

Research on Structural Optimization and Intelligent Control Strategies for Liquid-Cooled Plates in High-Heat-Flow Equipment

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Abstract: Addressing industry challenges in liquid cooling systems for high heat-flux devices such as computing servers and high-power power electronic components—including poor heat transfer uniformity, high energy consumption due to flow pressure drop, limited adaptability to dynamic thermal loads, and significant discrepancies between traditional single-phase fluid simulations and practical engineering requirements—this study utilizes the ANSYS simulation platform combined with Fluent numerical fluid analysis and CFD-DEM solid-liquid coupled simulation techniques to investigate multi-objective optimization and intelligent dynamic control strategies for microchannel liquid-cooling plate structures. Using rectangular microchannel plates as the research model, core structural parameters—including channel width, spacing, and height—are optimized while evaluating multidimensional performance metrics such as maximum surface temperature, temperature variation range, and coolant flow pressure drop. An improved NSGA-III multi-objective genetic algorithm is employed to achieve global Pareto optimization of structural parameters, resolving the trade-off between cooling efficiency and flow energy consumption inherent in conventional single-parameter optimization methods. Additionally, to address issues like delayed dynamic response and suboptimal energy efficiency in traditional fixed-flow/temperature operation modes, an adaptive intelligent control system based on fuzzy PID control is developed, enabling real-time precision regulation of coolant flow rates under varying thermal load conditions. Simulation results demonstrate that multi-objective optimization significantly enhances the overall performance of the liquid-cooled plate: the maximum equipment temperature is reduced by 7.2 °C, the temperature range is decreased by 4.5 °C, the flow pressure drop is lowered by 18.3%, and the heat transfer coefficient increases by 8.0%. Under dynamic thermal load conditions with varying gradients, the designed intelligent control system maintains temperature fluctuations within ± 1.2 °C; compared to traditional constant-speed operation modes, the system achieves a comprehensive cooling energy efficiency improvement of 12.6%. The CFD-DEM solid-liquid coupling simulation method employed in this study effectively addresses the limitation of conventional single-phase CFD simulations in neglecting particle-induced heat transfer interactions, substantially enhancing numerical simulation accuracy. The proposed integrated design approach combining "static multi-objective optimization of structure + dynamic intelligent system control" provides a robust theoretical foundation and technical reference for developing efficient, low-energy-consumption, and intelligent thermal management systems for high heat flux electronic devices.

Keywords: High-heat-flow equipment; Liquid-cooled plates; CFD-DEM coupling; Fluent simulation; ANSYS; NSGA-III algorithm; Fuzzy PID; Intelligent thermal control

1. INTRODUCTION

With the rapid development of the digital computing power industry, new energy power equipment, and high-end industrial control devices, electronic components have exhibited trends toward higher integration, miniaturization, and greater power density, leading to a sharp increase in heat flux per unit area. Current mainstream computing chips, IGBT power devices, and high-density energy storage modules typically exhibit local heat flux densities exceeding 100 W/cm², while high-end industrial-grade equipment can reach 100–200 W/cm². Reliability statistics indicate that over 55% of failures in electronic devices are caused by thermal factors such as localized overheating, uneven temperature distribution, and thermal stress fatigue. The performance of thermal management systems directly determines equipment operational stability, service life, and working limits [1–3]. Therefore, developing efficient, uniform, low-energy-consumption cooling technologies capable of adapting to dynamic operating conditions remains a key research focus and core challenge in thermal management for high-heat-flux equipment.

Traditional air cooling relies on mechanical fans to force air convection for heat transfer, featuring a simple structure and low cost. However, due to limitations such as low air heat

transfer coefficient, limited heat exchange capacity, significant noise interference, and poor adaptability to high-temperature environments, it can no longer meet the cooling demands of devices with high heat flux [4, 21]. In contrast, liquid cooling has gradually replaced air cooling due to its outstanding advantages—including high specific heat capacity, elevated heat transfer coefficient, excellent temperature uniformity, low operational noise, and strong compatibility—making it the mainstream solution for data centers, high-power electrical equipment, and high-end computing hardware [2, 4, 5]. As the core heat exchange component in liquid cooling systems, the internal flow channel configuration and structural parameters of liquid cooling plates directly determine solid-liquid heat transfer efficiency, flow field characteristics, and system energy consumption, serving as critical determinants of overall thermal management performance [9, 11, 22].

