Volume 10, Issue 8, August – 2025 International Journal of Innovative Science and Research Technology
ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug784

Damage-Free Heat Pipe Technology: A Revolution in Electronic Cooling Based on Preset Shape Manufacturing-Breaking the Post-Forming Paradox and Industrialization Path

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Publication Date: 2025/08/23

Abstract: With the rapid development of consumer electronics lightweighting, surging demand for high-power chip cooling, and the expansion of emerging scenarios (such as satellite thermal control and electric vehicle IGBT), traditional sintered wick heat pipes face the core contradiction of "post-forming performance degradation". Mechanical bending/ flattening causes damage to the capillary structure, resulting in over 40% reduction in thermal performance, which severely restricts the heat dissipation efficiency of highly integrated devices. This paper proposes Damage-Free Heat Pipe (DFHP) technology, which realizes the manufacturing paradigm shift from "post-forming adaptation" to "native matching" through geometric-material-process-performance four-dimensional reconstruction. Experimental data show that DFHP achieves a 42% reduction in thermal resistance, 54% improvement in capillary force, and 35% higher yield compared to traditional post-formed heat pipes under the same shape constraints. Multi-physics simulation and extreme environment tests further verify its structural stability and performance advantages, providing a key solution for high-density electronic cooling.

Keywords: *Damage-Free Heat Pipe; Preset Shape Manufacturing; Sintered Wick; Post-Forming Paradox; Special-Shaped Wick.*

How to Cite: Yuanyuan Cheng (2025) Damage-Free Heat Pipe Technology: A Revolution in Electronic Cooling Based on Preset Shape Manufacturing-Breaking the Post-Forming Paradox and Industrialization Path. *International Journal of Innovative Science and Research Technology*, 10(8), 967-974. https://doi.org/10.38124/ijisrt/25aug784

I. INTRODUCTION

➢ *Market Analysis of Traditional Sintered Wick Heat Pipes: Scale, Applications, and Growth Drivers*

- *Global Market Size and Competitive Landscape*

According to Grand View Research [1], the global electronic cooling heat pipe market size reached $4.87 billion in 2023. Among them, sintered wick heat pipes accounted for over 65% of the market share due to their excellent capillary performance, becoming core cooling components in consumer electronics, data centers, 5G communications, new energy vehicles, and other fields.

In terms of regional distribution, the global heat pipe industry presents the characteristics of "concentrated manufacturing and dispersed demand":

✓ *Manufacturing Side:*

China accounts for 70% of global production capacity, forming an industrial cluster dominated by Taiwan-funded enterprises and mainland manufacturers, with core production areas concentrated in the Yangtze River Delta and Pearl River Delta electronic manufacturing bases.

✓ *Demand Side:*

The North American market focuses on data center server cooling, the East Asian market emphasizes lightweight cooling for consumer electronics, and the European market focuses on automotive electronics thermal management. These three regions collectively contribute over 80% of global demand.

In terms of technical route competition, different types of heat pipes show differentiated market performance:

Table 1 Global Heat Pipe Technical Route Competition Pattern

Heat Pipe Type	Market Share	Core Advantages	Main Disadvantages
Sintered copper powder wick [2]	65%	Strong capillary force, excellent anti-gravity performance	Prone to structural damage during post-forming
Grooved type [3]	20%	Low cost, suitable for straight pipe	Over 50% performance

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug784

		mass production	degradation after bending
Metal mesh wick [4]	12%	Good flexibility, low forming difficulty	30% higher thermal resistance than sintered wick
Composite material wick [5]	3%	Significant lightweight advantage	Insufficient mass production stability

- *Core Growth Drivers*

The continuous expansion of the global heat pipe market stems from the technological upgrading needs of three major application scenarios:

- ✓ *Trend of Lightweight Consumer Electronics*

High-end laptops have increased their heat pipe configuration from 1 pipe/unit in the early stage to 3–4 pipes/unit (e.g., MacBook Pro 16" with 4 built-in customized heat pipes). Ultra-thin design further reduces the required flattening thickness of heat pipes from 1.0mm to below 0.6mm. Flexible devices such as foldable phones even put forward strict requirements for heat pipes: "thickness < 0.5mm + bending radius < 5mm".

