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

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Introduction

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

Challenges for 3D IC Liquid Cooling
> Hot downstream and cool upstream
> large thermal gradient
> reliability and timing issues
> limited channel diameter
> high pumping requirement
> overhead to whole system
> No considering thermal gradient
> Assuming unidirectional straight channels
> Assuming unrealistic constant-temperature heat source

Thermal Modeling

Most existing models assume unidirectional straight channels
> 4-register model (4RM) in 3D-ICE (Bransh, 2009)
> 4RM Model
  > Thermal cell = basic cell
  > Solid-liquid: vertical heat transfer between two adjacent thermal cells
> Solid-solid: horizontal heat transfer between two adjacent thermal cells

4RM Model
> No conforming channel geometry
> larger and fewer thermal cells
> speed-up

Problem Formulations

Decision variables
> Cooling network topology \( N \)
> System pressure drop \( P_{sys} \)

Metrics
> Pumping power \( W_{pump} \)
> \( Q_{sys} \): system flow rate; \( \eta \): efficiency term
> Thermal gradient \( \Delta T \)
> \( \Delta T \): range of node temperatures in the source layer
> Peak temperature \( T_{max} \)

Design Rules
> TSV positions are at alternating basic cells in both dimensions
> Inlets and outlets can only occur at edges of channel layer
> At most one "continuous" inlet and outlet on each side

Problem 1: Pumping Power Minimization

\[
\min W_{pump} \quad \text{s.t. } \begin{cases} P_{sys} \in \mathbb{R}^+ \wedge N \in \mathbb{N}^+ \wedge T_{max} \leq T_{mean} \wedge \Delta T \leq \Delta T^* 
\end{cases}
\]

Problem 2: Thermal Gradient Minimization

\[
\min \Delta T \quad \text{s.t. } \begin{cases} P_{sys} \in \mathbb{R}^+ \wedge N \in \mathbb{N}^+ \wedge T_{max} \leq T_{mean} \wedge \Delta T \leq \Delta T^* 
\end{cases}
\]

Pumping Power Minimization

The problem is divided into two levels:
> Inner: \( P_{sys} \) varied to minimize \( W_{pump} \)
> Outer: \( W_{pump} \) is solved using SA searches for a good \( N \)

Overall Flow of Pumping Power Minimization

Input:
> \( N_{sys}, \Delta T_{sys}, T_{mean} \)
Output:
> \( N, P_{sys} \)

General considerations
> \( W_{pump} \) vs. \( T_{max} \) is a simple trade-off under a specific \( N \)
> Liquid cooling alleviates \( T_{max} \) and worsens \( \Delta T \)

Three inducing factors for \( \Delta T \)
1. Temperature rise of coolant
2. Non-uniform power source distribution
3. Non-uniform channel distribution

Factor 3 can be used to compensate for factors 1 & 2

Thermal Gradient Minimization

Similar to solving pumping power minimization with some optimization

Special cases
> \( f(P_{sys}) \) = \( P_{sys} \)

Network Topology Optimization

Stage 1: \( f(P_{sys}) \) is used as cost function to accelerate
Stage 2: more rounds are performed to fully explore solution space

Eight types of global flow directions are attempted

Network Evaluation

\( f(P_{sys}) \) is simplified form becomes:

\[
\min f(P_{sys}) \quad \text{s.t. } P_{sys} \in \mathbb{R}^+ ; \quad P_{sys} \leq P_{sys}^* \quad \text{(4)}
\]

Solving (4) is simpler:
> If \( P_{sys}^* \) locates on falling side of \( f \), it is optimal already
> Otherwise, adopt golden section search

Experimental Results

Faster 4RM Model

5 benchmarks, 40 network samples, 6 thermal cell sizes and 13 pressures

Tree-like Liquid Cooling Network
> Regional tree-like structure is simple and can balance cooling
> Between upstream and downstream (factor 1)
> Among different thermal cells (factor 2)

Pumping Power Minimization

40 min for cases 1-3 and 240 min for case 4
> 79.61% better than baseline (unidirectional straight channels)
> 16.35% better than 1st place in ICCAD 2015 Contest

Thermal Gradient Minimization

Minimizing \( W_{pump} \) under a fixed \( P_{sys} \) is an issue of cost function optimization

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