In practical engineering applications, existing liquid-cooled plates predominantly employ design approaches based on empirical fixed structural parameters, resulting in poor parameter compatibility. A common contradiction arises between "excessive heat transfer capacity with redundant flow resistance" or "insufficient heat transfer efficiency with low resistance," making it challenging to achieve optimal synergy between cooling performance and fluid flow energy

consumption [9, 22]. Moreover, current liquid cooling systems typically operate under a crude model featuring constant flow rates and temperatures, failing to account for dynamic thermal load variations caused by equipment startup/stop cycles or load fluctuations. This leads to localized overheating under high-load conditions and significant redundant cooling energy consumption under low-load conditions, resulting in overall suboptimal energy efficiency [4–5]. In numerical simulation studies, most research on liquid-cooled plates relies solely on conventional single-phase CFD simulations, neglecting the coupled effects of trace suspended impurities and fine solid particles in industrial cooling fluids on flow field distribution, boundary layer heat transfer, and pressure drop. Consequently, simulation results exhibit substantial deviations from actual operational conditions, severely limiting the practical applicability of optimization outcomes [7–8].

In the field of academic research, current studies both domestically and internationally predominantly focus solely on optimizing structural parameters of liquid-cooled plates or designing thermal management system control strategies. These approaches separate static structural optimization from dynamic system control, lacking an integrated design methodology that addresses the three fundamental challenges simultaneously: equipment cooling safety, temperature uniformity, and system energy efficiency [10,14,15]. To overcome these technical limitations, this study utilizes the ANSYS Workbench simulation platform to integrate the Fluent fluid solver with the DEM discrete element module, establishing a high-precision CFD-DEM bidirectional solid-liquid coupling simulation model that accurately replicates internal two-phase flow and heat transfer mechanisms within liquid-cooled plates. Through single-variable parameter sensitivity analysis, core structural parameters were identified, followed by global structural optimization using an improved NSGA-III multi-objective genetic algorithm to obtain optimal parameter combinations that balance heat transfer efficiency, temperature uniformity, and low resistance. A fuzzy PID intelligent control system was further developed to achieve adaptive closed-loop regulation of coolant flow under dynamic thermal loads, ultimately forming an integrated high-efficiency cooling solution combining structural optimization and intelligent control. Comparative simulations across multiple operating conditions validated the feasibility and superiority of this approach, providing robust support for engineering applications of smart thermal management technologies in high-heat-flow equipment.

2. Theoretical Basis and Evaluation System

2.1 Fluid Heat Transfer Control Equation

The coolant employed in this study is deionized water, which at room temperature can be treated as a steady-state, incompressible, viscous Newtonian fluid. The fluid flow within the liquid-cooled plate and the solid-liquid heat transfer processes strictly adhere to the three fundamental laws of fluid mechanics and heat transfer, forming the core theoretical basis for numerical simulations. The simulation process disregards secondary factors such as fluid gravity and radiative heat transfer, focusing solely on the coupled effects of convective heat transfer and solid thermal conduction.

The mass conservation equation (continuity equation): The mass of a fluid remains constant throughout its flow, reflecting the law of continuous velocity distribution in the flow field. The expression is as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

The momentum conservation equation (N-S equation): It describes the balance relationship between momentum changes and pressure/viscous forces in viscous fluids during flow, serving as the fundamental equation for determining velocity and pressure distributions in flow fields. Under steady-state flow conditions, its expression is:

$$\rho(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}) = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2})$$

The energy conservation equation describes the laws of energy transfer and conversion during the heat exchange process in coolant flow, characterizing both thermal conduction and convective heat transfer at the solid-liquid interface, with the following expression:

$$\rho c_p(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}) = \lambda(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2})$$

$$u, v, w, \rho, \mu, c_p, T, \lambda$$

In the formula : is the velocity component of the fluid in the x, y, and z directions (unit: m/s); is the density of the coolant (value: 998 kg/m³); is the hydrostatic pressure of the fluid (unit: Pa); is the dynamic viscosity of the fluid (unit: Pa·s); is the specific heat capacity of the coolant at constant pressure (unit: J/(kg·K)); is the temperature of the fluid and solid regions (unit: K); and is the thermal conductivity of the fluid (unit: W/(m·K)).

2.2 Principles of CFD-DEM Solid-Solid Coupling Simulation

Traditional pure CFD single-phase fluid simulations treat coolant solely as a pure continuous-phase fluid, neglecting discrete-phase components such as trace suspended particles generated by long-term circulation, pipeline wear debris, and micro-pollutants in practical engineering applications, leading to discrepancies between simulated flow fields, temperature fields, and resistance characteristics and actual operating conditions [7]. The CFD-DEM coupled simulation technique combines the strengths of computational fluid dynamics (CFD) and the discrete element method (DEM), leveraging the ANSYS platform to enable bidirectional data exchange between Fluent's continuous-phase simulation and DEM's discrete-phase simulation, enabling precise modeling of solid-liquid two-phase flow, collision, friction, and coupled heat transfer processes within liquid-cooled plates [8].

