Bio-Inspired Leaf Vein Microchannel Cooling System for EV Batteries

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ABSTRACT:
Thermal management is a critical challenge in electric vehicle (EV) battery systems. This paper presents a bio-inspired microchannel cooling system that mimics the hierarchical branching architecture of leaf veins to achieve efficient and uniform heat dissipation across lithium-ion battery packs. The proposed fractal-based microchannel network, governed by Murray's law, is designed to minimize flow resistance while maximizing the surface area for heat exchange. Computational fluid dynamics (CFD) simulations and experimental validation demonstrate that the leaf vein-inspired design outperforms conventional parallel and serpentine channel configurations in terms of temperature uniformity and pressure drop.

KEYWORDS: Leaf Vein Microchannel, Bio-Inspired Cooling, EV Battery Thermal Management, Fractal Channel Network, Murray's Law, CFD Simulation, Lithium-Ion Battery

1. INTRODUCTION

The rapid proliferation of electric vehicles (EVs) has intensified the demand for high-performance battery thermal management systems (BTMS). Lithium-ion batteries, which are the dominant energy storage technology in modern EVs, exhibit performance degradation and accelerated aging when operated outside the optimal temperature range of 15°C to 35°C. Excessive heat generation during charge–discharge cycles can lead to thermal runaway, posing serious safety risks. Consequently, effective cooling strategies are essential for reliable and safe EV operation.

Conventional cooling approaches—including air cooling, liquid cooling with parallel or serpentine channels, and phase-change material (PCM) systems—often suffer from trade-offs between cooling efficiency, pressure drop, weight, and manufacturing complexity. Bio-inspired design, which draws from millions of years of natural optimization, offers a promising avenue to overcome these limitations.

Leaf venation networks represent one of the most efficient fluid distribution architectures found in nature. The hierarchical branching pattern of leaf veins, governed by Murray's law, minimizes transport resistance while ensuring uniform distribution of nutrients and water across the entire leaf surface. This paper proposes a microchannel cooling system for EV battery packs that is architecturally inspired by this natural vascular network.

2. LITERATURE REVIEW

Extensive research has been conducted on BTMS for lithium-ion battery packs. It is reported that liquid-cooled systems provide superior heat transfer compared to air-cooled counterparts, particularly at high discharge rates [1]. Studies on serpentine channel designs have demonstrated improved temperature uniformity but at the cost of higher pressure drop [2]. Bio-inspired heat exchangers have gained increasing attention in recent years [3].

Murray's law, originally formulated to describe the branching geometry of blood vessels, states that the cube of the radius of a parent vessel equals the sum of the cubes of the radii of its daughter vessels. Application of this principle to microchannel heat exchangers has been demonstrated to reduce pumping power requirements while maintaining adequate flow distribution [4]. However, direct application to battery cooling systems remains limited in the literature.

3. EXISTING SYSTEM

3.1 Conventional Battery Thermal Management Approaches

The existing battery thermal management systems primarily rely on three conventional approaches: air cooling, liquid cooling, and phase-change material (PCM)-based cooling. Air cooling is the simplest and most cost-effective method, utilizing forced convection to remove heat from the battery surface. However, it is limited by the low thermal conductivity and specific heat capacity of air, making it inadequate for high-power EV applications.

3.2 Parallel and Serpentine Microchannel Cooling

Liquid-cooled microchannel systems using parallel or serpentine channel configurations represent the current state of the art in high-performance EV battery cooling. Parallel channel designs offer low pressure drop but suffer from non-uniform flow distribution, resulting in temperature gradients across the battery module. Serpentine designs improve temperature uniformity at the expense of significantly higher pressure drop and pumping power requirements.

3.3 Limitations of Existing Systems

The key limitations identified in existing cooling systems include: (i) poor temperature uniformity across the battery module leading to differential aging and reduced cycle life; (ii) high pressure drop in serpentine designs requiring additional pumping power; (iii) complex manifold geometries increasing manufacturing cost and weight; and (iv) inability to scale efficiently with increasing battery module sizes. These shortcomings motivate the development of the novel bio-inspired cooling architecture presented in this work.

