Variable Pumping Control for Low Power Microfluidic Chip Cooling

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STREAMS
Smart Technologies for eneRgy Efficient Active cooling in Advanced Microelectronic Systems

Introduction

Microelectronic modules increase in power density

→ liquid cooling required to maintain acceptable chip temperatures

→ µchannels:

low thermal resistance – fabrication using MEMS technology - easy integration in system.

increased pressure drop compared to larger scale cold plates.

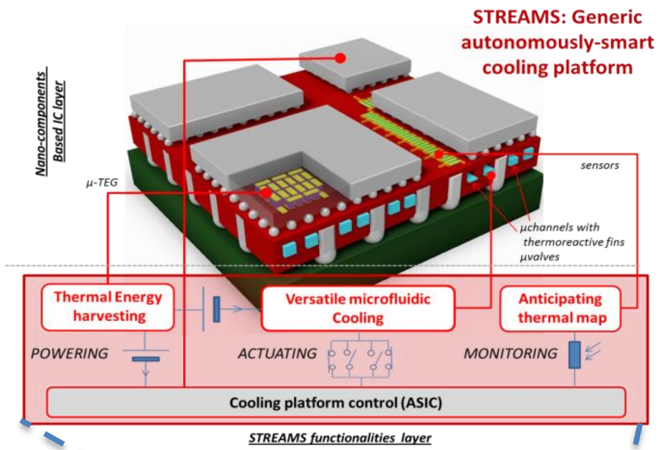
→ pressure drop reduction: optimal design of flow distribution

→ limited energy in portable applications, power consumption by the cooling system should be minimized.

→ flow rate reduction by adapting the pumping power

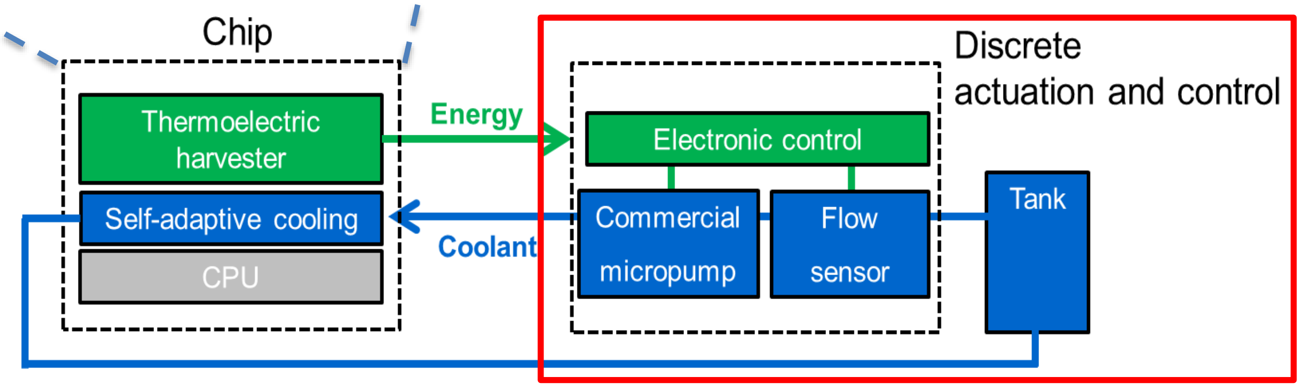
Introduction

Optimization of the system cooling based on µfluidic channels to minimize the power consumption by using variable pumping power.



