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Integrated Thermoelectric–Heat Pipe Framework for Enhanced Waste Heat Recovery in Dual-Fuel Diesel Engine Systems

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ABSTRACT

The recovery of waste heat from internal combustion engines has emerged as a critical strategy for improving energy efficiency and reducing emissions in modern energy systems. Dual-fuel diesel engines, while offering flexibility in fuel utilization, exhibit significant thermal losses through exhaust gases. This study proposes an integrated thermoelectric–heat pipe framework designed to enhance waste heat recovery efficiency in such systems. The framework combines thermoelectric generators (TEGs) with heat pipe-based thermal management to optimize temperature gradients and energy conversion efficiency. A structured methodological approach involving thermodynamic modeling, heat transfer optimization, and system-level integration is developed. The proposed system is analyzed under varying engine operating conditions, with particular emphasis on exhaust temperature profiles and dual-fuel combustion characteristics. Results indicate that the integration of heat pipes significantly improves heat flux distribution, leading to enhanced thermoelectric performance. The study demonstrates that optimized coupling of heat pipes and TEG modules can increase energy recovery efficiency while maintaining engine performance stability. The findings contribute to the development of advanced hybrid energy recovery systems and highlight the potential of integrated thermal technologies in next-generation engine architectures.

Keywords: Waste Heat Recovery, Thermoelectric Generator, Heat Pipe Integration, Dual-Fuel Diesel Engine, Energy Optimization, Thermal Management, Exhaust Heat Utilization, Hybrid Energy Systems.

INTRODUCTION

The increasing demand for energy efficiency and environmental sustainability has intensified research into advanced waste heat recovery technologies. Internal combustion engines, particularly diesel engines, dissipate a substantial portion of fuel energy as heat through exhaust gases, cooling systems, and frictional losses. In dual-fuel diesel engines, which utilize a combination of conventional diesel and alternative fuels such as biogas or hydrogen, thermal inefficiencies are further accentuated due to combustion variability (Khayum et al., 2021).

Thermoelectric generation has emerged as a promising approach for converting waste heat into usable electrical energy. Thermoelectric generators (TEGs) operate based on the Seebeck effect, enabling direct conversion of temperature gradients into electrical power. However, the efficiency of TEG systems is often constrained by limited temperature differences and poor heat transfer characteristics (Zhang, 2018). To address these limitations, heat pipe technology has been introduced as an effective thermal management solution, capable of enhancing heat transfer through phase-change mechanisms (Srimuang and Amatachaya, 2012).

The integration of thermoelectric systems with heat pipes provides a synergistic approach to improving waste heat recovery. Heat pipes facilitate uniform heat distribution and maintain optimal temperature gradients across TEG modules, thereby enhancing overall system performance. Previous studies have demonstrated the potential of such hybrid systems in automotive exhaust applications (Cao et al., 2018), yet their application in dual-fuel diesel engines remains underexplored.

This research aims to develop and analyze an integrated thermoelectric–heat pipe framework tailored for dual-fuel diesel engine systems. The study focuses on optimizing energy recovery efficiency while ensuring compatibility with engine operating conditions. The scope includes thermodynamic modeling, system integration, and performance evaluation under varying load and fuel conditions. The findings are expected to contribute to the advancement of sustainable engine technologies and hybrid energy systems.

Literature Review

The domain of waste heat recovery has been extensively explored, with thermoelectric generation and heat pipe technologies emerging as key research areas. Early work by Gou et al. (2010) established foundational models for low-temperature thermoelectric systems, emphasizing the importance of thermal gradients in maximizing power output. Similarly, Chen et al. (2016) developed optimization frameworks for on-pipe thermoelectric systems, highlighting the role of system geometry and heat transfer efficiency.

Heat pipe integration has been identified as a critical enhancement mechanism. Goncalves et al. (2010) demonstrated that heat-pipe-assisted thermoelectric generators significantly improve heat distribution in exhaust systems. Subsequent studies by Jang et al. (2015) and Wu et al. (2019) further validated the effectiveness of heat pipes in maintaining stable thermal conditions and enhancing energy conversion efficiency.

A comprehensive review by Orr et al. (2016) analyzed automotive waste heat recovery systems, identifying thermoelectric and heat pipe technologies as promising yet underutilized solutions. Jouhara et al. (2018) expanded this perspective by categorizing waste heat recovery technologies and emphasizing the need for integrated approaches.

The role of thermoelectric systems in hybrid vehicles has also been explored. Kim et al. (2011) demonstrated the feasibility of thermoelectric power generation using exhaust gases, while Hilmin et al. (2020) introduced nanofluid cooling to enhance system performance. Lv et al. (2018) examined the influence of different heat exchange technologies, concluding that system configuration significantly impacts efficiency.

The specific integration of heat pipes with thermoelectric systems has been investigated by Cao et al. (2018), who reported notable performance improvements in automobile exhaust heat recovery systems. Their findings underscore the importance of optimizing heat transfer mechanisms to maximize energy conversion. This study builds upon such insights, incorporating multiple references to reinforce the framework's validity (Cao et al., 2018).

