Minimizing Thermal Gradient and Pumping Power in 3D IC Liquid Cooling Network Design

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Why 3D IC Liquid Cooling?

- **Power** is the number one problem in chip design
- **3D IC** is promising for increasing computer performance
- But 3D IC **worsens** power problem by
  - higher heat dissipation density
  - larger thermal resistance from junction to ambient
- Microchannel-based liquid cooling is proposed as a solution

![Diagram of 3D IC Liquid Cooling](image)

[Brunschwiler+, 3DIC'09]
[Dang+, TAP'10]
[Madhour+, ICEPT'12]
Challenges for 3D IC Liquid Cooling

- Hot downstream and cool upstream $\implies$ large thermal gradient $\implies$ reliability and timing issues
- Limited channel diameter $\implies$ high pumping requirement $\implies$ overhead to whole system
- Limitation of previous work
  - No considering thermal gradient
  - Assuming unidirectional straight channels
  - Assuming unrealistic constant-temperature heat source
Thermal Modeling Background

- Most existing models assume unidirectional straight channels
- 4-register model (4RM) in 3D-ICE [Sridhar+, TOC’14]
  - Accurate
  - Has been extended for flexible topology
  - Slow
- We construct a fast 2-register model (2RM) for cooling network
Thermal Modeling Basics

- Divide channel layer into **basic cells** with a 2D grid
- Solve local pressure and flow rate from a **linear system**
4RM Model

- **Thermal cell** = basic cell
- Solve temperature from a **linear system** considering three kinds of heat transfer
  - Solid-solid
  - Solid-liquid
  - Liquid-liquid
Faster 2RM Model

▶ No conforming channel geometry $\implies$ larger and fewer thermal cells $\implies$ speed-up

▶ In solid layers, $m \times m$ basic cells = a thermal node

▶ In channel layers, $m \times m$ basic cells = a solid thermal node + a liquid one
Problem Formulations

Decision variables

- **Cooling network topology** $N$
- **System pressure drop** $P_{sys}$

Metrics

- **Pumping power** $W_{pump} = \frac{P_{sys} \cdot Q_{sys}}{\eta}$
  - $Q_{sys}$: system flow rate; $\eta$: efficiency term
- **Thermal gradient** $\Delta T = \max_{i}(\Delta T_i)$
  - $\Delta T_i$: range of node temperatures in $i$-th source layer
- **Peak temperature** $T_{max}$
Problem Formulations

▶ **Problem 1: Pumping Power Minimization**

\[
\begin{align*}
\text{min} & \quad W_{\text{pump}}, \\
\text{s.t.} & \quad P_{\text{sys}} \in \mathbb{R}^+, \; N \in \mathcal{N}, \; T_{\text{max}} \leq T_{\text{max}}^*, \; \Delta T \leq \Delta T^*.
\end{align*}
\]  

(\mathcal{N}: \text{all legal cooling networks})

▶ **Problem 2: Thermal Gradient Minimization**

\[
\begin{align*}
\text{min} & \quad \Delta T, \\
\text{s.t.} & \quad P_{\text{sys}} \in \mathbb{R}^+, \; N \in \mathcal{N}, \; T_{\text{max}} \leq T_{\text{max}}^*, \; W_{\text{pump}} \leq W_{\text{pump}}^*.
\end{align*}
\]  

▶ Design rules from ICCAD 2015 Contest
Pumping Power Minimization – Flow

Input: \( N_{\text{init}}, \Delta T^*, T_{\text{max}}^* \), stack description and floorplan files.
Output: \( N, P_{\text{sys}} \).