Energy efficient controllable pump module

- Pump
- Sensors: temperature, pressure and flow
- electronics drive



concept of the pump module

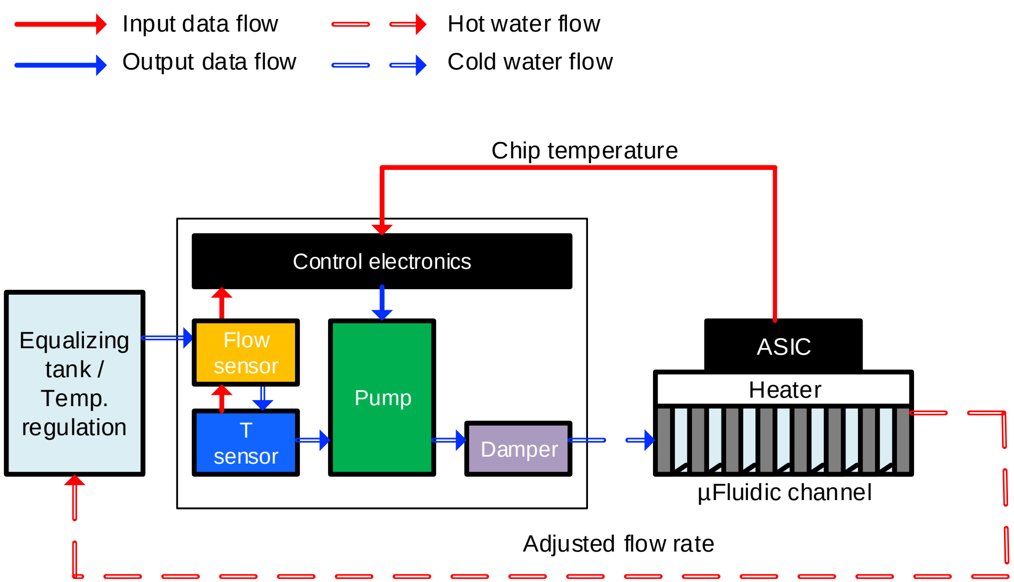
- **Constraints and parameters for the µFluidic design**

  Max. surface temperature 85°C and inlet temperature 50°C

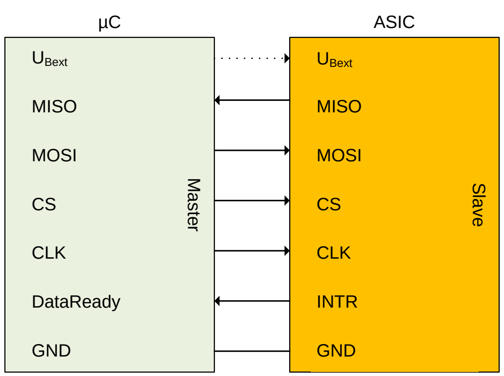
  Total pressure drop 10 kPa

- **Pump module design** :

  closed loop regulation → realized as a test bench during configuration phase



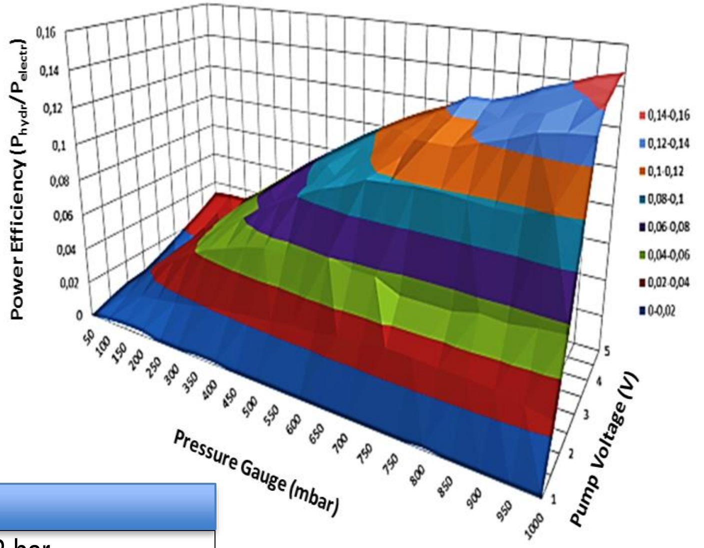
SPI interface



The membrane pump

KNF Neuberger

- oscillating displacement (eccentric system)
- operates against pressure drop up to 1 bar (10 kPa)
- adjustable pumping power: proportional to the resulting flow rate.
- maximum flow rate of around 50 ml/min

