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SINGLE-PHASE IMMERSION COOLING MULTI-DESIGN VARIABLE HEAT SINK OPTIMIZATION FOR NATURAL CONVECTION

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ABSTRACT

This paper proposes a computational fluid dynamics (CFD) simulation methodology for the multi-design variable optimization of heat sinks for natural convection single-phase immersion cooling of high power-density Data Center server electronics. Immersion cooling provides the capability to cool higher power-densities than air cooling. Due to this, retrofitting Data Center servers initially designed for air-cooling for immersion cooling is of interest. A common area of improvement is in optimizing the air-cooled component heat sinks for the fluid and thermal properties of liquid cooling dielectric fluids. Current heat sink optimization methodologies for immersion cooling demonstrated within the literature rely on a server-level optimization approach. This paper proposes a server-agnostic approach to immersion cooling heat sink optimization by developing a heat sink-level CFD to generate a dataset of optimized heat sinks for a range of variable input parameters: inlet fluid temperature, power dissipation, fin thickness, and number of fins. The objective function of optimization is minimizing heat sink thermal resistance. This research demonstrates an effective modeling and optimization approach for heat sinks. The optimized heat sink designs exhibit improved cooling performance and reduced pressure drop compared to traditional heat sink designs. This study also shows the importance of considering multiple design variables in the heat sink optimization process and extends immersion heat sink optimization beyond server-dependent solutions. The proposed approach can also be extended to other cooling techniques and applications, where optimizing the design variables of heat sinks can improve cooling performance and reduce energy consumption. Keywords: Data Center, Thermal Management, Immersion Cooling, Heat Sink, Optimization, CFD

NOMENCLATURE

β	Volumetric Expansion Coefficient
μ	Dynamic Viscosity
ρ	Density
ρ_0	Constant Density
CoP	Coefficient of Prognosis
$\vec{F}$	External Force
$\vec{g}$	Gravity
h	Sensible Enthalpy
k	Molecular Conductivity
k_t	Turbulence Transport Conductivity
S_h	Volumetric Heat Generation
SS_E	Regression Variation
SS_T	Total Variation
T	Temperature
T_0	Operating Temperature
t	Time
$\vec{v}$	Velocity

1. INTRODUCTION

Liquid immersion cooling technology has proven the potential to provide improved thermal management for data center computation and storage systems [1]. Fully submerging server systems in dielectric fluid provides improved heat transfer, reduced operating noise, and increased energy efficiency over forced-air cooling [2]. The adoption of immersion cooling in existing data centers requires additional retrofitting of server components to take full advantage of the potential performance improvements of immersion cooling [3]. Heat sinks are critical in effectively dissipating heat from electronic devices to the surrounding dielectric fluid in an immersion cooling system.

An optimal heat sink fin configuration enhances heat transfer by increasing the convective heat transfer area. The optimization of heat sinks for single-phase immersion cooling is a topic of growing research interest [4-6]. Achieving an optimal design which utilizes natural convection inlet conditions can result in more efficient and cost-effective cooling solutions without the use of external pumping power. This decreases energy consumption and operating costs leading to enhanced system reliability and reduced energy consumption. Natural convection flow relies on buoyancy-induced flow of the dielectric liquid, driven by a density difference caused by the temperature difference between the heat sink and the fluid. This paper aims to optimize heat sinks for single-phase immersion cooling using natural convection.

In order to maximize the potential thermal performance benefits of single-phase immersion cooling, the heat sink must be optimized for the fluid properties of liquid cooling dielectric fluids. The general design optimization of parallel plate-fin heat sinks has been studied within the existing literature, primarily for heat transfer to air [7-8]. The primary research question of this study revolves around identifying the key design parameters that significantly impact the heat sink performance and determining the optimal configurations for minimizing heat sink thermal resistance specifically for immersion cooling natural convection.

This study proposes a CFD modeling methodology and multi-variable design optimization approach for determining the optimal fin characteristics for parallel plate-fin heat sinks for natural convection single-phase immersion cooling.