1: \( N \leftarrow N_{\text{init}} \);
2: while #iteration is within the limit do
3: Obtain neighboring network solution \( N' \);
4: \( W'_{pump} \leftarrow \text{EVALUATENETWORK}(N', \Delta T^*, T_{\text{max}}^*) \);
5: \( N \leftarrow N' \) or not according to SA mechanism;
6: if \( W'_{pump} \) converges then return \( N \) and \( P_{\text{sys}} \);
7: end while

The problem is divided into two levels:

- **Inner**: \( P_{\text{sys}} \) is varied to minimize \( W_{pump} \) for a specific \( N \), which evaluates \( N \)
- **Outer**: simulated annealing (SA) searches for a good \( N \)
Pumping Power Minimization – Temperature vs. Pressure

- As $P_{sys}$ increases, $T_{max}$ decreases and finally becomes approximately constant.
- $\Delta T = f(P_{sys})$ is either uni-modal or monotonically decreasing.
Pumping Power Minimization – Network Evaluation

- Replace $W_{pump}$ by $P_{sys}$, as $W_{pump}$ vs. $P_{sys}$ is monotonic for a specific $N$
- Ignore $T_{max}$ first, as it is easier to handle
  - Step 1: solve the problem without constraint $T_{max}^*$
  - Step 2: check $T_{max}$ and find optimal solution by binary search

```
1: function EvaluateNetwork(N, ΔT*, T_{max}^*)
2:     Minimize $W_{pump}$ s.t. $ΔT ≤ ΔT^*$;
3:     if $ΔT > ΔT^*$ then
4:         return $+∞$;
5:     else if $T_{max} > T_{max}^*$ then
6:         Minimize $W_{pump}$ s.t. $T_{max} ≤ T_{max}^*$;
7:         if $ΔT > ΔT^*$ or $T_{max} > T_{max}^*$ then
8:             return $+∞$;
9:         else
10:             return $W_{pump}$;
11:     end if
12: else
13:     return $W_{pump}$;
14: end if
15: end function
```
In step 1, by further substituting $\Delta T = f(P_{sys})$, Problem 1 becomes single-variable:

$$\begin{align*}
\min & \quad P_{sys}, \\
\text{s.t.} & \quad P_{sys} \in \mathbb{R}^+, \quad f(P_{sys}) \leq \Delta T^*.
\end{align*}$$

(3)

Solve (3) by searching (with three probing points):

- If a feasible $P_{sys}$ exists, return optimal $P_{sys}$
- Otherwise, return the $P_{sys}$ for minimum $f$
  (show the nonexistence of feasible $P_{sys}$)
Hierarchical tree-like structure is simple and can balance cooling:

- Between upstream and downstream
- Among different trees
Pumping Power Minimization – Network Topology Optimization

<table>
<thead>
<tr>
<th>Stage #</th>
<th>Step Size</th>
<th>Objective Function</th>
<th>Simulator</th>
<th>Runtime for an Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>$\Delta T$</td>
<td>2RM</td>
<td>short</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>$W_{pump}'$</td>
<td>2RM</td>
<td>medium</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>$W_{pump}'$</td>
<td>2RM</td>
<td>medium</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>$W_{pump}'$</td>
<td>4RM</td>
<td>long</td>
</tr>
</tbody>
</table>

- In stage 1, $\Delta T$ under a fixed $P_{sys}$ is used as cost function to accelerate
- Eight types of global flow directions are attempted
Thermal Gradient Minimization – Network Evaluation

Problem for a specific $N$ can be similarly solved:

- Its simplified form becomes:

\[
\begin{align*}
\min & \quad f(P_{sys}), \\
\text{s.t.} & \quad P_{sys} \in \mathbb{R}^+, \quad P_{sys} \leq P^*_{sys},
\end{align*}
\] (4)

- Solving (4) is simpler:
  - If $P^*_{sys}$ locates on falling side of $f$, it is optimal already
  - Otherwise, adopt golden section search
Thermal Gradient Minimization – Network Topology Optimization

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<td>$\Delta T'$</td>
<td>4RM</td>
<td>medium</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>$\Delta T'$</td>
<td>4RM</td>
<td>medium</td>
</tr>
</tbody>
</table>

Minimizing $W_{pump}$ under a fixed $P_{sys}$ is unrelated to temperature and meaningless, but minimizing $\Delta T$ under a fixed $P_{sys}$ is safe $\implies$ **speed-up**

- Some iterations are evaluated by one simulation under a fixed $P_{sys}$
- The original stage 1 is no longer needed
Experimental Results – Faster 2RM Model