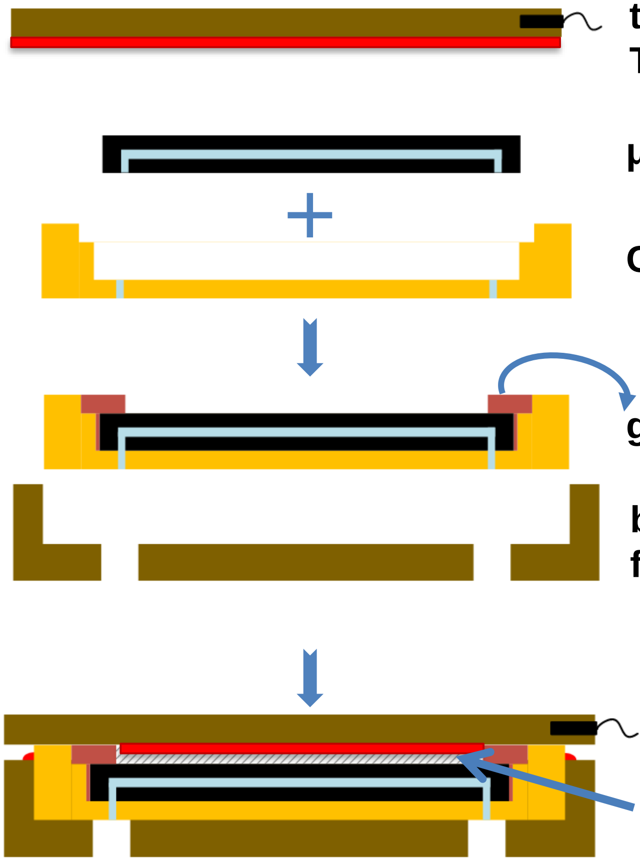


$$Pump\ efficiency = \frac{P_{hydraulic}}{P_{pump}}$$

$$P_{hydraulic} = Q \cdot \Delta P$$ (across the microfluidic structure)

Specification	NF 60	NF 25	NF 5
Type	Micro diaphragm, brushless DC motor, self-suctioning at 0.3 bar		
Materials	PP (head), EPDM (valves, diaphragms)		
Control voltage	0.3-5 V DC		
Input voltage	12 V		
Pressure drop	Max. 1 bar		
Flow rate range	Max. 600 ml/min	250 ml/min	60 ml/min
Power consumption	18 W	2.6 W	1.5 W

µfluidic structure



top copper plate with T-Sensor and heat foil

µ fluidic Chip

Chip frame

glue

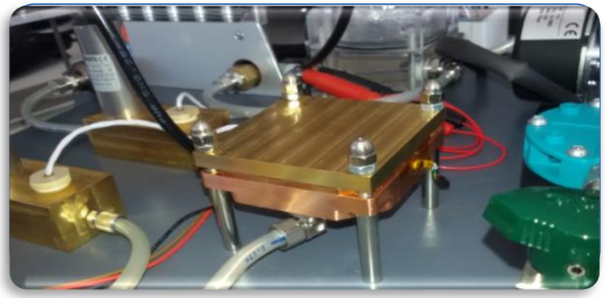
bottom plate with fluidic connections

thermal paste

20mm

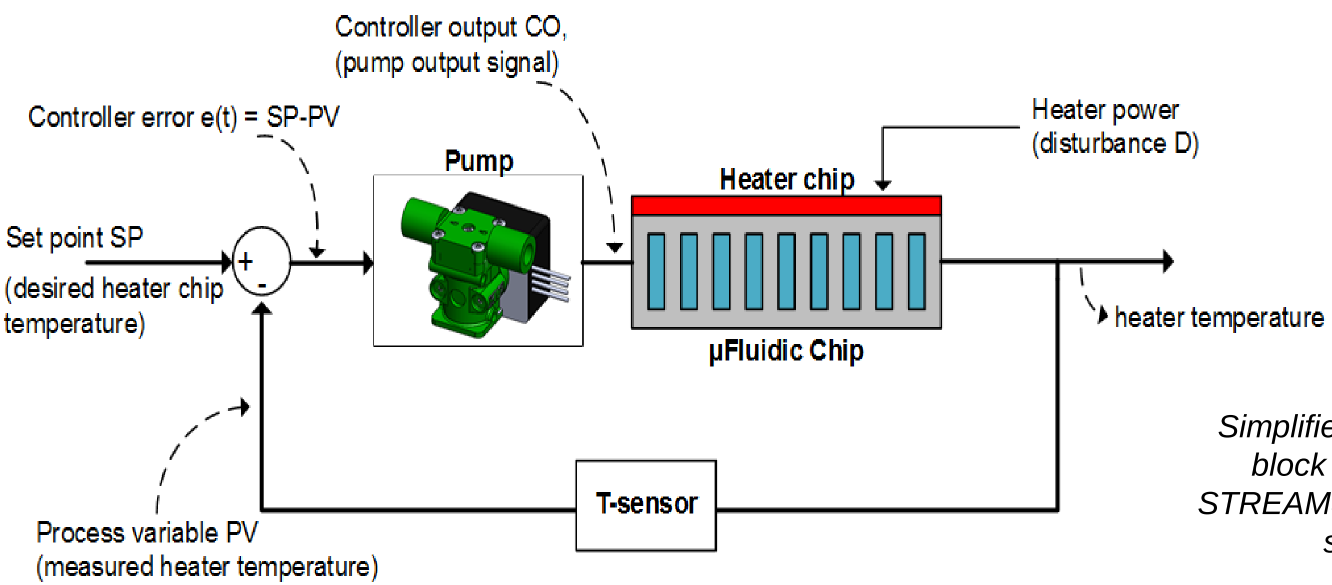
µ fluidic Chip:

- 32 channels in parallel
- with a 200x200µm² cross section
- and 150 µm glass for the cover with inlet and outlet



Water cooling system

- Variable pumping power on micro fluidic channels can minimize the power consumption.
- Parameterization is done by calculating the step response
- control based on temperature signals



Simplified control loop block diagram for STREAMS water cooling system

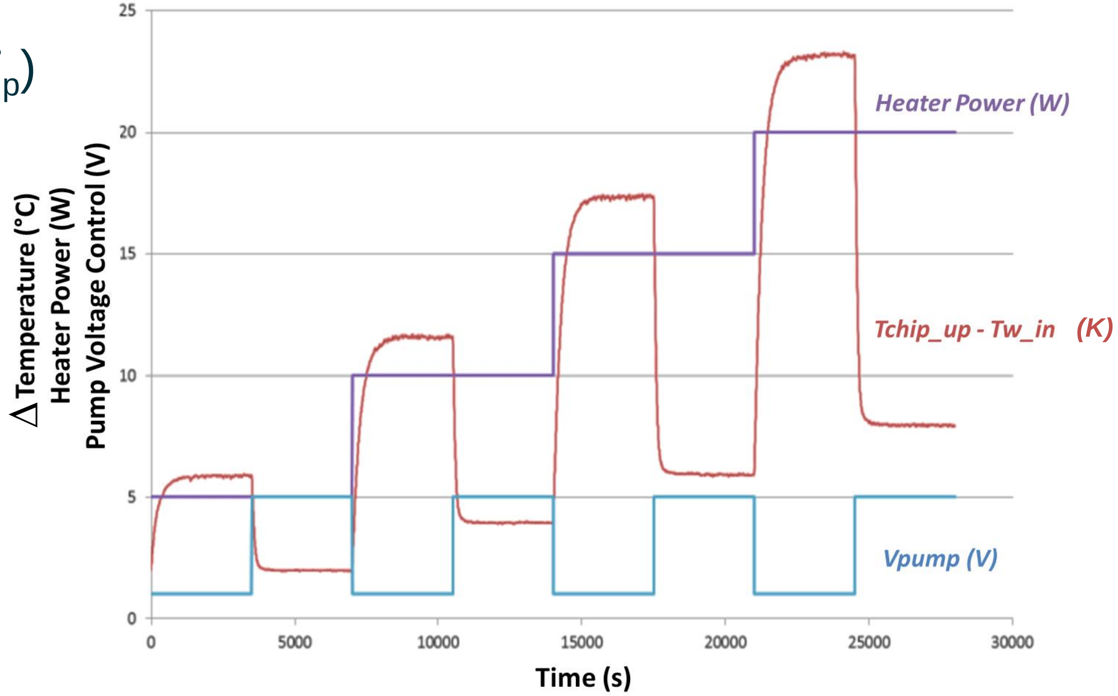
Step response @ Heater power variation

- Pump voltage increased step by step after steady-state at different heating power
- experimental determination of :

process gain $K_P = PV_2 - PV_1$

process time constant (T_p)

and dead time (θ_p).



