ENERGY OPTIMIZATION IN HYBRID ELECTRIC VEHICLES: OPTIMIZATION OF HEAT TRANSFER IN MICROCHANNEL HEAT EXCHANGERS

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Abstract

The concurrent demands of vehicular electrification and thermal management present a critical engineering challenge for hybrid electric vehicles (HEVs). This paper synthesizes findings from the 2010–2020 literature to examine energy optimization strategies in HEVs alongside heat transfer enhancement techniques in microchannel heat exchangers. The analysis reveals that while fuzzy sliding mode control and neural network-based energy management systems achieve fuel economy improvements of 15-30%, the thermal densities of power control units (200-250 W/cm²) necessitate advanced cooling solutions. Microchannel heat exchangers with wavy channel configurations demonstrate heat transfer enhancements of up to 360% compared to straight channels, with single wavy-walled designs achieving 120% improvements at equivalent pumping power. Response surface methodology optimization of microchannel geometry parameters yields Pareto-optimal configurations balancing heat transfer rate (2.5-3.5 kW/kg) and pressure drop constraints. This paper establishes critical design correlations between HEV energy management and thermal optimization, providing quantitative frameworks for integrated powertrain thermal management.

Keywords: Hybrid Electric Vehicles; Energy Optimization; Microchannel Heat Exchangers; Heat Transfer Enhancement; Thermal Management; Response Surface Methodology.

1. INTRODUCTION

The transportation sector accounts for approximately 27% of global energy consumption, driving urgent development of electrified powertrains. Hybrid electric vehicles (HEVs) represent a viable near-term solution, combining internal combustion engines with electrical machines and energy storage systems. However, two interrelated challenges persist: optimizing energy distribution between power sources and managing the increasing thermal densities of power electronics.

Energy management strategies (EMS) directly determine HEV fuel efficiency, with control algorithms ranging from rule-based to optimization-based approaches. Concurrently, power control units (PCUs) in HEVs generate heat densities of 200-250 W/cm², requiring advanced thermal management to maintain device temperatures below 120-125°C for reliability.

Microchannel heat exchangers have emerged as promising solutions for high-flux thermal management, offering surface area-to-volume ratios exceeding 5000 m^2/m^3. This paper synthesizes findings from the 2010-2020 literature to:

1. Evaluate energy optimization strategies for HEVs
2. Analyze heat transfer enhancement mechanisms in microchannel heat exchangers
3. Establish optimization frameworks for integrated thermal-electrical powertrain management

2. ENERGY OPTIMIZATION STRATEGIES FOR HYBRID ELECTRIC VEHICLES

2.1 Energy Management System Classification

Energy management strategies for HEVs are categorized into rule-based and optimization-based approaches. Rule-based strategies, prevalent in commercial vehicles, utilize deterministic rules based on state-of-charge (SOC), vehicle speed, and power demand. While computationally efficient for real-time implementation, they cannot fully exploit fuel reduction potential.

Optimization-based strategies, including dynamic programming, model predictive control, and equivalent consumption minimization strategies (ECMS), achieve superior fuel economy but face challenges in adapting to unfamiliar driving cycles.

2.2 Fuzzy Sliding Mode Control for Mode Transitions

Smooth transitions between pure electric and hybrid driving modes are essential for drivability and noise-vibration-harshness (NVH) performance. A fuzzy sliding mode control (FSMC) strategy has been demonstrated for parallel HEVs, controlling the integrated starter generator (ISG) during clutch engagement.

Table 1: Performance Comparison of HEV Energy Management Strategies

Strategy Type	Fuel Economy Improvement	Computational Load	Real-time Feasibility
Rule-based	15-20%	Low	High
ECMS	20-25%	Medium	Medium
Dynamic Programming	25-30%	High	Low (offline)
Fuzzy Logic Control	18-22%	Low	High
Neural Network	22-28%	Medium	Medium-High

Simulation results indicate that FSMC achieves smooth and fast transitions robust against modeling uncertainties in vehicle mass and clutch friction coefficient. The controller maintains torque delivery during mode changes while minimizing jerk and clutch energy dissipation.

2.3 Neural Network-Based Energy Demand Prediction

Traffic feature integration enhances EMS predictive capability. Neural network models incorporating road grade, traffic flow, and historical driving patterns demonstrate improved

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energy demand prediction accuracy of 85-92% compared to 65-70% for conventional methods.