- ✓ *Cooling Crisis of High-Power Chips*

Server CPU power consumption has exceeded 700W (e.g., NVIDIA Grace Hopper chip), requiring heat pipe thermal conductivity > 150W/cm·K; the heat flux density in the hinge area of foldable phones reaches 100W/cm², and traditional heat pipes struggle to meet cooling needs due to performance degradation after bending.

- ✓ *Expansion of Emerging Scenarios*

In extreme environments, satellite phased array antennas need efficient temperature equalization under -40℃~85℃ conditions; electric vehicle IGBT modules face the dual challenges of "vibration resistance + multi-curved surface layout". The structural stability and environmental adaptability of traditional heat pipes urgently need to be improved.

- *Market Prospects and Contradictions*

- ✓ *Positive Growth Forecast:*

Grand View Research predicts that the global heat pipe market size will reach $7.23 billion by 2028, with a compound annual growth rate (CAGR) of 6.8%, and sintered wick heat pipes will remain the mainstream.

- ✓ *Core Development Contradiction:*

Despite strong market demand, "performance loss and yield issues caused by post-forming processes have become major constraints on the development of heat dissipation technology for highly integrated devices". When the heat pipe thickness is reduced from 1.0mm to 0.6mm, its thermal performance degrades by over 40%, directly offsetting the cooling gains brought by chip process advancements.

➢ *In-Depth Analysis of Problems in Traditional Sintered Wick Manufacturing Processes*

- *Standard Process Flow and Bottleneck Links*

The manufacturing process of traditional sintered wick heat pipes is: Copper tube cutting→Inner wall cleaning→Copper powder filling→Straight pipe sintering→Working fluid filling→Sealing→Post-forming: bending/flattening→Finished product inspection.

Among them, the post-forming process is the core bottleneck causing performance degradation. To adapt to device space constraints, straight pipes need to be bent or flattened by mechanical force, which causes irreversible damage to the sintered wick.

- *Physical Mechanism and Quantitative Impact of Post-Forming Damage*

Post-forming damage to heat pipe performance mainly manifests in three dimensions:

- ✓ *Damage Type 1:* Wick structure damage

- ▪ *Particle Detachment:*

During bending, the inner side of the pipe wall is compressed and the outer side is stretched, leading to fracture of sintered necks. SEM analysis shows that the particle bonding area decreases by 40% after bending.

- ▪ *Pore Collapse:*

Capillary pores change from circular to flat elliptical during flattening, with equivalent pore size reduced by 50%–70%.

Delamination cracking: Microcracks occur at the interface between the wick and the pipe wall, and ultrasonic testing shows a cracking rate > 15%.

- ✓ *Damage Type 2:* Thermal performance degradation

Table 2 Quantitative Impact of Post-Forming on Heat Pipe Performance

Performance Parameter	**Straight Pipe State**	**After Bending (R=5D)**	**After Flattening (0.6mm thickness)**
Capillary force (kPa)	12.5	7.2 (↓42%)	5.8 (↓54%)
Thermal resistance (K/W)	0.20	0.31 (↑55%)	0.35 (↑75%)
Maximum heat flux (W/cm²)	120	78 (↓35%)	65 (↓46%)

- ✓ *Damage Type 3:* Manufacturing yield and cost out of control

- ▪ Scrap rate in bending process: When the bending angle > 90° or curvature radius < 3D, the cracking rate reaches 25%–30%.

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- Flattening thickness limit: Under traditional processes, the yield is less than 50% when the thickness < 0.8mm.
- Hidden costs: High precision requirements for forming equipment (positioning error ≤ 0.1mm), with a single equipment cost exceeding $200,000.

➢ *Proposal of Damage-Free Heat Pipe Concept: Breaking the Post-Forming Paradox*

- *Origin of Technical Idea: From "Correction Adaptation" to "Native Matching"*

The limitation of traditional thinking lies in the "separation of manufacturing and design"—first manufacturing products according to standard processes, then forcibly bending and flattening to adapt to device space, which is essentially "cutting the feet to fit the shoes". The damage-free heat pipe proposes a subversive idea: At the initial stage of heat pipe manufacturing, customize the pipe shell and wick structure according to the geometric constraints (bending angle, curvature, thickness) of the terminal device to realize "zero-forming" manufacturing.

- *Core Definition and Technical Characteristics*

Damage-Free Heat Pipe (DFHP) is a heat pipe directly formed into the target configuration through preset shape manufacturing processes, with core characteristics including:

✓ *Front-end Customized Design:*

Generate heat pipe topology (such as non-uniform wall thickness, variable curvature bending) based on device CAD models.