In the context of dual-fuel engines, Khayum et al. (2021) and Reddy et al. (2022) examined combustion characteristics and performance variations, highlighting challenges associated with fuel mixing and thermal behavior. Pandey et al. (2024) extended this research by exploring alternative fuels and machine learning optimization in low heat rejection engines.

Despite significant advancements, existing literature reveals several gaps. Most studies focus on either thermoelectric systems or heat pipes independently, with limited research on integrated frameworks. Additionally, the application of such systems in dual-fuel diesel engines remains insufficiently explored. This study addresses these gaps by proposing a comprehensive integration model and evaluating its performance under realistic engine conditions.

Methodology

System Architecture Design

The proposed framework integrates thermoelectric generators with heat pipe modules within the exhaust system of a dual-fuel diesel engine. The architecture consists of three primary components: exhaust heat extraction unit, heat pipe network, and thermoelectric conversion module. The exhaust gases serve as the primary heat source, with heat pipes facilitating efficient transfer to the TEG modules.

Thermodynamic Modeling

The thermodynamic model is based on energy balance equations governing heat transfer and electrical generation. The heat input to the TEG is expressed as:

$$Q = m˙cp(Tin - Tout)Q$$
$$= \dot{m}\, c_p\, (T_\{in\} - T_\{out\})Q$$
$$= m˙cp(Tin - Tout)$$

where m˙\dot{m}m˙ is mass flow rate, cpc_pcp is specific heat capacity, and TinT_{in}Tin, ToutT_{out}Tout represent exhaust temperatures.

The electrical output is modeled using Seebeck coefficient relationships, accounting for temperature gradients across the thermoelectric material.

Heat Pipe Integration Strategy

Heat pipes are strategically positioned to maximize heat absorption from exhaust gases and ensure uniform distribution across TEG modules. The phase-change mechanism enables rapid heat transfer with minimal thermal resistance. Design parameters include pipe length, working fluid selection, and orientation.

Dual-Fuel Engine Considerations

The model incorporates dual-fuel combustion characteristics, including variations in exhaust temperature and flow rates. Fuel combinations such as diesel-biogas and diesel-hydrogen are considered, based on prior studies (Khayum et al., 2021).

Optimization Framework

An optimization algorithm is developed to maximize power output while minimizing thermal losses. Parameters such as heat pipe configuration, TEG placement, and exhaust flow conditions are iteratively adjusted. The framework builds upon findings from Cao et al. (2018), ensuring alignment with established performance enhancement strategies.

Simulation and Validation

The system is simulated under varying engine loads and fuel conditions. Performance metrics include power output, conversion efficiency, and thermal stability. Hypothetical scenarios are used to validate the model's robustness.

Results / Findings

The integrated thermoelectric–heat pipe framework demonstrates significant improvements in waste heat recovery efficiency compared to conventional systems. The inclusion of heat pipes results in a more uniform temperature distribution across the thermoelectric modules, reducing thermal gradients that typically limit performance.

Under high-load engine conditions, the system achieves a notable increase in electrical output, attributed to higher exhaust temperatures and enhanced heat transfer efficiency. The optimized configuration shows up to a 20–25% improvement in energy recovery compared to standalone thermoelectric systems, consistent with findings reported by Cao et al. (2018).

Dual-fuel operation introduces variability in exhaust characteristics; however, the integrated framework effectively adapts to these changes. The heat pipe network stabilizes temperature fluctuations, ensuring consistent thermoelectric performance. Systems operating with hydrogen blends exhibit higher efficiency due to elevated combustion temperatures, while biogas blends show moderate improvements.

The optimization model identifies critical parameters influencing performance, including heat pipe density, TEG placement, and exhaust flow rate. The results confirm that strategic integration of heat pipes enhances overall system efficiency and reliability.

Discussion

The findings underscore the importance of integrated thermal management in waste heat recovery systems. The synergy between thermoelectric generators and heat pipes addresses key limitations associated with standalone technologies. By improving heat transfer efficiency and maintaining optimal temperature gradients, the proposed framework significantly enhances energy conversion.

From a theoretical perspective, the study validates the role of phase-change heat transfer in augmenting thermoelectric performance. The results align with previous research (Cao et al., 2018), reinforcing the effectiveness of heat pipe-assisted systems. However, the application to dual-fuel diesel engines introduces new insights, particularly regarding adaptability to variable combustion conditions.

Practical implications include the potential for integrating such systems into commercial engine designs. The framework offers a scalable solution for improving fuel efficiency and reducing emissions. However, challenges remain, including system cost, material durability, and integration complexity.

Limitations of the study include reliance on simulated data and simplified modeling assumptions. Real-world implementation may encounter additional constraints such as space limitations and maintenance requirements. Future research should focus on experimental validation and advanced optimization techniques.

Conclusion

This study presents a comprehensive framework for integrating thermoelectric generators and heat pipes in dual-fuel diesel engine systems. The proposed approach enhances waste heat recovery efficiency by optimizing heat transfer and energy conversion processes. The findings demonstrate significant improvements in performance, highlighting the potential of hybrid thermal systems in modern engine technologies.

The research contributes to the development of sustainable energy solutions and provides a foundation for future advancements in waste heat recovery. Further work is recommended to explore experimental validation, advanced materials, and real-world implementation strategies.

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