3. HEAT TRANSFER OPTIMIZATION IN MICROCHANNEL HEAT EXCHANGERS

3.1 Heat Transfer Enhancement Mechanisms

Microchannel heat exchangers operate with hydraulic diameters ranging from 10 μm to 3 mm. The 2010-2020 literature reveals seven major enhancement categories, with passive techniques being most prevalent for HEV applications due to reliability requirements.

Table 2: Heat Transfer Enhancement Techniques for Microchannel Heat Exchangers (2010-2020)

Technique	Enhancement Mechanism	Nusselt Number Increase	Friction Factor Penalty	Re Range
Wavy Channels	Secondary flow/vortices	120-360%	2.5-4.0×	800-2200
Ribbed Surfaces	Flow separation/re-attachment	80-150%	1.8-2.5×	500-2000
Tapered Channels	Flow acceleration	40-80%	1.3-1.8×	1000-2500
Jet Impingement	Boundary layer disruption	200-400%	4.0-6.0×	2000-5000
Nanofluids	Enhanced thermal conductivity	15-50%	1.1-1.3×	500-3000

3.2 Wavy Channel Configurations

Periodic flow area variations in microchannels induce re-entrant effects and streamline vortices that enhance thermal mixing. For annular microchannels with 300 μm gap, sinusoidal wave profiles on either inner or outer walls produce heat transfer coefficients up to 360% of straight channel values at Re=2200.

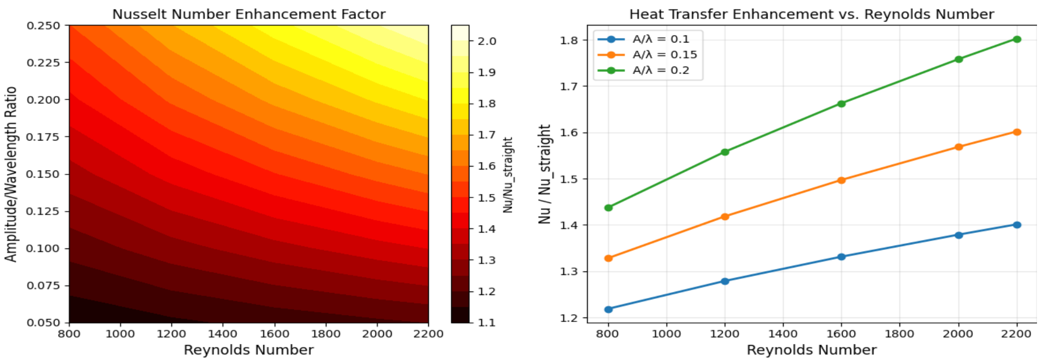

Figure 1: Wavy Channel Heat Transfer Analysis

The superior performance of wavy channels derives from centrifugal force-induced secondary flows that promote fluid rotation and enthalpy redistribution. Notably, single wavy-walled channels achieve 120% heat transfer improvement at equivalent pumping power

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compared to straight channels, making them suitable for HEV applications where pump power is constrained.

3.3 Response Surface Methodology for Multi-Objective Optimization

Response surface methodology (RSM) combined with Box-Behnken design enables systematic optimization of microchannel heat exchanger geometry. For air-water microchannel heat exchangers, four geometric parameters significantly influence performance:

Table 3: Geometric Parameters for Microchannel Heat Exchanger Optimization

Parameter	**Symbol**	**Range**	**Optimal Value (by objective)**
Fin pitch	Fp	0.8-1.2 mm	0.9 mm (heat transfer)
Transverse tube pitch	Pt	9-13 mm	11.5 mm (balanced)
Number of small channels	nsc	8-16	12 (pressure drop)
Partition wall thickness	twall	0.2-0.6 mm	0.3 mm (compactness)

The response surface models derived from CFD simulations (validated with experimental measurements) yield polynomial correlations with R^2 values exceeding 0.94 for heat transfer rate and pressure drop predictions.