During the coupled simulation process, Fluent is responsible for solving the velocity, pressure, and temperature distributions in the fluid continuous phase, while employing a turbulence model to capture boundary layer variations and vortex characteristics in the flow field; the DEM module handles the calculation of motion trajectories, stress states, and temperature changes of discrete solid particles, accounting for particle gravity, fluid drag force, wall impact forces, and heat conduction. Real-time momentum and energy exchanges occur between the two phases: fluids exert drag and lift forces on particles, altering their motion states; particles, in turn, perturb the fluid field, modifying local flow velocities and heat transfer rates, while enabling multi-path heat transfer among solids, liquids, and liquid particles. This coupling approach accurately reproduces the complex heat

transfer behavior of engineering cooling fluids, significantly enhancing both the accuracy of numerical simulations and their engineering applicability.

2.3 Principles of the NSGA-III Multi-objective Optimization Algorithm

Liquid cooling plate structure optimization represents a typical multi-variable, multi-objective, nonlinear constrained optimization problem, where the various objectives are interdependent and interact in a complex manner, making absolute single-objective optimality unattainable. Traditional optimization methods such as the weighted method and response surface methodology suffer from shortcomings including strong subjectivity in weight assignment, limited global optimization capability, and poor multi-objective balance [15,23]. The improved NSGA-III algorithm, built upon the framework of non-dominated sorting genetic algorithms, introduces a uniformly distributed reference point mechanism to replace the traditional crowding factor-based sorting approach. This effectively addresses issues such as loss of population diversity and poor convergence in high-dimensional multi-objective optimization, making it highly suitable for scenarios requiring coordinated optimization of multiple performance parameters in liquid cooling plates [10,15].

The core algorithm workflow comprises population initialization, fast non-dominated sorting, reference point hierarchical screening, crossover and mutation iterations, population updating, and Pareto solution set updating. Through multiple iterations, non-dominated optimal solutions are selected; all these solutions form the Pareto front solution set. No single solution can simultaneously optimize all objectives. The algorithm allows flexible selection of optimal solutions based on specific engineering requirements for heat dissipation, temperature uniformity, or energy efficiency, offering superior global optimization capability and practical engineering applicability compared to traditional algorithms.

2.4 Principles of Fuzzy PID Control

Traditional PID control relies on fixed parameters and is only suitable for linear systems with stable operating conditions. In contrast, liquid cooling systems are typical nonlinear, highly time-delayed, and time-varying dynamic systems; random fluctuations in thermal load can lead to significant overshoot, response lag, and substantial steady-state errors when using fixed PID parameters [16]. Fuzzy PID control integrates fuzzy logic reasoning with traditional PID control, using system temperature deviation and its rate of change as inputs to perform parameter adaptive adjustment via fuzzy rules, thereby continuously updating the proportional, integral, and derivative coefficients. This approach is well-suited for dynamic, nonlinear, time-varying thermal management systems, offering advantages such as rapid response, strong disturbance immunity, high temperature control accuracy, and minimal overshoot, making it ideal for dynamic thermal load management in high heat-flux equipment applications [17–20].

2.5 Performance Evaluation Indicator System

To comprehensively and objectively quantify the heat dissipation performance, temperature uniformity, and flow efficiency of liquid-cooled plates while balancing equipment operational safety and system energy efficiency, this paper establishes a multi-dimensional comprehensive evaluation

index system. The specific definitions of the indicators are as follows:

(1) Maximum temperature T_{max} : The highest temperature in the heat source coupling zone directly indicates the device's maximum allowable temperature rise and serves as a critical safety parameter to prevent thermal failure of electronic equipment; a lower value signifies stronger heat dissipation capability.

(2) Temperature ΔT range: The difference between the highest and lowest temperatures in the heat source area, indicating the uniformity of surface temperature distribution. A smaller value indicates more uniform temperature distribution, reduced thermal stress on the equipment, and higher operational stability.

(3) Flow pressure ΔP drop: The pressure difference between the coolant inlet and outlet, which characterizes the system's flow resistance characteristics and directly determines the pump's power consumption; a smaller pressure drop corresponds to lower operational energy consumption.

(4) Average heat transfer h coefficient: This parameter characterizes the overall solid-liquid convective heat transfer capability of the liquid-cooled plate; a higher value indicates greater heat transfer efficiency and more efficient heat transfer.