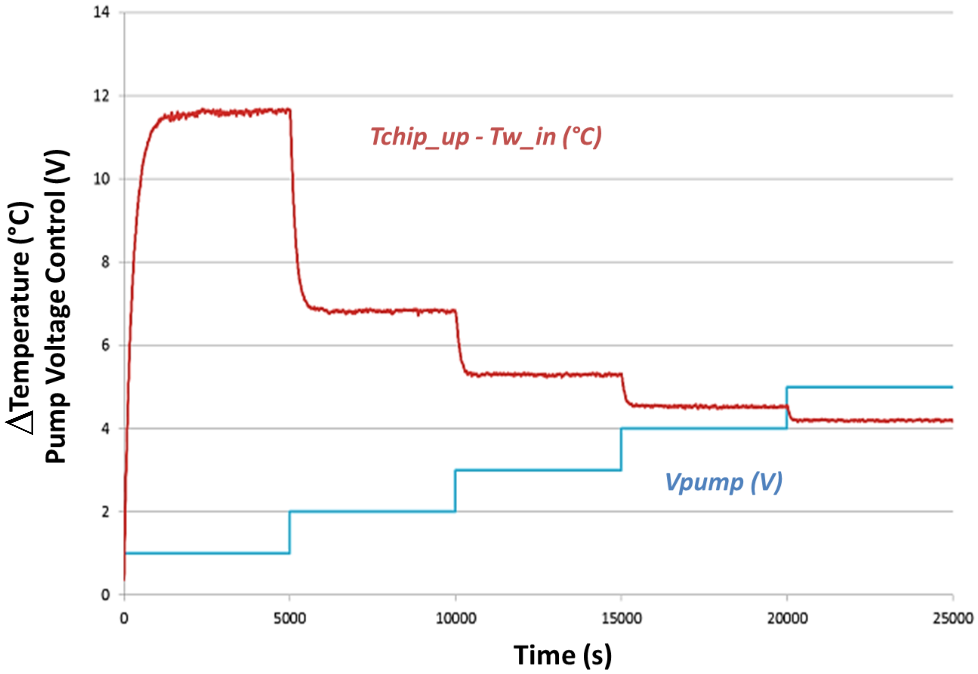
- $K_p = \frac{PV_2 - PV_1}{CO_2 - CO_1} \cdot CO_{range}$
- $T_p = t_{0,63PV2} - t_{start}$
- $\theta_p = dead\ time = 5\ s$

Step response @ Pump voltage variation

Non-linear system

→ Equal Controller Output *CO* step doesn´t result in equal process variable *PV* response

→ differences in calculated controller gain K_P for each operation level



Non-linear system : Temperature progression curve of the step test during open loop modus (Tchip-Twater) at 10 W heater power

Construction of the controller

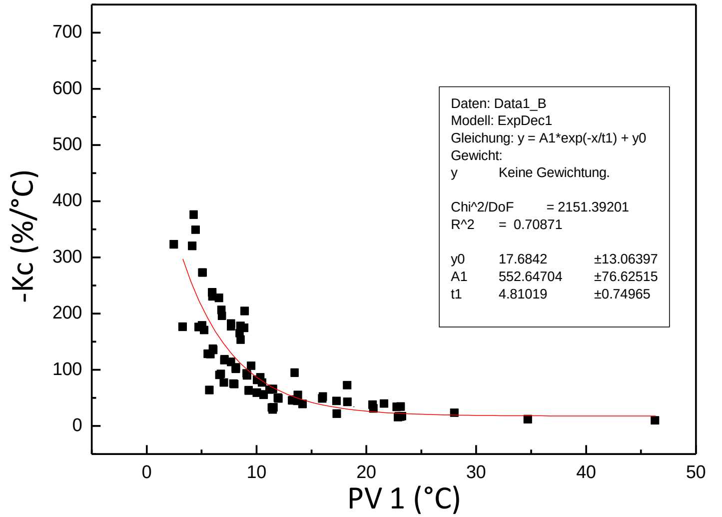
Controller output CO = $K_p e(t) + \frac{K_c}{T_i} \int e(t)\, dt$

Closed loop time constant Tc = $|0.1\ T_p,\ 0.8\ \theta_p|_{max}$

Controller gain Kc = $\frac{1}{K_p} \frac{T_p}{(\theta_p + T_c)}$

and Reset time $T_i = T_p$

non linear model: $-K_C = f\,(T_{chip} - T_{water})$



Exponential dependency between controller gain and process variable
Solution: gain scheduling