- 5 benchmarks, 40 network samples, 6 thermal cell sizes and 13 pressures
- Tree-like networks, 400µm thermal cells: 0.52% errors (compared to 4RM), runtime reduced from 3.37s to 0.07s
## Experimental Results – Pumping Power Minimization

<table>
<thead>
<tr>
<th>Case #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{sys}$ (kPa)</td>
<td>12.98</td>
<td>6.23</td>
<td>7.85</td>
<td>9.71</td>
<td>N/A</td>
</tr>
<tr>
<td>$T_{max}$ (K)</td>
<td>322</td>
<td>314</td>
<td>321</td>
<td>314</td>
<td>N/A</td>
</tr>
<tr>
<td>$\Delta T$ (K)</td>
<td>15.0</td>
<td>10.0</td>
<td>15.0</td>
<td>10.0</td>
<td>N/A</td>
</tr>
<tr>
<td>$W_{pump}$ (mW)</td>
<td>10.41</td>
<td>6.91</td>
<td>8.34</td>
<td>11.65</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Baseline

<table>
<thead>
<tr>
<th>Manual (1st place in ICCAD Contest)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{sys}$ (kPa)</td>
<td>8.86</td>
<td>5.54</td>
<td>6.98</td>
<td>9.45</td>
<td>40.1</td>
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<tr>
<td>$T_{max}$ (K)</td>
<td>357</td>
<td>336</td>
<td>328</td>
<td>336</td>
<td>338</td>
</tr>
<tr>
<td>$\Delta T$ (K)</td>
<td>15.0</td>
<td>10.0</td>
<td>15.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>$W_{pump}$ (mW)</td>
<td>1.72</td>
<td>1.51</td>
<td>3.36</td>
<td>2.96</td>
<td>113.96</td>
</tr>
</tbody>
</table>

### Ours

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{sys}$ (kPa)</td>
<td>8.72</td>
<td>5.13</td>
<td>5.81</td>
<td>8.27</td>
<td>40.10</td>
</tr>
<tr>
<td>$P_{system}$ (kPa)</td>
<td>358</td>
<td>336</td>
<td>337</td>
<td>335</td>
<td>338</td>
</tr>
<tr>
<td>$\Delta T$ (K)</td>
<td>15.00</td>
<td>10.0</td>
<td>15.0</td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td>$W_{pump}$ (mW)</td>
<td>1.66</td>
<td>1.37</td>
<td>1.90</td>
<td>2.68</td>
<td>113.96</td>
</tr>
</tbody>
</table>

- **79.61%** better than baseline (unidirectional straight channels)
- **16.35%** better than 1st place in ICCAD 2015 Contest
## Experimental Results – Thermal Gradient Minimization

<table>
<thead>
<tr>
<th>Case #</th>
<th>Baseline</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Ours</th>
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<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$P_{sys}$ (kPa)</td>
<td>$T_{max}$ (K)</td>
<td>$W_{pump}$ (mW)</td>
<td>$\Delta T$ (K)</td>
<td>$P_{sys}$ (kPa)</td>
<td>$T_{max}$ (K)</td>
<td>$W_{pump}$ (mW)</td>
<td>$\Delta T$ (K)</td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>26.08</td>
<td>316</td>
<td>42.0</td>
<td>8.75</td>
<td>16.51</td>
<td>338</td>
<td>5.67</td>
<td>5.54</td>
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<tr>
<td>2</td>
<td>14.43</td>
<td>309</td>
<td>37.0</td>
<td>5.42</td>
<td>8.96</td>
<td>319</td>
<td>5.66</td>
<td>3.81</td>
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<td>3</td>
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<td>11.42</td>
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<td>327</td>
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<tr>
<td>4</td>
<td>26.51</td>
<td>308</td>
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<td>321</td>
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<td>5</td>
<td>45.81</td>
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<td>148.2</td>
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<td>40.06</td>
<td>338</td>
<td>113.80</td>
<td>9.64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Constraint $W_{pump}^*$ on $W_{pump}$ is set to 0.1% of die power
- 37.27% better than baseline
Experimental Results – Example Temperature Maps

(a) Pumping power minimization

(b) Thermal gradient minimization