Table 1: Comparison of Existing Battery Cooling Systems

Parameter	Air Cooling	Parallel Liquid	Serpentine Liquid	PCM Cooling
Cooling Efficiency	Low	Moderate	High	High
Pressure Drop	Very Low	Low	High	N/A
Temp. Uniformity	Poor	Moderate	Good	Good
Pumping Power	Low	Low	High	None

Parameter	Air Cooling	Parallel Liquid	Serpentine Liquid	PCM Cooling
Manufacturing Cost	Low	Moderate	Moderate	High
Scalability	Limited	Good	Limited	Limited

4. PROPOSED SYSTEM

4.1 Overview of the Bio-Inspired Design

The proposed system is a bio-inspired microchannel cold plate whose internal fluid network replicates the hierarchical branching topology of a dicotyledonous leaf vein pattern. Unlike conventional parallel or serpentine channels, the proposed architecture distributes coolant through progressively finer branching levels—analogous to the midrib, primary veins, secondary veins, and tertiary veins of a leaf—ensuring both low pressure drop and highly uniform flow distribution across the entire battery cooling surface.

4.2 Design Principles Based on Murray's Law

The channel dimensions at each branching level are determined by Murray's law, which states that the optimal branching ratio minimizes the total power required to drive fluid through the network. For a symmetric bifurcation, the branching ratio is 2^(−1/3) ≈ 0.794, meaning each daughter channel has approximately 79.4% of the diameter of its parent channel. This principle is applied iteratively through four branching levels to generate the complete microchannel network.

The channel radii at each branching level satisfy the relation:

$$r_0^3 = r_1^3 + r_2^3 \qquad (1)$$

where r_0 is the radius of the parent channel, and r_1, r_2 are the radii of the two daughter channels at each bifurcation node.

4.3 Material and Fabrication

The cold plate is fabricated from 6061-T6 aluminium alloy (thermal conductivity: 167 W/m·K) using a combination of CNC micro-milling and diffusion bonding. The microchannel features are machined into the base plate with a surface roughness of $Ra \leq 0.8$ μm. The coolant used is a 50:50 (by volume) mixture of ethylene glycol and deionized water.

4.4 Advantages Over Existing Systems

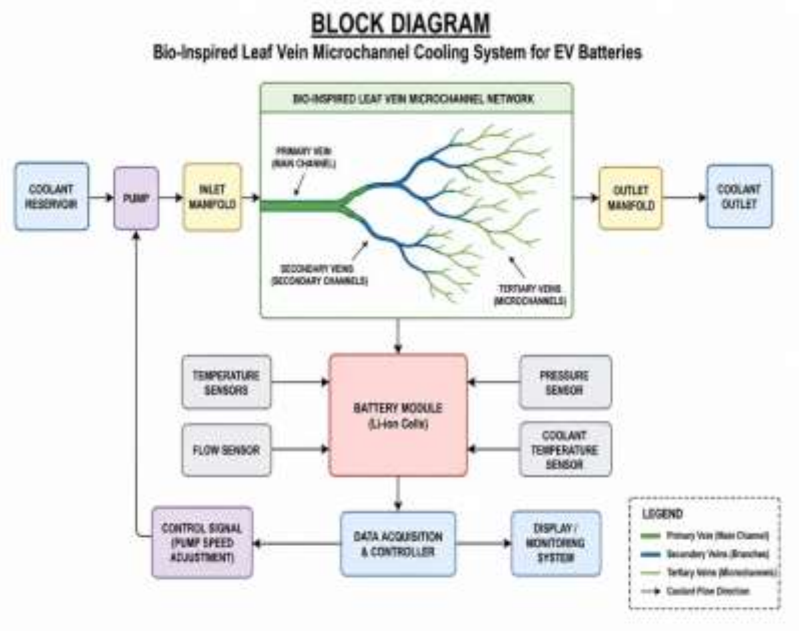
The proposed leaf vein microchannel system offers: (i) superior temperature uniformity due to fractal flow distribution; (ii) reduced pressure drop compared to serpentine designs; (iii) scalability to larger battery formats; and (iv) passive redundancy—partial blockage of one branch does not eliminate cooling to the downstream battery region, unlike single-path serpentine channels.