2. CFD MODEL METHODOLOGY

2.1 CFD Model Setup

A Computational Fluid Dynamics (CFD) model was developed in ANSYS Icepak consisting of a heat sink, thermal interface material (TIM), and 2D heat source as shown in Figure 1. A fluid domain cabinet was created to model the flow domain around the heat sink in natural convection single-phase immersion cooling.

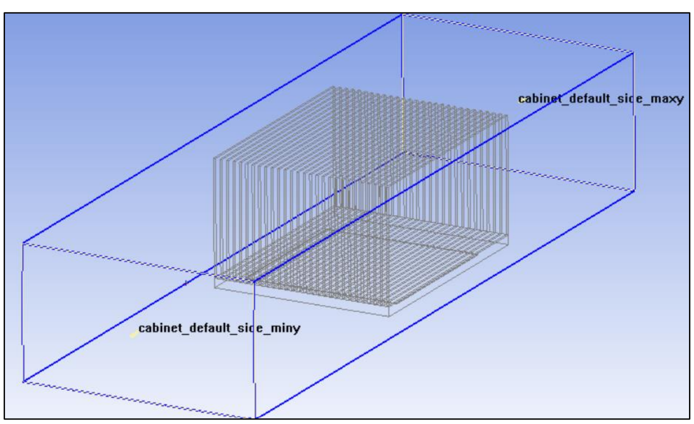

Figure 1. ANSYS Icepak Heat Sink Model

The model consists of both fixed and variable design parameters. For this study, the fluid domain is modeled as EC-110 dielectric fluid. The heat sink is modeled as an extruded aluminum parallel fin heat sink configuration with a fixed overall length of 110 mm, overall width of 86.1, base height of 4.5 mm, and overall height of 59.5 mm to model a 2U server heat sink configuration. The heater dimensions are modeled as 75 x 75 mm^2, based upon a review of current generation state-of-the-art server CPU sizes available.

Table I. Fixed CFD Model Parameters

Model Parameter	Value
Heat Sink Base Thickness	4.5 mm
Heat Sink Overall Length	110 mm
Heat Sink Overall Width	86.1 mm
Heat Sink Overall Height	59.5 mm (2U)
Heat Sink Material	Al
CPU Heater Area Size	75 x 75 mm^2
Fluid Cabinet Length	350 mm
Fluid Cabinet Width	114.1 mm
Fluid Cabinet Height	63.5 mm
TIM Thickness	0.2 mm
Tim Thermal Conductivity	8 W/m-K
Fluid Inlet Condition	1.39e-05 kg/s
Fluid Outlet Condition	101,325 N/m^2

Computational Fluid Dynamics numerical modeling solves the Navier–Stokes equations of mass, momentum, species, and energy elementwise to calculate heat transfer in laminar flow conditions. For the current study, the flow is assumed to be laminar flow and therefore the transport equations for turbulence were not used. The following equations are solved elementwise to calculate laminar flow heat transfer:

Conservation of Mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

Note that for incompressible fluid flow, this equation reduces to:

$$\nabla \cdot (\vec{v}) = 0 \quad (2)$$

Momentum Equation:

$$\rho \frac{\partial}{\partial t}(\vec{v}) + \rho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \rho \vec{g} + \mu \nabla^2 \vec{v} \quad (3)$$

Fluid Domain Energy Equation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h \vec{v}) = -\nabla p + \nabla \cdot [(k + k_t)\nabla T] + S_h \quad (4)$$

Solid Domain Energy Equation:

$$\frac{\partial}{\partial t}(\rho h) = \nabla \cdot (k \nabla T) + S_h \quad (5)$$

The Bousinessq approximative model is used to model a buoyancy-driven flow field by ignoring variable fluid densities except in the direction of a specified gravity vector. This approach treats fluid density as constant in the above equations, except for the momentum equation buoyancy term, which becomes:

$$(\rho - \rho_0)\vec{g} \approx -\rho_0 \beta (T - T_0)\vec{g} \qquad (6)$$

Where ρ_0 is the constant fluid density, T_0 is the constant operating fluid temperature, and β is the fluid volumetric expansion coefficient.