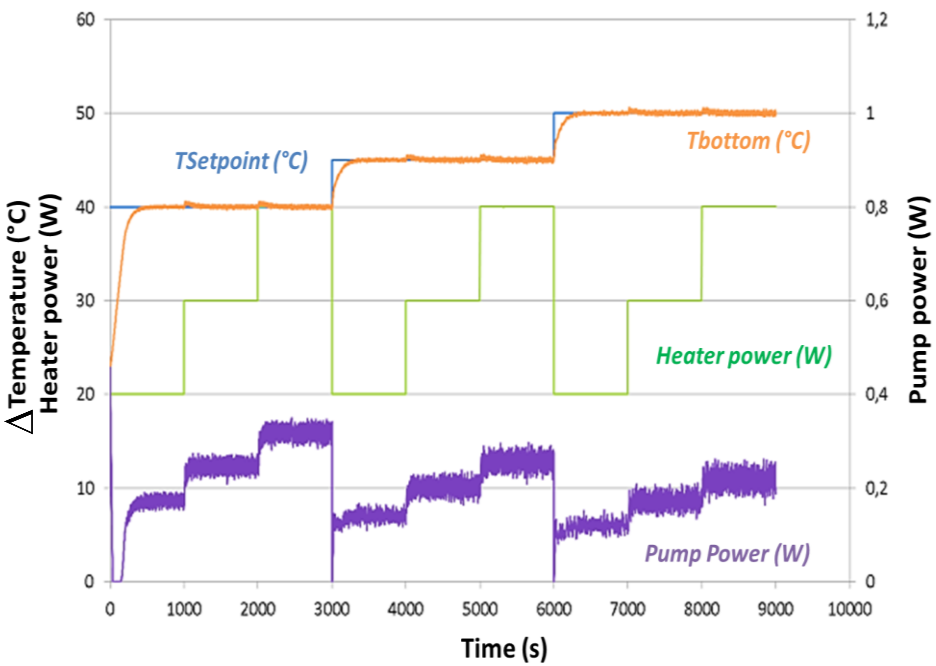
→ controller gain depends on the temperature set point range

→ Parameter values have to be adapted, depending on system

- Anti wind-up logic $\int e(t) = \frac{T_i}{K_c}(CO_{desired} - K_c\, e(t))$

Results with PWM

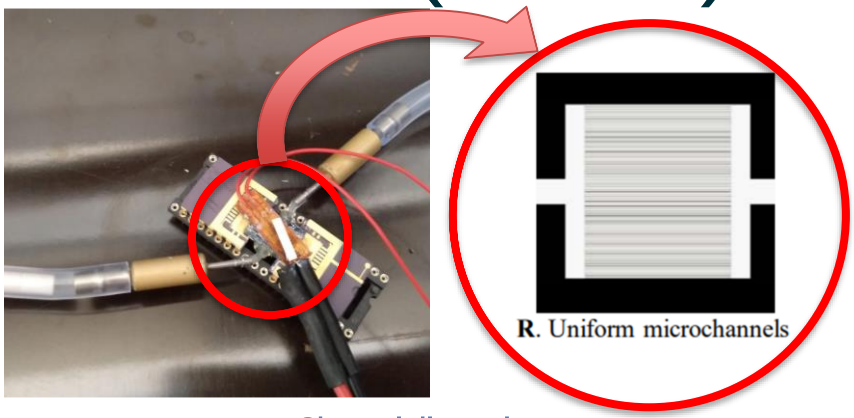
- Reduction of electrical power consumption: implementation of PWM
  The pump is turned on and off in certain frequency and duration by a PWM controller loop while the voltage output control is kept constant (5 V)
- Reduction of the average power consumption up to 50%
- Hydraulic power decreases with the increase of the allowed maximum chip temperature



Pump control with Puls Width Modulation

Experimental conditions (Lleida)

Validation on a silicon microchannel based cooling device



Channel dimension

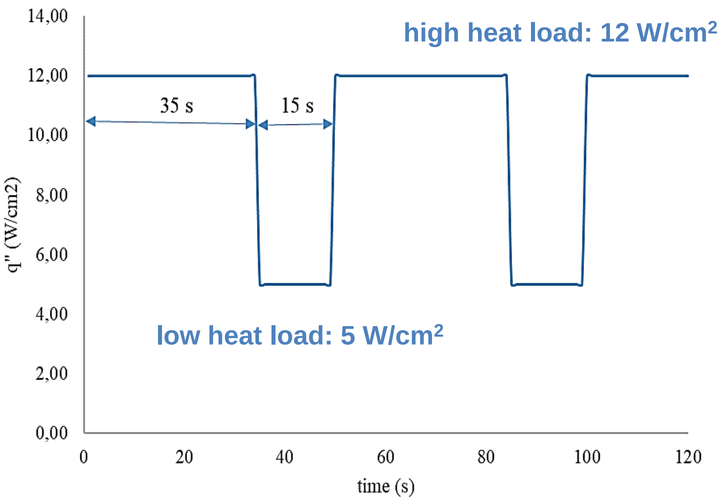
100 x 100 µm²

Comparison:

- cooling device with variable flow rate
- scenario of constant flow

under same load

- µchannel Inlet temperature: 25ºC



temporal and non uniform heat load

Experimental validation

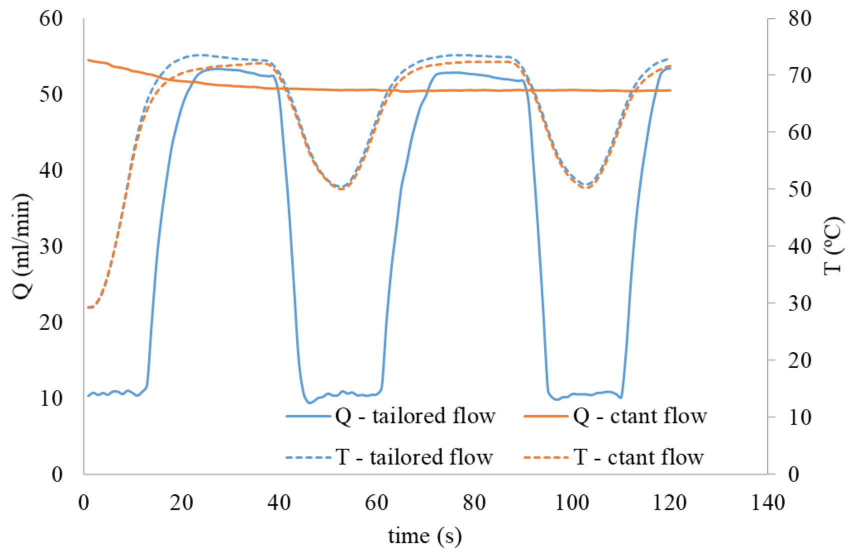
- Temperature set point: 70ºC
- Pump tailors the flow rate to maintain the maximum temperature limit.

  high heat load → flow rate is increased

  low heat load → flow rate is reduced

- Scenario of constant flow rate: maximum flow achieved by the variable pump is set to ensure a temperature under the set point

Chip temperature



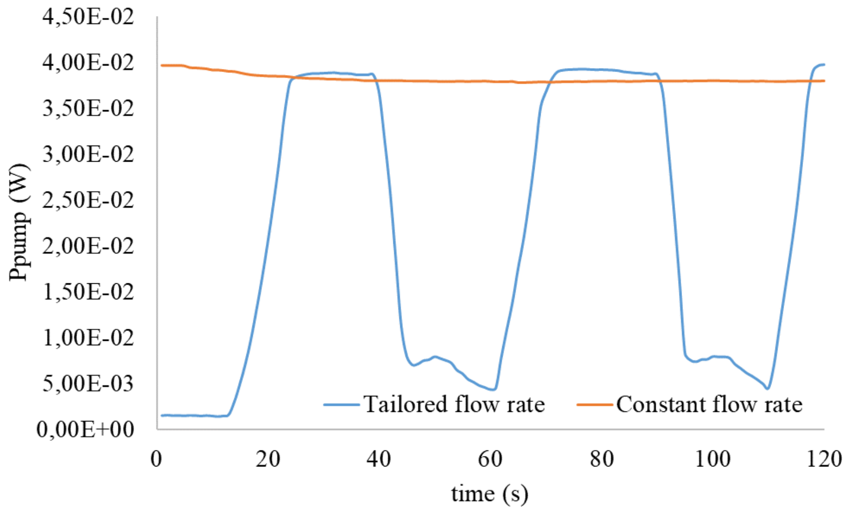
Conclusion

Pumping power (P_{pump}) of the device for both studied cases

A reduction of 46% is obtained for this heat load scenario

Additionally, the COP is 1.8 times higher when the flow rate is tailored.

$$COP = \frac{P_{heater}}{P_{pump}}$$



Use of a control algorithm with a variable pump
→ 75% reduction of the pumping power @ constant chip temperature independent of the power dissipated
→ reduction of thermal cycling
→ potential higher reliability.

The overall increase of the COP is 84%.

Thank you for your attention!

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