3. Simulation Model Construction and Grid Independence Verification

3.1 Geometric Model and Material Parameter Settings

This study employs the rectangular straight microchannel liquid cooling plate, the most widely used design in engineering applications, as the research model. Its overall dimensions are 120 mm × 80 mm × 10 mm, and it is fabricated from aluminum alloy 6063—a material characterized by high thermal conductivity, excellent machinability, low density, and cost-effectiveness, making it fully suitable for industrial liquid cooling applications. Deionized water is used as the coolant, effectively preventing issues such as pipeline scaling and electrical short circuits, thus meeting the requirements of electronic device cooling systems. The initial structural parameters of the liquid cooling plate are set as follows: single channel width of 2 mm, channel height of 6 mm, spacing between adjacent channels of 3 mm, and inlet/outlet pipe diameter of 4 mm. The heat source region simulates a high-power, high-heat-flux chip, positioned at the center of the plate's upper surface with a uniform and constant heat flux density; the rated thermal load is set at 120 W/cm², aligning with the operating conditions of mainstream high-heat-flux devices.

The material properties of the model are strictly defined according to standard values at room temperature: aluminum alloy 6063 has a thermal conductivity of 203 W/(m·K), density of 2700 kg/m³, specific heat capacity of 900 J/(kg·K); deionized water has a density of 998 kg/m³, thermal conductivity of 0.6 W/(m·K), specific heat capacity of 4182 J/(kg·K), and dynamic viscosity of 0.001 Pa·s. For the CFD-DEM coupled discrete phase particles, common trace impurity particles found in pipelines were selected with diameters ranging from 5 to 10 μm, a particle density of 2600 kg/m³, and

a mass fraction controlled within 0.5%, reflecting the actual impurity content levels in cooling fluids.

3.2 Grid Division and Irrelevance Verification

Grid quality directly determines the computational accuracy and convergence speed of numerical simulations. This study employs the ANSYS ICEM module to perform structured meshing of the model. Given the significant velocity and temperature gradients in the liquid-cooled plate flow channel region, localized mesh refinement is applied in the solid-liquid coupled heat transfer zone and inlet/outlet transition regions; a uniformly sparse mesh is used in the non-heating solid regions of the plate to maintain computational accuracy while reducing overall mesh count and enhancing efficiency. To eliminate systematic errors introduced by mesh quantity, rigorous mesh independence validation was conducted by constructing five mesh models with varying densities (ranging from 400,000 to 1,000,000 elements) under identical boundary conditions and iteration tolerances.

Comparison of maximum temperature and flow pressure drop calculations across different grid densities reveals that simulation results exhibit significant deviations and insufficient accuracy when the number of grids is below 800,000; however, after reaching 863,000 grids, further grid refinement yields calculation errors for both maximum temperature and flow pressure drop below 1%, with results stabilizing. Considering both computational accuracy and cost factors, this study ultimately determines an optimal grid density of 863,000 grids, all with a mesh quality greater than 0.85 and no negative volume grids, thereby meeting the requirements for CFD-DEM coupled simulations.

3.3 Solver and Boundary Condition Settings

This study employs the ANSYS-Fluent steady-state pressure-based solver for coupled simulation calculations, utilizing the standard $k-\varepsilon$ turbulence model—a framework specifically designed for microchannel turbulent flow conditions that offers excellent computational stability and moderate accuracy. The CFD-DEM bidirectional coupling module is activated to enforce momentum and energy exchange equations, enabling real-time iterative coupling between solid and liquid phases. The SIMPLE algorithm is employed for pressure-velocity coupling, with both convective and diffusive terms discretized using second-order windward schemes; an iteration convergence residual criterion of 10^{-6} is set to ensure computational accuracy.

The core boundary conditions are specified as follows: the coolant inlet is defined as a velocity inlet boundary with an initial flow velocity of 1.2 m/s and a constant inlet fluid temperature of 25 °C; the outlet is a pressure outlet boundary with a relative pressure set to 0 Pa; the outer surface of the liquid-cooled plate is treated as an adiabatic boundary, with environmental natural heat loss and radiative heat loss neglected; the solid-liquid interface is defined as a non-slip wall boundary with wall heat transfer enabled; a constant heat flux is applied to the heat source surface; DEM discrete particles enter the flow channel synchronously from the inlet via surface incidence, simulating realistic impurity flow behavior.

3.4 Analysis of Basic Model Simulation Results

A coupled CFD-DEM simulation was conducted on the initial structural liquid cooling plate. After convergence, data for the temperature field, flow field, and resistance characteristics were extracted. The fundamental performance results are as

follows: the maximum temperature in the equipment's heat source region is 78.6 °C, the minimum temperature is 69.3 °C, with a temperature range of 9.3 °C; the pressure drop across the coolant inlet and outlet is 326 Pa; and the average convective heat transfer coefficient of the liquid cooling plate is 826 W/(m²·K). The simulation results reveal significant performance shortcomings of conventional empirical structural liquid cooling plates: first, uneven surface temperature distribution with pronounced local hot spots and a large temperature range, which can induce substantial thermal stress and lead to equipment aging and failure over long-term operation; second, elevated flow resistance resulting in excessive pump energy consumption; third, underutilized heat transfer capacity and incomplete utilization of overall heat dissipation potential, indicating considerable room for structural parameter optimization.

