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Thermoelectric Generators for Automotive Waste Heat Recovery Systems Part I: Numerical Modeling and Baseline Model Analysis

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A numerical model has been developed to simulate coupled thermal and electrical energy transfer processes in a thermoelectric generator (TEG) designed for automotive waste heat recovery systems. This model is capable of computing the overall heat transferred, the electrical power output, and the associated pressure drop for given inlet conditions of the exhaust gas and the available TEG volume. Multiple-filled skutterudites and conventional bismuth telluride are considered for thermoelectric modules (TEMs) for conversion of waste heat from exhaust into usable electrical power. Heat transfer between the hot exhaust gas and the hot side of the TEMs is enhanced with the use of a plate-fin heat exchanger integrated within the TEG and using liquid coolant on the cold side. The TEG is discretized along the exhaust flow direction using a finite-volume method. Each control volume is modeled as a thermal resistance network which consists of integrated submodels including a heat exchanger and a thermoelectric device. The pressure drop along the TEG is calculated using standard pressure loss correlations and viscous drag models. The model is validated to preserve global energy balances and is applied to analyze a prototype TEG with data provided by General Motors. Detailed results are provided for local and global heat transfer and electric power generation. In the companion paper, the model is then applied to consider various TEG topologies using skutterudite and bismuth telluride TEMs.

Key words: Thermoelectric generators, waste heat recovery, automotive exhaust, skutterudites

INTRODUCTION

Substantial thermal energy is available from the exhaust gas in modern automotive engines. Two-thirds of the energy from combustion in a vehicle is lost as waste heat, of which 40% is in the form of hot exhaust gas.[1,2] Use of TEGs has the potential to recover some of this waste energy in the exhaust stream, potentially improving fuel economy (FE) by as much as 5%. A comprehensive theoretical study concluded that a TEG powered by exhaust heat could meet the electrical requirements of a medium-sized vehicle.[1]

Over the last several decades, alloy-based thermoelectric (TE) materials including Bi_2Te_3—Sb_2Te_3 and Si-Ge systems have been extensively studied for use in their different temperature ranges.[3–5] As the temperatures of automobile exhaust gases are typically in the range of 400°C to 800°C, high-temperature TE devices are required for at least a part of the flow path. Established TE semiconductors exhibit poor figures of merit when operating temperatures exceed 500°C.[4,5] Crane et al.[6] have implemented

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