2.2 CFD Model Validation

2.2.1 Mesh Sensitivity and Grid Independence

A mesh sensitivity analysis was performed considering a baseline heat sink design to verify analysis results are grid independent and mesh density and quality is sufficient. The default minimum element size generated by ANSYS Icepak is 1/20 of the specified lengthwise direction. For the conducted grid independence study, the model mesh was varied from coarse to fine by redefining a lengthwise mesh of 1/5, 1/20, 1/30, 1/40, 1/50, 1/60, and 1/100. Heat sink thermal resistance and heater temperature were calculated and tabulated for each mesh element count, shown in Figure 2. Localized object parameter meshing control was utilized on the heatsink object within the Icepak model to ensure that a minimum of 5 elements are across the fin width, 15 elements along fin length, and 8 elements along fin height in all mesh density cases of the mesh sensitivity study. The junction temperature is within 3.2% of the value at 2,155,073 elements at 244,814 elements. Therefore, this overall mesh density was selected to conduct the optimization to significantly reduce computational workload.

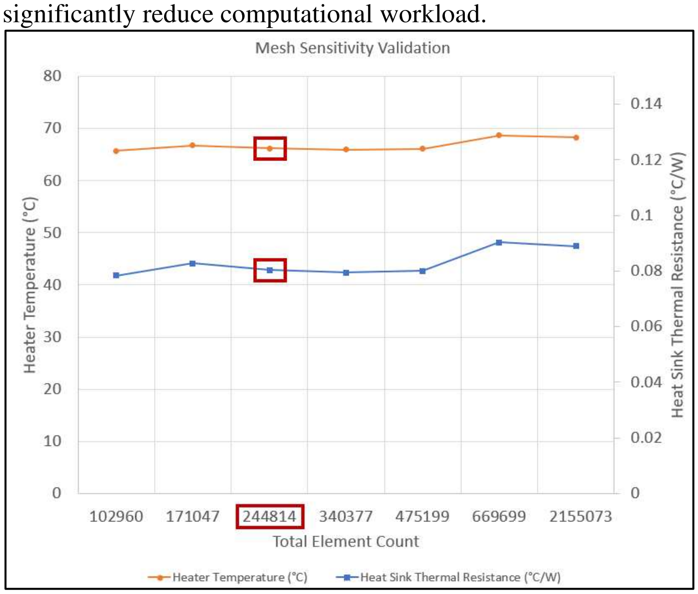

Figure 2. Mesh Sensitivity Model Validation

2.2.2 Natural Convection Modeling Approach

Validation of the fluid inlet flow conditions was carried out by determining the heater temperature for variable mass flow rate inlet conditions. This was conducted to determine the validity of assuming that at low inlet flow rates, the flow may be assumed to be fully buoyancy-driven. The mass flow inlet validation shows that the forced convection component is non-impactful to steady state heater temperatures below 0.01 LPM. Therefore, a mass flow rate fluid inlet condition of 0.001 LPM (1.39e-05 kg/s) was selected for the purpose of modeling buoyancy driven natural convection flow for the heat sink optimization process.