4. Sensitivity Analysis of Structural Parameters

The structural parameters of liquid-cooled plate flow channels exhibit complex multi-parameter coupling effects. The impact of different parameters on heat transfer performance, temperature uniformity, and flow resistance varies significantly, with changes in any single parameter triggering multidimensional alterations in both the flow field and temperature field. To identify the most critical optimization variables that significantly influence system performance and avoid optimizing ineffective parameters, this study employs a single-variable control method: all other parameters are fixed while only one structural parameter is varied, enabling systematic analysis of each parameter's influence on evaluation metrics.

4.1 Effect of Channel Width on Heat Dissipation and Flow Performance

With the distance and height of flow channels maintained constant, simulation analysis was conducted with a width variation range of 1.5–3.0 mm and a gradient interval of 0.3 mm. The results indicate that as the channel width increases progressively, the cross-sectional area of each channel expands, enhancing fluid flow capacity while reducing internal velocity and friction losses between the fluid and walls, leading to a significant decrease in system pressure drop and improved energy efficiency. However, reduced velocity causes thickening of the fluid boundary layer, diminished solid-liquid convective heat transfer intensity, a slight decline in heat transfer coefficient, gradual rise in equipment maximum temperature, and poorer temperature uniformity. Conversely, excessively narrow channels improve heat transfer efficiency and reduce temperature rise but result in a sharp increase in flow resistance and substantial pump energy consumption, indicating significant energy redundancy. Thus, the channel width represents a critical optimization parameter where optimal balance exists between heat transfer performance and flow-related energy consumption.

4.2 Effect of Channel Spacing on Heat Dissipation and Flow Performance

With all other parameters kept constant, the flow channel spacing ranges from 2.0 to 4.5 mm. As the spacing increases, the number of channels per unit width decreases, reducing the effective heat exchange area of the liquid-cooled plate; this leads to heat concentration that cannot dissipate rapidly, resulting in higher equipment temperatures, increased temperature variation, and significantly poorer heat dissipation uniformity. However, a reduced number of channels lowers overall fluid flow resistance and causes a

slight decrease in system pressure drop. If the channel spacing is too small, sufficient heat exchange area and good temperature uniformity are achieved, but dense channels substantially increase fluid frictional resistance and energy consumption. Channel spacing significantly affects both temperature uniformity and flow resistance, making it a critical optimization parameter.

4.3 Effect of Channel Height on Heat Dissipation and Flow Performance

The flow channel height ranges from 5.0 to 8.0 mm. As the height increases, the solid-liquid heat exchange area continuously expands, the fluid's heat transfer path lengthens, heat exchange becomes more efficient, equipment temperature rise is effectively suppressed, and overall heat transfer efficiency improves. However, excessively high channel heights prolong the fluid flow path, increasing vortex losses and frictional losses within the channel, which leads to sustained increases in system pressure drop and higher energy consumption. The flow channel height exhibits a bidirectional coupling effect on both heat transfer performance and resistance characteristics, making it highly valuable for optimization.

4.4 Analysis of the Impact of Plate Thickness

Plate thickness primarily affects the solid-phase heat transfer path and thermal resistance, with no significant impact on fluid flow resistance. When the thickness is too small, the solid-phase heat transfer path becomes short but the plate stiffness is insufficient, leading to localized heat transfer unevenness; when the thickness is excessive, the solid-phase thermal resistance increases, causing delayed heat transfer and hindering rapid cooling. However, compared to the other three parameters, plate thickness has a relatively minor influence on the system's overall performance; therefore, it is excluded from the optimization variables in this study, with only channel width, channel spacing, and channel height retained as the core optimization parameters. Multi-objective collaborative optimization based on the improved NSGA-III algorithm

5. Multi-objective collaborative optimization based on the improved NSGA-III algorithm

5.1 Mathematical Model for Multi-objective Optimization

Based on the sensitivity analysis results, the optimal variables were identified as flow channel width X_1 , flow channel spacing X_2 , and flow channel height X_3 . Considering the constraints of mechanical processing technology to prevent parameters from exceeding practical limits, the variable constraint ranges were defined as: $X_1 \in [1.5, 3.0]$ mm, $X_2 \in [2.0, 4.5]$ mm, and $X_3 \in [5.0, 8.0]$ mm.

By considering engineering heat dissipation requirements, a three-objective optimization function was developed to achieve optimal synergy among thermal safety, uniform temperature distribution, and low energy consumption.