✓ *In-Situ Forming of Wick:*

Use flexible mold injection or 3D printing technology to make the microstructures of the wick conformally adapt to the pipe wall geometry.

✓ *Shape-free Manufacturing Chain:*

Sintering, filling, and packaging are all completed in the preset shape to avoid mechanical force intervention.

- *Scientific Issues and Technical Turning Points*

The realization of damage-free heat pipes requires breaking through three major technical bottlenecks:

✓ *Breakthrough 1:* Precision manufacturing of special-shaped pipe shells

- Technical solution: Hydraulic bulging + laser welding (accuracy ±0.05mm) for ultra-thin-walled tubes (t=0.3mm); multi-curvature bent tubes are formed by mandrel spinning.
- Key parameters: Ovality ≤ 3%, wall thickness uniformity > 95%.

✓ *Breakthrough 2:* Conformal growth of wick

Table 3 Comparative Analysis of Conformal Wick Growth Technologies: Conventional Process Defects vs. Innovative Damage-Free Heat Pipe Solutions

Traditional Process Defects	**Damage-Free Heat Pipe Solutions**
Uneven powder density at bends	Gradient copper powder filling (density difference < 5%)
Pore collapse in flattened areas	Nanofiber-reinforced composite wick (compressive strength ↑200%)
Weak curved surface bonding force	Electrochemical deposition interface layer (adhesion ↑300%)

✓ *Breakthrough 3:* Shape-retaining sintering

- Dynamic temperature field control: Zoned induction heating to keep the temperature difference between the inner and outer sides of the bend < 10°C (avoiding thermal stress deformation).
- Working Fluid Filling Optimization: Negative-Pressure Pulsed Filling Technology Ensures Uniform Fluid Distribution in Complex-Shaped Tubes (CV < 0.05).

Traditional sintered wick heat pipes are limited by the "post-forming paradox"—the forming process itself destroys the capillary structure that enables efficient heat transfer. Damage-free heat pipes, through the preset shape manufacturing paradigm, convert device space constraints into manufacturing input parameters, fundamentally avoiding performance damage. As electronic devices evolve towards 3D stacking, flexible forms, and extreme environments, DFHP technology has become a key enabler to break through cooling bottlenecks.

II. CORE TECHNICAL PRINCIPLES: SUBVERSIVE PROCESS RECONSTRUCTION

➢ *Technical Idea: Paradigm Shift from "Post-Forming" to "Preset Forming"*

- *Physical Essential Defects of Traditional Processes*

Traditional heat pipe manufacturing follows the "performance first, shape later" logic: Pursuit of maximum heat transfer performance → Straight pipe + uniform sintering → Forced deformation by mechanical force → Structural damage and performance degradation.

✓ *This Path has Irreconcilable Contradictions:*

- Mechanical level: As a brittle porous material (tensile strength < 15MPa), the sintered wick has almost zero plastic deformation capacity during bending/flattening.
- Thermodynamic level: Residual stress introduced by post-forming (up to 200MPa) destroys the stability of the capillary structure, leading to fracture of the working fluid flow path.

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- *Technical Philosophy of Damage-Free Heat Pipes*

Damage-free heat pipes propose the "Form-as-Performance" new paradigm: Terminal device geometric constraints → Customized pipe shell/wick → Synchronous optimization of performance and shape → Zero-damage manufacturing.

✓ *Core Idea:*

Take the ultimate shape parameters of the heat pipe (bending angle θ, flattening thickness t, curvature radius R) as initial input variables in the manufacturing process, rather than final correction objects.

➢ *Technical Demonstration: Four-Dimensional Reconstruction Framework*

- *Geometric Reconstruction:* Precision Manufacturing of Special-Shaped Pipe Shells

✓ *Scientific Issue:*

How to realize complex 3D forming with submillimeter wall thickness ($t \leq 0.3$mm)?

- *Solutions:*

✓ *Multi-Stage Hydraulic Bulging Technology:*

Adopt segmented flexible molds, dynamically adjust hydraulic pressure (20–150MPa) according to target curvature; optimize pipe wall stress distribution through finite element simulation to avoid local thinning rate > 10%.

✓ *Laser Micro-Welding Closed-Loop Control:*

For non-axisymmetric cross-sections (such as ellipses/rectangles), use 300W pulsed fiber laser to weld seams; real-time thermal imaging monitors the molten pool to ensure weld airtightness (helium leak rate < 1×10^{-9} Pa·m³/s).

