Variable Pumping Control for Low Power Microfluidic Chip Cooling

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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
The membrane pump

- 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

\[
Pump \ efficiency = \frac{P_{\text{hydraulic}}}{P_{\text{pump}}}
\]

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

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

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μfluidic structure

μ fluidic Chip:
• 32 channels in parallel
• with a 200x200µm² cross section
• and 150 µm glass for the cover with inlet and outlet

Chip frame

glue

bottom plate with fluidic connections

thermal paste

top copper plate with T-Sensor and heat foil

µ fluidic structure

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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.
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 ($\theta_p$).
  
  $K_p = \frac{PV_2 - PV_1}{CO_2 - CO_1} \cdot CO_{range}$
  
  $T_p = t_{0.63PV2} - t_{start}$
  
  $\theta_p = \text{dead time} = 5 \text{ s}$
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 ($T_{chip}$-$T_{water}$) 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 \( T_c = |0.1 \, T_p, 0.8 \, \theta_p|_{\text{max}} \)

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

and Reset time \( T_i = T_p \)

non linear model: \(-K_c = f(T_{\text{chip}} - T_{\text{water}})\)

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 \( \int e(t) = \frac{T_i}{K_c} (CO_{\text{desired}} - K_c \, e(t)) \)
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
Validation on a silicon microchannel based cooling device

Comparison:
- cooling device with variable flow rate
- scenario of constant flow
- μchannel Inlet temperature: 25°C

Experimental conditions (Lleida)

Channel dimension
100 x 100 µm²

under same load

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Experimental validation

• Temperature set point: 70ºC

• Pump tailors the flow rate to maintain the maximum temperature limit.
  high heat load $\rightarrow$ flow rate is increased
  low heat load $\rightarrow$ 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
Conclusion

Pumping power \( (P_{\text{pump}}) \) 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.

\[
\text{COP} = \frac{P_{\text{heater}}}{P_{\text{pump}}}
\]

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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