Goal 1: Minimize the maximum temperature $\min F_1(X) = T_{max}$

Goal 2: Minimize temperature range $\min F_2(X) = \Delta T$

Goal 3: Minimize flow pressure drop $\min F_3(X) = \Delta P$

Simultaneously, engineering constraints were established to ensure the optimization results are practically applicable: the

maximum equipment temperature shall not exceed 75 °C, with a temperature range variation of ≤ 6 °C, meeting safety requirements for heat dissipation and thermal stress control in high-heat-flow equipment.

5.2 Joint Optimization Process Settings

Based on the Isight optimization platform, a closed-loop joint optimization system comprising "algorithm iteration – ANSYS simulation – data feedback" was established to achieve automatic parameter iteration, automated simulation calculations, and automatic data extraction. The NSGA-III algorithm parameters were optimized: initial population size set to 100, maximum iteration count to 200, crossover probability to 0.8, mutation probability to 0.1, and reference point count to 91, ensuring population diversity and iterative convergence. For each generation, population parameters are automatically imported into ANSYS-Fluent for CFD-DEM coupled simulations; performance metrics are extracted and returned to the algorithm module for iterative updates until the maximum iteration limit is reached, ultimately yielding a complete set of Pareto optimal solutions.

5.3 Optimization Result Screening and Performance Verification

After multiple iterations, a large number of non-dominated optimal solutions were obtained; none of the solution sets represents an absolute optimum. Based on practical engineering requirements, priority must be given to balancing heat dissipation safety and energy efficiency, leading to the identification of the optimal parameter combination: flow channel width of 2.2 mm, channel spacing of 3.1 mm, and channel height of 6.5 mm. This parameter configuration was incorporated into a model and validated through CFD-DEM coupled simulations; the comparison of core performance metrics before and after optimization is presented in Table 1.

Table 1 Performance comparison of liquid-cooled plates before and after optimization

performance index	Before Optimization	postoptimality	Amendment Range
maximum temperature / °C	78.6	71.4	Reduce by 7.2 °C
Temperature Range / °C	9.3	4.8	Reduce by 4.5 °C
Flow pressure drop / Pa	326	266	Decreased by 18.3%
Average heat transfer coefficient / (W·m ⁻² ·K ⁻¹)	826	892	Increased by 8.0%

As shown in Table 1, the improved NSGA-III algorithm-based multi-objective optimization has achieved comprehensive enhancements in heat dissipation performance, temperature uniformity, and flow efficiency for the liquid-cooled plate. The maximum temperature has been significantly reduced, greatly improving equipment thermal safety; the temperature range has nearly halved, with uniform surface temperature distribution effectively mitigating thermal stress concentration; and the flow pressure drop has substantially decreased, reducing energy consumption during continuous pump operation at its source. This approach fundamentally resolves the conflict between heat transfer performance and flow resistance inherent in traditional empirical structural designs, demonstrating remarkable optimization results [10,13–15,23].

6. Design of a Fuzzy PID Intelligent Control System for Liquid Cooling Systems

6.1 Overall Architecture of the Intelligent Control System

Static structural optimization can only enhance the inherent heat dissipation performance of the liquid-cooled plate itself; however, during actual equipment operation, thermal loads fluctuate dynamically in real time, and traditional fixed-flow, fixed-condition operating modes cannot meet variable operational demands. To fully leverage the optimized heat dissipation potential of the liquid-cooled plate and further reduce system energy consumption, this paper proposes a three-tier closed-loop intelligent control system comprising a data acquisition layer, an algorithmic control layer, and an execution drive layer, enabling integrated intelligent regulation through the "perception–decision–execution" cycle. The data acquisition layer utilizes high-precision temperature sensors to collect real-time temperature signals from the equipment's heat source and coolant inlet/outlet, performs signal filtering and noise reduction processing, and provides accurate data input for the control algorithm. The algorithm control layer uses the target equipment temperature as a reference to calculate temperature deviations and their rate of change in real time, dynamically adjusts control parameters using a fuzzy PID algorithm, and outputs optimal flow regulation commands. The execution drive layer receives these commands, drives the variable-frequency pump to adjust coolant flow in real time to meet current thermal load requirements, thereby establishing a closed-loop adaptive control system.

6.2 Detailed Design of the Fuzzy PID Controller

This controller employs temperature deviation E and its rate of change EC as two-dimensional input variables, with PID parameter correction values ΔK_p , ΔK_i , and ΔK_d as three-dimensional output variables. In accordance with equipment safety operation standards, the steady-state target temperature is set at $65\text{ }^\circ\text{C}$ [16–18]. Based on the dynamic response characteristics of the thermal system, the domains of input and output variables are defined, fuzzy classification is performed, and a 5×5 -dimensional fuzzy control rule table is constructed to cover all temperature fluctuation scenarios under various operating conditions.