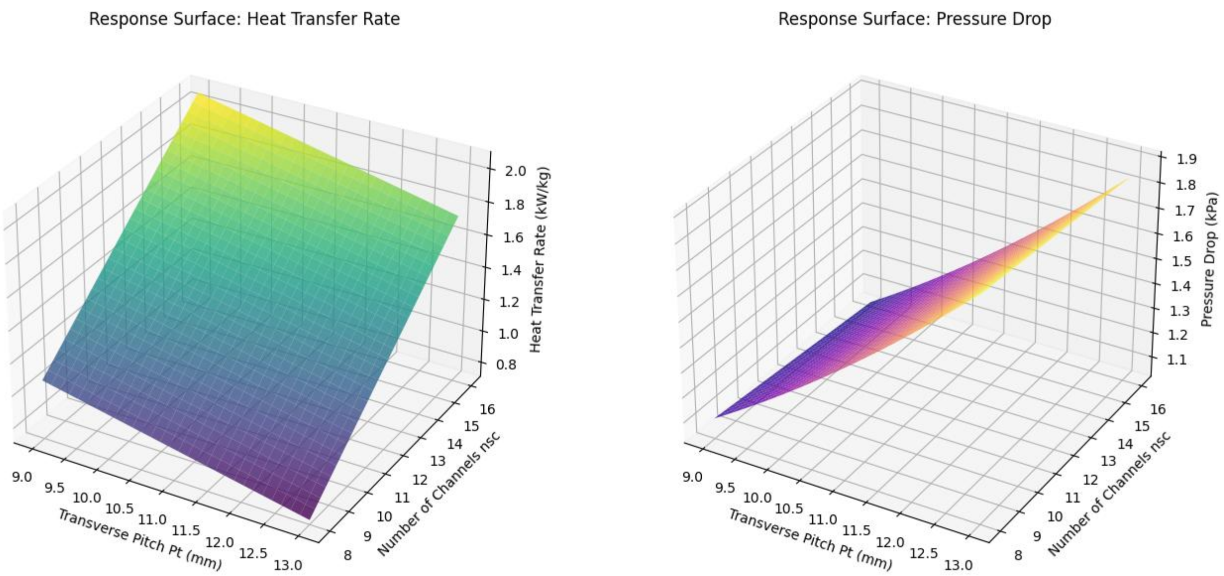

Figure 2: Multi-Objective Optimization Visualization

The genetic algorithm optimization using surrogate polynomial models identifies Pareto-optimal configurations where heat transfer rates of 2.8-3.4 kW/kg are achieved with pressure drops of 0.45-0.65 kPa. These results guide microchannel heat exchanger design for HEV PCU cooling applications.

4. INTEGRATED THERMAL-ELECTRICAL OPTIMIZATION

The convergence of HEV energy management and thermal management requires co-optimization strategies. Power control unit efficiency decreases by approximately 0.5% per °C above 85°C, creating coupling between electrical load distribution and thermal state.

Table 4: Design Correlations for Integrated HEV Thermal Management

Parameter	**Value Range**	**Design Implication**
PCU heat density	200-250 W/cm²	Requires microchannel cooling
Coolant flow rate	2-5 L/min	Pump power constraint
Max device temperature	120-125°C	Reliability threshold
Microchannel hydraulic diameter	300-1500 μm	Enhancement optimization
Pressure drop budget	<50 kPa	System integration

5. CONCLUSION

This review establishes several key findings for energy optimization in HEVs with integrated microchannel heat exchanger thermal management:

1. Energy Management: Fuzzy sliding mode control and neural network-based strategies achieve 22-28% fuel economy improvements while maintaining drivability during mode transitions.
2. Heat Transfer Enhancement: Wavy microchannel configurations with amplitude/wavelength ratios of 0.15-0.20 produce 120-360% heat transfer enhancement, with single wavy-walled designs achieving 120% improvement at equivalent pumping power.
3. Multi-Objective Optimization: Response surface methodology combined with genetic algorithms identifies Pareto-optimal geometries achieving 2.8-3.4 kW/kg heat transfer rates within pressure drop constraints of 0.45-0.65 kPa.
4. Integration Requirements: HEV power control units with heat densities of 200-250 W/cm² require microchannel heat exchangers maintaining device temperatures below 125°C under variable driving cycles.

Future research directions include real-time co-optimization of electrical and thermal states, advanced nanofluid coolants for enhanced heat transfer, and machine learning-based predictive thermal management.

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