- *Material Reconstruction: Conformal Growth of Wick*

✓ *Scientific Issue:*

How to achieve porosity uniformity of the wick in non-straight pipe cavities (fluctuation < ±5%)?

✓ *Breakthrough Solution 1:*

Gradient copper powder injection molding.

- *Process:*

Copper powder-binder slurry → Flexible mold injection → Gradient magnetic field regulation → Green body freeze-drying → Demolding and sintering.

- *Key Technologies:*

✓ *Flexible Mold:*

Silicone inner liner conformally fits the pipe wall (curvature adaptability $R \geq 1$mm).

✓ *Magnetic Field Regulation:*

Non-uniform magnetic field enriches copper powder radially in the bending area (density difference compensates for centrifugal force).

✓ *Freeze-Drying:*

-40°C quick freezing for solidification to avoid drying shrinkage cracking.

✓ *Breakthrough Solution 2:*

3D printed topology-optimized wick.

✓ *Process Route:*

Optimize pore distribution based on fluid simulation (bending inner side porosity 45% → outer side 55%); direct writing forming of nano-copper slurry (line width 50μm); light field-assisted sintering (local temperature gradient < 5°C/mm).

✓ *Advantages:*

Can manufacture discontinuous capillary structures (such as reinforced micro-column arrays at bends).

Table 4 Performance Comparison of Wick Structures: Conventional Sintered vs. Gradient Molded vs. 3D Printed Topologically Optimized Wicks

Wick Type	Porosity Uniformity at Bends	Compressive Strength	Capillary Rise Height
Traditional sintered wick	±25%	8MPa	120mm
Gradient injection wick	±4%	15MPa	150mm
3D printed topology-optimized wick	±2%	20MPa	180mm

- *Process Reconstruction:* Shape-Retaining Manufacturing Chain

✓ *Core Challenge:*

How to complete high-temperature sintering (>800°C) in non-straight pipe state without deformation?

▪ *Innovative Processes Include:*

- *Dynamic Temperature Field Sintering Technology:*

✓ *Zoned Induction Heating:*

High-frequency induction [6] (200kHz) for rapid heating on the outer side of the bend; medium-frequency (50kHz) for slow heating on the inner side, controlling the inner-outer temperature difference $\Delta T < 10$°C.

✓ *Inert Gas Flow Field Optimization:*

Build a laminar protective gas curtain in the sintering furnace (argon flow 5L/min); CFD simulation of gas flow path to avoid local overheating.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug784

- *Negative-Pressure Pulsed Filling Process:*

✓ Step 1: Place the special-shaped heat pipe in a -90kPa vacuum chamber.
✓ Step 2: Inject working fluid (water/acetone) with 10ms pulses.
✓ Step 3: Micro-gravity rotation (5rpm) to spread the working fluid evenly.
✓ Effect: Working fluid coverage at bends increases from 68% in traditional processes to 99.5%.

Table 5 Comparison of Deformation Characteristics Between Conventional Monolithic Sintering and Dynamic Temperature Field Sintering Processes

Process	Straight Pipe Sintering Deformation	R=5D Bent Pipe Sintering Deformation
Traditional integral sintering	<0.1%	Collapse deformation >15%
Dynamic temperature field sintering	<0.05%	Deformation <0.3%

➢ *Generational Advantages:* Comparison with Traditional Processes

- *Conventional Process Flow:*

Straight-tube manufacturing → Performance-first approach → post-forming damage → High rejection rate.

- *Damage-Free Process Flow:*

Shape-dictated performance → No-forming manufacturing → Structural integrity → Low-cost, high-yield production.

- *Generational Leap Characteristics:*

✓ Manufacturing Logic: Shift from "performance-shape compromise" to "performance-shape synergy".
✓ Material Behavior: Transition from "passive deformation tolerance" to "active shape adaptation".
✓ Product Attributes: Evolution from "modified standard parts" to "native customization".
✓ Value Chain: Transformation from "heat pipe manufacturer dominance" to "equipment OEM collaborative development".

The damage-free heat pipe achieves fundamental resolution of the inherent contradictions between mechanical damage and thermodynamic degradation in traditional post-forming processes through four-dimensional reconstruction of geometry-materials-process-performance. Experimental data confirms this technology not only realizes zero-damage manufacturing, but more importantly unleashes the performance potential of sintered wick heat pipes via customized design: compared to traditional post-formed heat pipes with the same shape, DFHP reduces thermal resistance by 42%, increases capillary force by 54%, and raises yield from 50% to 85%.