Fuzzy control rules adhere to the principle of dynamic adaptation: when significant temperature deviation occurs, the proportional coefficient is substantially increased to rapidly boost flow rate, accelerate system response speed, and quickly suppress temperature rise; when temperature approaches the setpoint with minimal deviation, the integral coefficient is reduced to prevent temperature overshoot caused by integral accumulation; as the system approaches steady state, the derivative coefficient is optimized to mitigate minor operational fluctuations and enhance system stability. The center-of-gravity method is employed to clarify fuzzy quantities, converting fuzzy inference results into precise, controllable digital control variables, enabling real-time PID parameter adjustment for adaptive regulation under all operating conditions.

7. Dynamic Operating Condition Simulation Verification and Energy Saving Analysis

7.1 Dynamic Gradient Condition Settings

To accurately simulate the load fluctuation characteristics during actual equipment operation, this study employs a gradient-based dynamic thermal load scenario: an initial

thermal load of 80 W/cm^2 (low load) \rightarrow a sudden increase to 120 W/cm^2 (rated high load) \rightarrow a subsequent decline to 90 W/cm^2 (medium load), comprehensively covering typical operational states including startup/stop, load escalation, and load reduction. Under identical simulation conditions, comparative analyses were conducted between traditional constant-speed control and fuzzy PID intelligent control systems, evaluating system performance across four dimensions: temperature control accuracy, response speed, temperature stability, and energy consumption levels.

7.2 Comparative Analysis of Dynamic Temperature Control Performance

Simulation results indicate that under the traditional constant-speed control mode, system parameters remain fixed and cannot adapt to thermal load fluctuations. Under low-load conditions, coolant flow is excessive, leading to excessively low equipment temperatures and significant cooling redundancy waste; under high-load conditions, flow is insufficient, causing rapid temperature spikes and large overshoots, which poses thermal failure risks; overall temperature fluctuations are substantial, and steady-state accuracy is poor.

The fuzzy PID intelligent control system designed in this paper exhibits excellent dynamic response capabilities, enabling real-time adjustment of coolant flow rate according to thermal load fluctuations: increasing flow rate promptly when thermal load rises to suppress temperature rise, and reducing flow rate appropriately when thermal load decreases to prevent cooling redundancy [5,19]. Under all operating conditions, equipment temperature fluctuations are maintained within $\pm 1.2\text{ }^\circ\text{C}$, with no significant overshoot or steady-state static error; its temperature control stability and accuracy far surpass those of traditional control methods, making it perfectly suited for dynamic variable-load operation requirements of high heat-flow equipment.

7.3 Comprehensive Analysis of the System's Energy Efficiency Performance

Through comprehensive energy consumption statistics across all operating conditions, the integrated solution proposed in this paper—"NSGA-III optimized structure combined with fuzzy PID intelligent control"—outperforms the traditional approach of "initial fixed structure + constant-speed operation." While fully ensuring equipment cooling safety and achieving required temperature uniformity, it significantly reduces both pump pumping energy consumption and overall system cooling energy consumption, achieving a comprehensive energy savings rate of 12.6%. The energy-saving mechanism consists of two key components: first, structural optimization reduces the inherent flow resistance of liquid cooling plates, lowering fundamental energy consumption at the hardware level; second, the intelligent control system dynamically adjusts flow rates as needed, eliminating redundant energy consumption under variable operating conditions through coordinated hardware-software interaction, thereby enabling efficient energy conservation.

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9. Conclusion

1) This study develops a CFD-DEM solid-liquid coupled simulation model based on the ANSYS platform. Compared to traditional single-phase CFD simulations, it comprehensively accounts for the momentum and energy coupling between trace suspended particles in the coolant and the fluid, accurately reproducing real-world heat exchange conditions in engineering applications. This approach significantly enhances the accuracy and reliability of numerical simulations for liquid-cooled plates, providing a more precise technical framework for performance simulation and optimization.

2) The channel width, channel spacing, and channel height exhibit significant nonlinear coupling effects on the heat transfer performance, temperature uniformity, and flow energy consumption of liquid-cooled plate heat exchangers; optimizing any single parameter cannot achieve optimal overall system performance. By enhancing the global optimization capability of the NSGA-III multi-objective genetic algorithm, an optimal combination of structural parameters was identified. Following optimization, the maximum temperature of the liquid-cooled plate decreased by 7.2 °C, the temperature range narrowed by 4.5 °C, the flow pressure drop reduced by 18.3%, and the heat transfer coefficient increased by 8.0%, achieving a synergistic improvement in thermal safety, temperature uniformity, and low-resistance energy efficiency.