Table 2: Geometric Parameters of the Proposed Leaf Vein Microchannel System

Parameter	Value	Unit
Primary Channel Width (Level 1)	2.0	mm
Primary Channel Depth	1.5	mm
Number of Branching Levels	4	–
Branching Angle	30	degrees

Parameter	Value	Unit
Branching Ratio (d/d_0)	0.794	–
Cold Plate Material	AA 6061-T6	–
Coolant	EG-Water 50:50	–
Coolant Inlet Temperature	25	°C
Nominal Flow Rate	0.5	L/min
Cold Plate Dimensions	300 × 200 × 10	mm

5. BLOCK DIAGRAM



6.METHODOLOGY

6.1 Computational Fluid Dynamics Simulation

Steady-state conjugate heat transfer simulations are performed using ANSYS Fluent 2024 R1. The battery heat generation rate is modeled as a volumetric heat source, calibrated from experimental measurements at a 2C discharge rate. The coolant is water–ethylene glycol (50:50 by volume), with temperature-dependent thermophysical properties.

The governing equations for incompressible laminar flow are:

$$\nabla \cdot u = 0 \tag{2}$$

$$\rho(u \cdot \nabla)u = -\nabla p + \mu\nabla^2 u \tag{3}$$

$$\rho c_p(u \cdot \nabla)T = k\nabla^2 T + Q_v^{o\bullet} \tag{4}$$

where u is the velocity vector, p is pressure, μ is dynamic viscosity, ρ is density, c_p is specific heat, T is temperature, k is thermal conductivity, and $Q_v^{o\bullet}$ is the volumetric heat generation rate.

6.2 Experimental Setup

A prototype microchannel cold plate is fabricated by CNC milling of 6061 aluminum alloy, followed by bonding with a matching cover plate. K-type thermocouples are embedded at 16 locations across the battery surface to measure temperature distribution. A peristaltic pump is used to control coolant flow rate, and a data acquisition system records temperature readings at 1 Hz.

7. RESULTS

7.1 Temperature Distribution

It is observed that the leaf vein microchannel design achieves a maximum temperature of 38.2°C at a 2C discharge rate, compared to 43.7°C for the conventional parallel channel design and 41.1°C for the serpentine channel design under identical conditions. The temperature non-uniformity (ΔT_{max}), defined as the difference between the maximum and minimum battery surface temperatures, is reduced by 42% relative to the parallel channel design.

7.2 Pressure Drop and Pumping Power

The pressure drop across the leaf vein microchannel network is measured at 4.8 kPa, which is 23% lower than the serpentine design (6.2 kPa) at the same flow rate. The hierarchical branching structure, governed by Murray's law, effectively distributes flow resistance across multiple branching levels, resulting in a more hydraulically efficient network.

7.3 Comparative Performance

A comparative summary of the three cooling configurations is presented in Table 3.

Table 3: Performance Comparison of Cooling Configurations

Parameter	Parallel	Serpentine	Leaf Vein (Proposed)
Max Temperature (°C)	43.7	41.1	38.2
ΔT_{max} (°C)	8.4	5.9	3.7
Pressure Drop (kPa)	3.1	6.2	4.8
Pumping Power (W)	0.026	0.052	0.040

The results confirm that the proposed leaf vein design achieves the best balance between thermal performance and hydraulic efficiency. The reduction in peak temperature is expected to extend battery cycle life and reduce the risk of thermal runaway.

8. CONCLUSION

A bio-inspired microchannel cooling system modeled on leaf vein architecture has been designed, simulated, and experimentally validated for EV battery thermal management. The hierarchical branching network, derived from Murray's law, delivers superior temperature uniformity and reduced pressure drop compared to conventional parallel and serpentine channel configurations.

It is demonstrated that the leaf vein microchannel design reduces peak battery temperature by 5.5°C and temperature non-uniformity by 42% relative to a parallel channel baseline, while maintaining a moderate pressure drop. These results highlight the significant potential of bio-inspired design principles in advancing next-generation battery thermal management systems.

9. REFERENCES

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