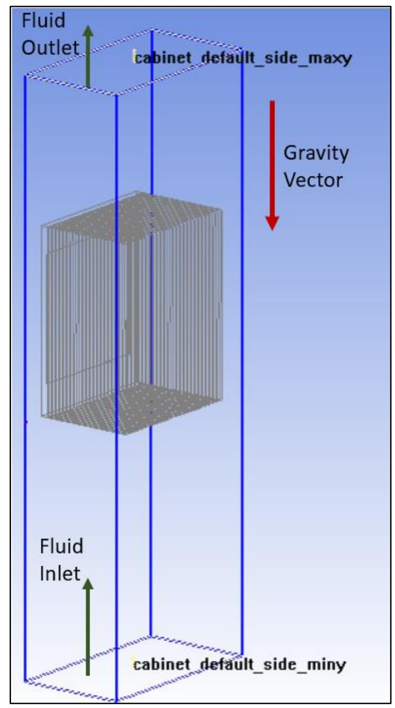

Figure 3. Natural Convection Boundary Conditions

Table II. Natural Convection Mass Flow Inlet Validation

Volumetric Flow Rate (LPM)	Mass Flow Rate (kg/s)	Heater Temp (°C)
0.00001	1.39E-07	72.1
0.0001	1.39E-06	72.1
0.001	**1.39E-05**	**72.1**
0.01	1.39E-04	72.1
0.1	1.39E-03	71.8
0.2	2.78E-03	71.4
0.4	5.55E-03	70.7
0.8	1.11E-02	69.1
1	1.39E-02	68.4

3. HEAT SINK OPTIMIZATION METHODOLOGY

ANSYS optiSLang is a process integration and design optimization tool that enables automated parametric design studies within ANSYS solvers. OptiSlang allows for multi-objective and multi-design variables to be solved independently for a range of optimization parameter bounds. The parametric optimization tool utilized is an Adaptive Meta-Model of Optimal Prognosis (AMOP) sampling approach. AMOP sampling calculates a Coefficient of Prognosis (CoP) to determine predictive approximation quality of the model variables [9].

$$\text{CoP} = 1 - \frac{SS_E}{SS_T} \qquad (7)$$

Where SS_T is the total model variation and SS_E is the variation due to regression calculated as the sum of the square of prediction errors. Higher CoP values indicate more accurate data representation within the model, reduce output data postprocessing requirements, and allow for more direct assessment of design variable trends and surface response plots for the investigated design space. AMOP is more practical for optimization cases that contain a large number of input variables, and overcomes this hurdle faced by traditional meta-modeling approaches by assessing importance of each variable to the overall model and eliminating unimportant design variables.

The objective of this multi-variable optimization model is to determine the heat sink fin parameters that provide optimal thermal performance within natural convection single-phase immersion cooling. To achieve this, an AMOP optimization is carried out for the range of variable input parameters below for the described CFD model. The optimal heat sink fin design parameters, fin thickness and fin count, are determined for variable Heater TDP and Fluid Inlet Temperature.

Table III. Variable Model Parameters

Model Parameter	Value
Heater TDP	250, 350, 450 W
Fluid Inlet Temperature	25, 35, 45 °C
Heat Sink Fin Thickness	0.6, 0.8, 1.0, 1.2, 1.4, 1.6 mm
Heat Sink Fin Count	20, 22, 24, 26, 28, 30
Objective Function	Minimize HS Thermal Resistance

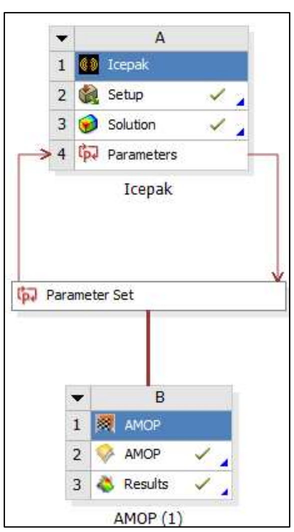

Figure 4. ANSYS Workbench optiSLang Integration

A design of experiments (DoE) is generated for the input design variables to conduct a sensitivity analysis for determining the effect of input variables on the objective function. This step is known as the design exploration phase where the design space is sampling using the selected sampling approach. In the current study, AMOP sampling is used to conduct the design space exploration. The outputs of heat sink thermal resistance and heater temperature are calculated for each sample and outputs from this phase are used to generate response surface plots and the total effects matrix in optiSLang. The total effects matrix is used to determine the weighted relationship between input design variables and the output parameters and the objective function.