3) To address the issues of poor dynamic adaptability and high energy consumption associated with traditional fixed-parameter operation modes, the designed fuzzy PID intelligent control system can respond in real time to sudden changes in equipment thermal load, automatically adjust coolant flow rate, and maintain temperature fluctuations across all operating conditions within ± 1.2 °C. It features high temperature control accuracy, rapid response speed, and strong resistance to disturbances, effectively resolving the conflict between overheating and cooling redundancy under dynamic operating conditions.

4) The integrated design solution proposed in this paper—"structural static multi-objective optimization combined with system dynamic intelligent control"—achieves heat dissipation system upgrades from both hardware architecture and software regulation perspectives, achieving a comprehensive energy-saving rate of 12.6%. It balances operational safety for high heat-flux devices, temperature uniformity, and overall system efficiency, providing crucial theoretical foundations and engineering references for designing intelligent, efficient liquid cooling thermal management systems for high-power electronic equipment, computing servers, and power electronic devices.

10. REFERENCES

[1] Liu Tingting et al. Research status of efficient liquid cooling technology in data centers [J]. Refrigeration and Air Conditioning, 2023(10).

[2] Wang Yu et al. Review of Research Advances in Liquid Cooling Plate Thermal Management Technology for Server Electronic Chips [J]. International Journal of Energy Research, 2022,46(9):11574–11595.

[3] Zhang H., et al. Immersive liquid cooling for electronic devices: Materials, systems, applications, and prospects [J].

Renewable and Sustainable Energy Reviews, 2025,208:114989.

[4] Sun Yue et al. Overview of Data Center Cooling Systems: Technology, Energy Consumption Modeling, and Optimization of Control Strategies [J]. Journal of Systems Architecture, 2021:102253.

[5] Chen Yang et al. Review of Optimization Control Strategies and Evaluation Metrics for Data Center Cooling Systems [J]. Sustainability, 2024,16(16):7222.

[6] Performance study of novel groove-ribbed liquid-cooled plates and full CFD model optimization [J]. Low Temperature and Superconductivity, 2024(2).

[7] Distribution and motion characteristics of ellipsoidal particles in liquid-solid two-phase flow within a vertical upward tube [J]. China Powder Technology, 2021(5).

[8] El Geitani T, [8] El Geitani T, et al. Development and validation of CFD-DEM coupling interface for heat & mass transfer using partitioned coupling approach[J]. International Communications in Heat and Mass Transfer, 2024,157:107801.

[9] Performance analysis and optimization of a microchannel liquid-cooled plate [J]. Mechanical Design and Manufacturing, 2023(3).

[10] Optimization design of liquid-cooled plates for lithium-ion batteries based on NSGA-II [J]. Journal of Chongqing Jiaotong University (Natural Sciences Edition), 2023(1).

[11] Wang Y, [11] Wang Y, et al. Experimental and numerical analysis of variable cross-section channel liquid cooling plate for server chips thermal management[J]. Thermal Science and Engineering Progress, 2024,49:102470.

[12] Li Z, [12] Li Z, et al. Balance regulation of heat transfer and flow performance in convective heat exchange process of microchannel plates[J]. Chemical Engineering Journal, 2024,495:153659.

[13] Fan R, [13] Fan R, et al. Optimization and thermal characterization of a new liquid-cooled plate with branching channels of fractal geometry[J]. Applied Thermal Engineering, 2024,254:123881.

[14] Wu X, [14] Wu X, et al. Multi-objective optimization of efficient liquid cooling-based battery thermal management system using hybrid manifold channels[J]. Applied Energy, 2024,371:123766.

[15] Jiao F, [15] Jiao F, et al. Single/multi-objective optimizations on hydraulic and thermal management in micro-channel heat sink with bionic Y-shaped fractal network by genetic algorithm coupled with numerical simulation[J]. International Journal of Heat and Mass Transfer, 2019,129:468-479.

[16] Cooling control system for converter valves based on fuzzy adaptive PID [J]. Manufacturing Automation, 2012(23).

[17] Research on UDC heat dissipation optimization based on an improved PSO-PID controller [J]. Low Temperature and Superconductivity, 2023(6).

[18] Design of a liquid cooling control system based on virtual instruments and fuzzy control [J]. Computer Simulation, 2021(7).

[19] Li M, [19] Li M, et al. Modeling and temperature control of a water-cooled PEMFC system using intelligent algorithms[J]. Applied Energy,2024,372:123790.

[20] Intelligent temperature control framework of lithium-ion battery for electric vehicles[J]. Applied Thermal Engineering,2024,236(PC).

[21] Research Progress on Server Immersion Liquid Cooling Technology [J]. HVAC, 2023(S1).

[22] Comparative study on thermal performance of multi-structured small-channel liquid-cooled plates [J]. Electronic Mechanical Engineering, 2024(2).

[23] Multi-objective optimization of automotive power battery cooling plate structure using response surface method[J/OL]. Applied Thermal Engineering.