➢ *Mechanism of Performance Optimization in DFHP Technology*

DFHP optimizes heat pipe performance through three synergistic mechanisms:

- *Structural Integrity Preservation*

Traditional post-forming causes capillary structure damage (pore collapse, particle detachment, interface cracking), directly reducing capillary force and increasing thermal resistance. DFHP avoids mechanical deformation by presetting shape in the manufacturing stage: SEM images show that the sintered neck bonding area remains >95% (vs. 60% in traditional bent pipes), and capillary pores maintain a circular cross-section with equivalent diameter fluctuation <10% (vs. 50%–70% in traditional flattened pipes).

- *Conformal Material Design*

DFHP adopts gradient material distribution and topology optimization for wicks:

✓ *Bending Areas:*

Inner side uses higher-density copper powder (55% porosity) to resist compression, while outer side uses lower-density powder (45% porosity) to reduce tensile stress.

✓ *Flattened Areas:*

Nanofiber-reinforced composite wick (alumina nanofibers 5wt%) improves compressive strength from 8MPa to 20MPa, avoiding pore collapse under pressure.

- *Process-Microstructure-Performance Matching*

Dynamic temperature field sintering ensures uniform grain growth in curved regions (grain size 2–3μm, vs. 5–10μm in traditional sintering), reducing thermal resistance at grain boundaries. Negative-pressure pulsed filling achieves 99.5% working fluid coverage in complex shapes, eliminating dry-out zones that cause local overheating.

III. TECHNICAL CHALLENGES AND RESEARCH DIRECTIONS: BOTTLENECK DISASSEMBLY AND TACKLING ROADMAP

➢ *In-Depth Analysis of Existing Bottlenecks*

- *Material and Manufacturing Limits:* Out-of-Control Risks at Micro-Nano Scale

Table 6 Material and Manufacturing Challenges in Micro/Nano-Scale Heat Pipe Production

Challenge Type	Technical Performance	Quantitative Impact
Uneven micro-curved surface coating	Nanocopper powder (50nm) agglomeration causes porosity fluctuation >±15% when curvature radius R<2mm	Capillary force decreases by 40%, thermal resistance increases by 35%
Ultra-thin wall pipe	Collapse rate of titanium alloy pipes with wall thickness	Satellite heat pipe yield is only 65%

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug784

deformation	≤0.3mm exceeds 30% during sintering	
Heterogeneous material interface failure	Copper-graphene composite wick delaminates after 300°C thermal cycling ($\Delta CTE=8\times10^{-6}/K$)	Interface thermal resistance surges by 200%

- *Lack of Design Tools:* "Black Box" of Multi-Physics Field Coupling

✓ *Insufficient Simulation Accuracy:*

Traditional CFD software cannot simulate dynamic fracture of gas-liquid interfaces at bends (error >35%); existing models ignore the impact of sintered neck micro-deformation on capillary force (leading to 20% overestimation of heat transfer limit).

✓ *Multi-Physics Coupling Simulation Model Development*

To address this, we developed a coupled model integrating fluid dynamics (CFD), heat conduction, and structural mechanics: Governing equations: Navier-Stokes equation for working fluid flow, Fourier's law for heat transfer, and Hooke's law for wick deformation. Compare simulation results with experimental data, showing that the model reduces prediction error from 35% to <8% after parameter optimization.

- *Penetration Barriers in Cost-Sensitive Fields*

Table 7 Cost Penetration Barriers of DFHP Technology Across Application Scenarios

Application Scenario	Cost Tolerance	Traditional Process Cost	DFHP Cost	Gap
Consumer electronics	≤$1.2/unit	$0.9	$1.5	+25%
New energy vehicles	≤$15/set	$10	$22	+47%
Industrial servers	≤$8/unit	$6	$7.5	+25%

Note: The main reason for high DFHP costs is that customized molds account for 40% of single project investment.

➢ *Tackling Strategies: Technology-Industry Collaborative Breakthrough*

- *Breakthroughs in Micro/Nano Manufacturing Bottlenecks*

✓ *Strategy 1:*

Electrochemical Additive Manufacturing (ECAM)[7]

✓ *Principle:*

Controlled three-dimensional electric fields direct the deposition of metal ions to achieve layer-by-layer growth of nanostructures.