4. RESULTS AND DISCUSSION

4.1 Optimization Variable Sensitivity Analysis Results

The first step in optimization data post-processing is assessing the sensitivity of the objective function and output variables to the input design variables through design exploration of the total effects matrix, to determine the relative impact of each design variable on the objective. Figure 5 displays the total effects matrix for the optimization sensitivity study. The objective function, heat sink thermal resistance, is primarily a function of Heater TDP, with a weight of 52.5%. In practice, this is often a hardware constraint rather than a tunable variable, with the goal of sufficiently cooling higher power dissipations. A key takeaway from the total effects matrix is that for the natural convection design space of this study, fin thickness has a significantly larger impact on heatsink thermal resistance than the number of fins, with a weight of 42.5% and 23.0%, respectively. Additionally, the total effects matrix is used to assess the total CoP of the model. The CoP is 100% for the objective function, and greater than 99% for all output variables. This indicates that the data points generated by the AMOP sampling approach was successful and all input variables are meaningful to the outputs.

Figure 5. Total Effects Matrix

4.2 Optimal Heat Sink Fin Parameter Results

Heat sink thermal resistance has been shown to be a function of both fin thickness (mm) and fin count from the total effects matrix (Figure 5). The dependent relationship between heat sink thermal resistance and fin design parameters can be visually represented with 3D response surfaces, shown in Figures 6 – 8 for various samples of Heater TDP and Inlet Fluid Temperature. The optimal heat sink fin thickness and fin count results for the design space are tabulated for each sampled TDP and Inlet Temperature in Table IV and V respectively.

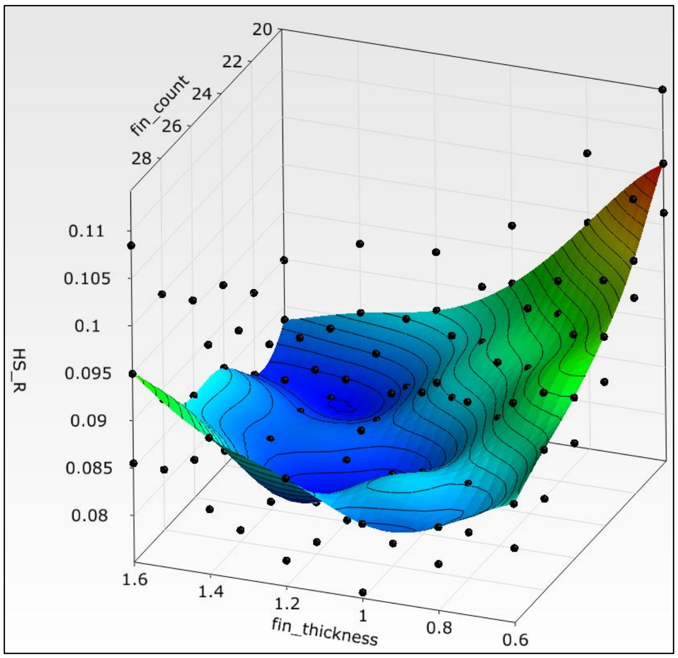

Figure 6. Optimization Response Surface Plot - Heat Sink Thermal Resistance for Fin Parameters at 25 C, 350 W

