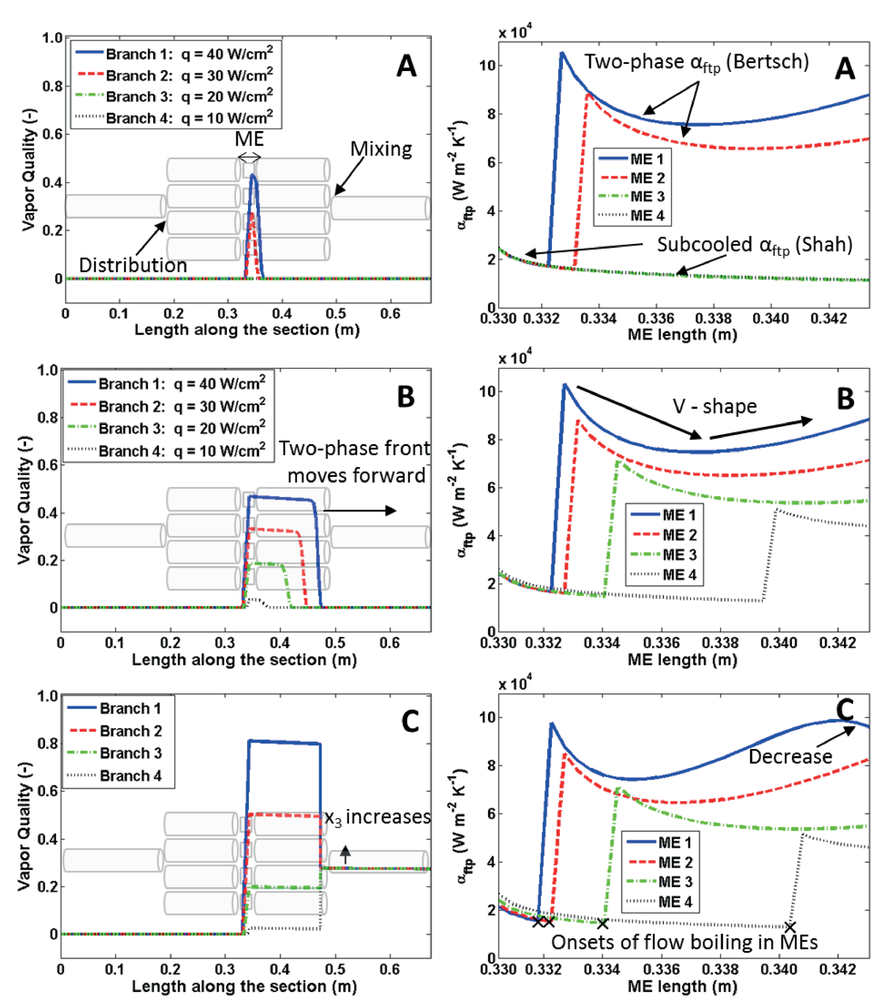
2-PHASE BLADE START UP

- 4 MEs (40, 30, 20 and 10 W.cm^{-2})
- P = 16 bar
- Subcooling of 3K
- x_{set} of 30%

SUDDEN IDLE STATE IN 1 PROCESSOR

- ME1 from 45 to 25 W.cm^{-2}
- ME2 fixed at 45 W.cm^{-2}
- Mixing Vapor Quality Control
- P = 16 bar



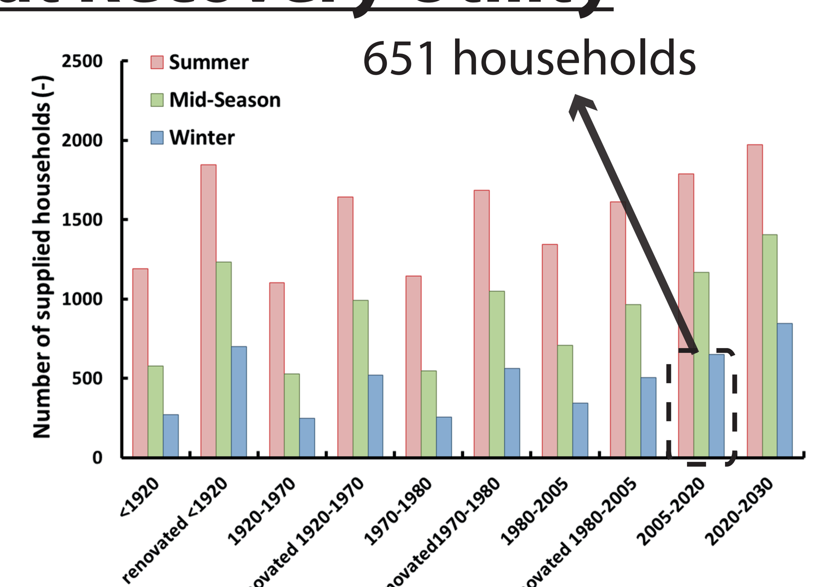


8 - Datacenter Integration with Heat Recovery Utility

- Feedwater Heater of a PowerPlant
- Absorption Cycle
- **District Heating Network**
- Desalination, ORC, Drying, etc.

1MW datacenter (EPFL)
93% heat recovery (Simulation)
Heat and Hot Water requirements using Energis tool (Girardin et al.)

651 households



SAVINGS

Heat supplier	Individual boilers	Centralized heat pump
CO_2 emissions reductions (tons/yr)	1050	163
Operating costs reductions (k\$/yr)	564	227

Very Promising

Publications

• Lamaison et al. ***Efficiency improvements of a thermal power plant by making use of the waste heat of large datacenters using two-phase on-chip cooling.*** World Engineers' Convention. Geneva, Switzerland, Sept.2011.
• Lamaison et al. ***Transient Simulation of Two-Phase On-Chip Cold Plates of a Liquid Pump Cycle for Cooling of High Performance Microprocessors in Parallel.*** InterPACK 2013, San Francisco, CA, USA, July 2013.
• Marcinichen et al. ***Advances in Electronics Cooling.*** Heat Transfer Engineering, 34:5-6, 434-446, 2013.
• Lamaison et al., ***Two-Phase Flow Control of Electronics Cooling with Pseudo-CPUs in Parallel Flow Circuits: Transient Modeling and Experimental Evaluation.*** Journal of Electronics Packaging, ASME, 135:3, 2013.