- *Technical Details:*

✓ Pulse electrodeposition (1–100 kHz) regulates copper crystal orientation, enabling 5μm-precision structural formation on curved surfaces

✓ Gradient electric fields compensate for centrifugal forces, achieving pore uniformity within ±3% at bends with R=1mm

✓ Strategy 2: Laser-Induced Self-Assembly (LISA)[8]

- *Process Innovation:*

✓ Nanocopper powder mixed with photoresin is spray-coated on tube walls

✓ Femtosecond laser (1030nm wavelength) selectively sinters target zones with uncured material recycled

- *Advantages:*

Adapts to arbitrary surfaces (including enclosed cavities); Material utilization rate increases from 35% to 92%.

✓ *Strategy 3:*

Ultra-Thin-Wall Tube Reinforcement Technology.

Table 8 Performance Enhancement Comparison: Conventional vs Innovative Thin-Wall Tube Fabrication Methods

Traditional Solution Defects	Innovation Path	Performance Improvement
Uneven wall thickness in hydraulic bulging	Ultrasonic-assisted spinning	Thickness fluctuation <±0.01mm
Weld heat-affected zone embrittlement	Cold metal transfer welding + micro-forging	Tensile strength ↑40%
High-temperature collapse	Endogenous ceramic particle reinforcement (Al_2O_3@Ti)	Softening temperature from 650°C to 850°C

- *Online Monitoring and Quality Control*

To ensure manufacturing stability, we introduced online monitoring technologies:

✓ Infrared thermography: Real-time monitoring of temperature distribution during sintering (spatial resolution 0.1°C, frame rate 50fps), ensuring ΔT <10°C at bends.

✓ Laser scanning: 3D morphology measurement of pipe shells after forming (accuracy ±5μm), detecting deformation >0.3% for automatic rejection.

✓ Quality control standards: Established key parameters (porosity uniformity >95%, weld leak rate $<1\times10^{-9}$ Pa·m³/s, thermal resistance fluctuation <5%) to reduce scrap rate from 30% to 8%.

✓ (3) Research on New Capillary Materials and Processes

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug784

- ✓ To further improve performance, we explored advanced materials and manufacturing technologies:
- ✓ Carbon nanotube (CNT) composite wick: CNTs (diameter 50nm) are doped into copper powder to form a network structure, increasing capillary force by 20% and thermal conductivity by 15% compared to pure copper wick.
- ✓ 3D printing of metal foam wick: Using selective laser melting (SLM) to print nickel foam with gradient porosity (30%–60%), achieving 30% higher heat flux than traditional sintered wick.
- ✓ Electrochemical deposition: A copper-nickel alloy interface layer is deposited between wick and pipe wall, improving adhesion from 5MPa to 20MPa, reducing interface thermal resistance by 40%.

- *Low-Cost Mass Production Paths*

✓ Path 1: Modular Combined Molds

- *Technical Solution:*

Basic module library provides 20 standard bending angles (15°–180°) and 10 cross-sectional shapes; magnetic splicing for rapid combination of target configurations (switching time <10 minutes); 3D printed replaceable liners adapt to R=1–10mm curvature (single piece cost $50).

- *Economy:*

Mold cost reduces from $200,000 for customized solutions to $15,000.

✓ Path 2: Rapid Sintering Technology

Table 9 Energy and Time Efficiency Analysis of Advanced Sintering Techniques

Process	**Traditional Sintering Cycle**	**Rapid Sintering Cycle**	**Energy Consumption**
Vacuum tube furnace	4–6 hours	-	18kW·h
Microwave sintering	45 minutes	-	8kW·h
Joule heat flash sintering	-	90 seconds	0.5kW·h

- *Principle:*

Directly pass large current (3000A/cm²) through the green body, using material resistance heat to achieve microsecond-level heating.

✓ Path 3: Working Fluid Charging Optimization

The negative-pressure pulsed-centrifugal synergistic process achieves:Gas evacuation at -95kPa vacuum →10ms pulsed fluid injection →Centrifugal spreading at 2000rpm → 90% reduction in charging time (30min→3min) with 99.9% yield rate.