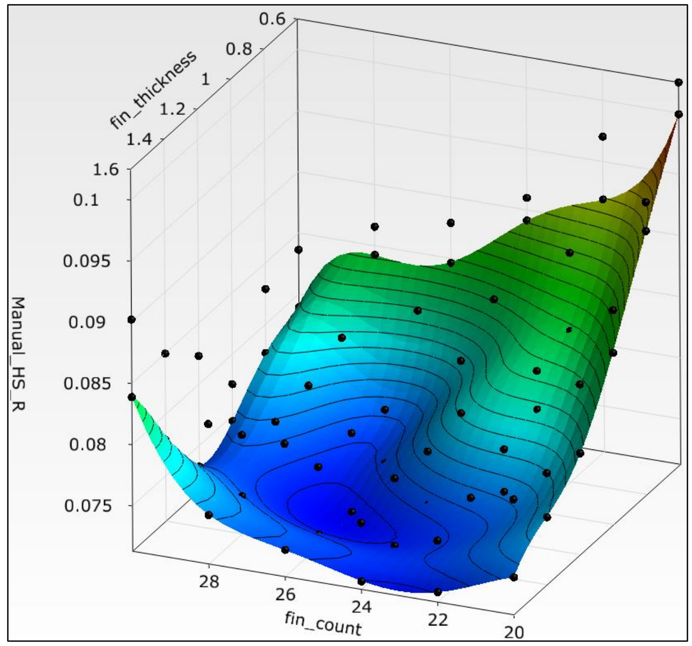

Figure 7. Optimization Response Surface Plot - Heat Sink Thermal Resistance for Fin Parameters at 35 C, 450 W

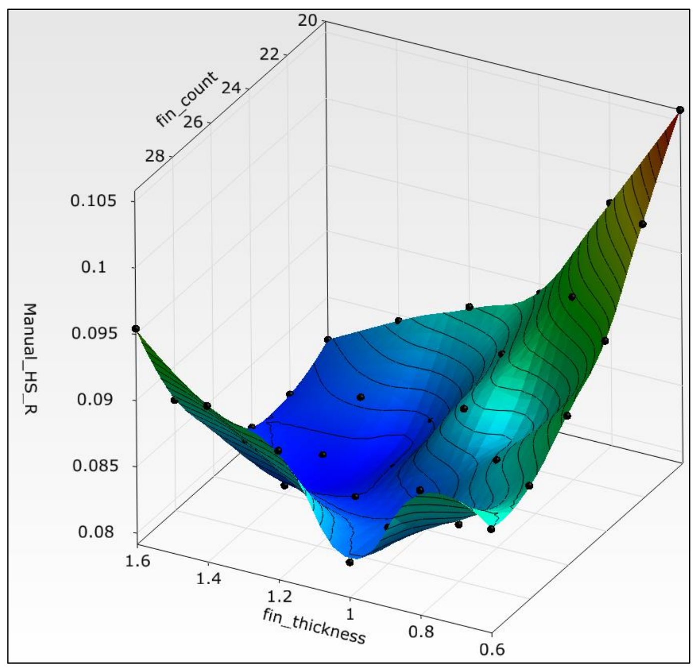

Figure 8. Optimization Response Surface Plot - Heat Sink Thermal Resistance for Fin Parameters at 45 C, 250 W

Table IV. Optimal Fin Thickness [mm]

Inlet Fluid Temperature	Heater TDP		
	250 W	350 W	450 W
25 °C	1.4	1.4	1.6
35 °C	1.4	1.6	1.2
45 °C	1.4	1.2	1.2

Table V. Optimal Fin Count (Spacing [mm])

Inlet Fluid Temperature	Heater TDP		
	250 W	350 W	450 W
25 °C	22 (2.63)	22 (2.63)	22 (2.42)
35 °C	24 (2.28)	22 (2.42)	26 (2.20)
45 °C	24 (2.28)	26 (2.20)	26 (2.20)

5. CONCLUSIONS

Natural convection single-phase immersion cooling is of interest for its ability to cool higher power densities than forced-air cooling while maintaining a more overall energy-efficient thermal management system [10-11]. This study analyzed and optimized parallel fin heat sink design parameters for natural convection single-phase immersion cooling for various inlet fluid temperatures and chip power dissipations using ANSYS Icepak and optiSLang for computational fluid dynamics simulations and multi-design variable sensitivity analysis and optimization. The relative weighted impact of TDP, inlet fluid temperature, fin thickness, and fin count (spacing) were determined with an AMOP sampling of CFD data points and optimized for the variable problem constraints and boundary conditions.

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