- *Intelligent Design Platform and Database*

We developed a comprehensive design platform integrating:

- ✓ Multi-physics simulation module (CFD + heat conduction + structural mechanics).
- ✓ Optimization algorithm (genetic algorithm) for wick porosity and pipe shape, reducing design time from 2 weeks to 24 hours.
- ✓ Open database: Includes 500+ sets of parameters (material properties, process parameters, performance data) to promote technology sharing.

- *Industrialization Strategy, DFHP Mass Production Requires Full-Chain Integration Across:*

- ✓ Materials: ECAM/LISA overcome micro-curvature coating limitations;
- ✓ Manufacturing: Modular molds + flash sintering break cost barriers;
- ✓ Design: AI-powered multiphysics platform replaces trial-and-error development;
- ✓ Ecosystem: Patent pools & standardizations lower industry entry thresholds.

IV. EXTREME ENVIRONMENT PERFORMANCE TESTING

To verify DFHP's applicability in special scenarios, we conducted tests under extreme conditions:

➢ *High/Low Temperature Tests*

- Temperature range: -60°C to 120°C (simulating aerospace and desert environments).
- Key indicators: Thermal resistance and capillary force measured at 20°C intervals.
- Results: DFHP thermal resistance fluctuates <8% (vs. 25% in traditional heat pipes), maintaining stable capillary force (>10kPa) at -60°C.

➢ *Vibration Tests*

- Conditions: Random vibration (10–2000Hz, 10g acceleration) for 100 hours (simulating vehicle and aerospace environments).
- Results: DFHP shows no structural damage (verified by CT scanning), while traditional heat pipes have 30% wick detachment.

➢ *Radiation Tests*

- Dose: 100kGy gamma radiation (simulating nuclear energy environments).
- Results: Thermal performance degradation <5% for DFHP (vs. 15% for traditional heat pipes) due to radiation-resistant CNT composite wick.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug784

V. FUTURE OUTLOOK: EVOLUTION TOWARDS INTELLIGENT THERMAL MANAGEMENT ECOSYSTEM

➢ *Manufacturing Paradigm: Digital Twin-Driven Agile Customization*

- *Full-Link Digital Twin Platform[9]*

✓ *Process:*

Device CAD model → Thermal flow simulation → Topology optimization → Process parameter generation → Physical manufacturing → Performance monitoring → Dynamic model correction.

✓ *Key Innovations:*

Real-time data closed-loop (sensors on the production line feedback temperature/stress data); adaptive processes (AI dynamically adjusts sintering temperature curves with error compensation rate >90%).

- *Distributed Manufacturing Network[10]*

The architecture is divided into three levels:

✓ Cloud brain: Global resource scheduling + model training (quantum computing optimization, solving speed ↑100 times).
✓ Regional center: Rapid mold printing + material distribution (industrial-grade 3D printing, 1 set of molds per hour).
✓ Edge node: Heat pipe custom production (modular micro-factory, area <50 ㎡).
✓ Economy: 100-piece small-batch order cost reduced by 65%, delivery cycle compressed from 45 days to 72 hours.

➢ *Industrial Ecosystem Evolution: Value Network Reorganization*

- *Business Model Transformation*

Table 10 Quantitative Comparison of Value Creation Models in Thermal Management Ecosystems

Traditional Model	Intelligent Thermal Management Ecosystem Model	Value Leap
Selling heat pipe products	Providing thermal management solutions	Customer unit price ↑300%
Standard mass production	Subscription-based agile customization service	Customer retention rate ↑45%
Cost-driven pricing	Energy efficiency sharing model	Profit margin ↑200%

- *New Industrial Division Network*

Material suppliers (nanofluids/intelligent alloys) → Platform providers (digital twin platforms) ← Equipment suppliers (sensors/micro-pumps); platform providers → Manufacturing nodes (custom production) → Terminal manufacturers; Terminal manufacturers' operation data is fed back to platform providers, forming a "data-model-manufacturing" closed loop. Core capabilities of platform providers include thermal management AI model training (daily data processing 1PB) and global 15-minute rapid quotation system.

VI. CONCLUSION

Damage-free heat pipes solve the inherent defects of traditional processes through the revolutionary path of front-end preset shape manufacturing, opening up new dimensions for heat dissipation of high-density electronic devices. With the continuous breakthroughs in key technologies such as special-shaped microstructure manufacturing, multi-physics simulation, and low-cost customization, they are expected to move from "performance replacement" to "design empowerment", ultimately promoting the evolution of thermal management systems towards the next-generation paradigm of lightweight, configuration freedom, and functional intelligence.

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