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Experiment on thermal uniformity and pressure drop of exhaust heat exchanger for automotive thermoelectric generator

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ABSTRACT

The power generation of exhaust TEG (thermoelectric generator) depends on heat energy and thermoelectric conversion efficiency. High efficiency heat exchanger is necessary to increase the amount of heat energy extracted from exhaust gas. On one hand, heat transfer is coupled with pressure drop for typical heat exchanger; on the other hand, the muffler unavoidably leads exhaust to large pressure drop for noise reduction. The present work tried to conceptually combine exhaust heat exchanger with muffler in the form of 1-inlet 2-outlet, 2-inlet 2-outlet and the baseline empty cavity. A test bench was developed to compare thermal uniformity and pressure drop characteristics over multiple vehicle operating conditions. 1-Inlet 2-outlet increased hydraulic disturbance and enhanced heat transfer, resulting in the more uniform flow distribution and higher surface temperature than the other. However, the averaged surface temperature was less than 100 °C, significantly limiting thermoelectric conversion efficiency. The pressure drops of 1-inlet 2-outlet, 2-inlet 2-outlet were 165%, 318% more than that of empty cavity when inlet temperature was 100 °C and mass flow rate was 131 kg/h, and were 319%, 523% more than that of empty cavity when inlet temperature 400 °C and mass flow rate 156 kg/h.

1. Introduction

For gasoline engine, about 40% of the primary gasoline energy is discharged as waste heat in exhaust gas [1]. The automotive exhaust is low in specific heat and small in time-averaged mass flow rate, so that an efficient heat exchanger is essential to extract heat energy from exhaust when thermoelectric conversation of conventional materials is 5%–7% for thermoelectric generator (TEG). Historically, several types of heat exchanger and different heat transfer enhancement measures such as the ribbing, grooving and protrusions have been investigated since the first automobile TEG was built in 1963. Serksnis [2] initially reported a stainless heat exchanger just like the exhaust pipe, no heat transfer enhancements were set in gas side. Birkholz et al. [3] designed a Hastelloy X rectangular heat exchanger with internal fins in exhaust side and an aluminum cold-side heat exchanger. Bass et al. [4] proposed a hexagonal cylinder and a center hollow displacement conic heat-diffuser for Cummins 14L NTC 350 diesel engine, discontinuous swirl fins were installed on surface of the center body to break laminar boundary layer and enhance gas turbulence. Thacher et al. [5] employed a rectangular, 1018 carbon steel compact heat exchanger with offset strip fins for a 5.3 L V8 gasoline engine. Crane et al. [6] improved thermal structure from a planar design to a cylindrical design with internal folded fins and stainless steel clad copper for BMW's 3 L inline six-cylinder engine. Su et al. [7] designed two different exhaust gas heat exchangers, and tested their acoustic characteristics, finally chose a "fishbone" finned internal structure with 12 mm interior thickness to increase thermal uniformity [8]. With the same requirements for exhaust heat exchanger in vehicle waste heat recovery by Rankine cycle, a shell and tube counter flow heat exchanger was used with exhaust gases in tubes and working fluids in shell [9].

For thermoelectric efficiency and generation capacity enhancement, heat exchanger's type, geometry, mounted location, contact area with thermoelectric modules, operating conditions and so on were optimized by numerical analyses and experiments. To obtain maximal net waste heat recovery performance, Crane et al. [10]

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integrated numerical cross flow heat exchanger model with TEG model, and optimized the hydraulic diameters of hot fluid, pitch of fins, pitch of tubes, height and width of thermoelectric legs in system level, the system with optimal design parameters could output a net power of 1000 W for a modestly sized heat exchanger. Chad et al. [11] compared 5 configurations by numerical model: single duct, single duct filled with porous metal foams, single duct with fins, multiple parallel counter flow ducts, and multiple serpentine-flow ducts, an unacceptable large pumping work requirement was found for the configurations using serpentine flow arrangement or porous media. Based on analytical method, the compromise programming was utilized to further improve the power density of TEG [12]. Astrain et al. [13] optimized the influence of heat exchangers' thermal resistances (in both the hot and cold side) and pressure drops by CFD [14] to maximize the electric power generated. Hsiao et al. [15] developed one dimensional thermal resistance model to predict TEG performance with two potential positions on an automobile: exhaust pipe and radiator. Wang [16] developed a three dimensional model to verify the significant effect of the variable properties and the heat losses to the ambient on thermoelectric conversion. The geometrical effect of TEG on heat transfer characteristics was investigated in a parallel microchannel heat sink [17]. Lagrandeur et al. [18] tested the pressure drop characteristics of TEG over a wide range of vehicle operating conditions, and the maximum static backpressure was about 60,000 Pa for the BMW X6. Katsunori et al. [19] proposed a reciprocating-flow super-adiabatic combustion in a catalytic and thermoelectric porous element, and announced a thermal efficiency of 4.7%, almost equal to the conversion efficiency of the thermoelectric element itself. Martins [20] adopted a variable conductance heat pipe as high efficiency means to supply the heat to a sufficiently low temperature while still maintain a high heat transfer rate, it could protect TEG against the extreme temperatures found in exhaust systems.

The amount of heat energy extracted from automotive exhaust is very important to promote system thermoelectric conversion capacity and efficiency. On one hand, the muffler necessarily leads exhaust to large pressure drop for noise reduction; on the other hand for a certain typical heat exchanger in general, the larger pressure drop, the more heat is transferred. The objective of present work is to conceptually combine the exhaust heat exchanger with the muffler in the form of 1-inlet 2-outlet, 2-inlet 2-outlet based on the referenced empty cavity. The prototype exhaust heat exchangers were designed and fabricated. The test bench was built to evaluate thermal uniformity and pressure drop characteristics over a wide range of operating conditions.

2. Experimental setup

2.1. Three typical structures of exhaust heat exchanger

Two exhaust heat exchangers with muffler-like internal structure were proposed as 1-inlet 2-outlet and 2-inlet 2-outlet based on the referenced structure: empty cavity. There was nothing in the empty cavity shown in Fig. 1a, but for 1-inlet 2-outlet the inlet pipe was inserted deeply into the cavity and the main outlet pipe was divided into 2 branch outlets shown in Fig. 1b, 2-inlet 2-outlet included two same pipes in the outlet and inlet shown in Fig. 1c. For the consistence of comparison, 3 structures were in the same shell with 670 mm × 360 mm × 81 mm, all the inlet and outlet of the structures were 51 mm in diameter.

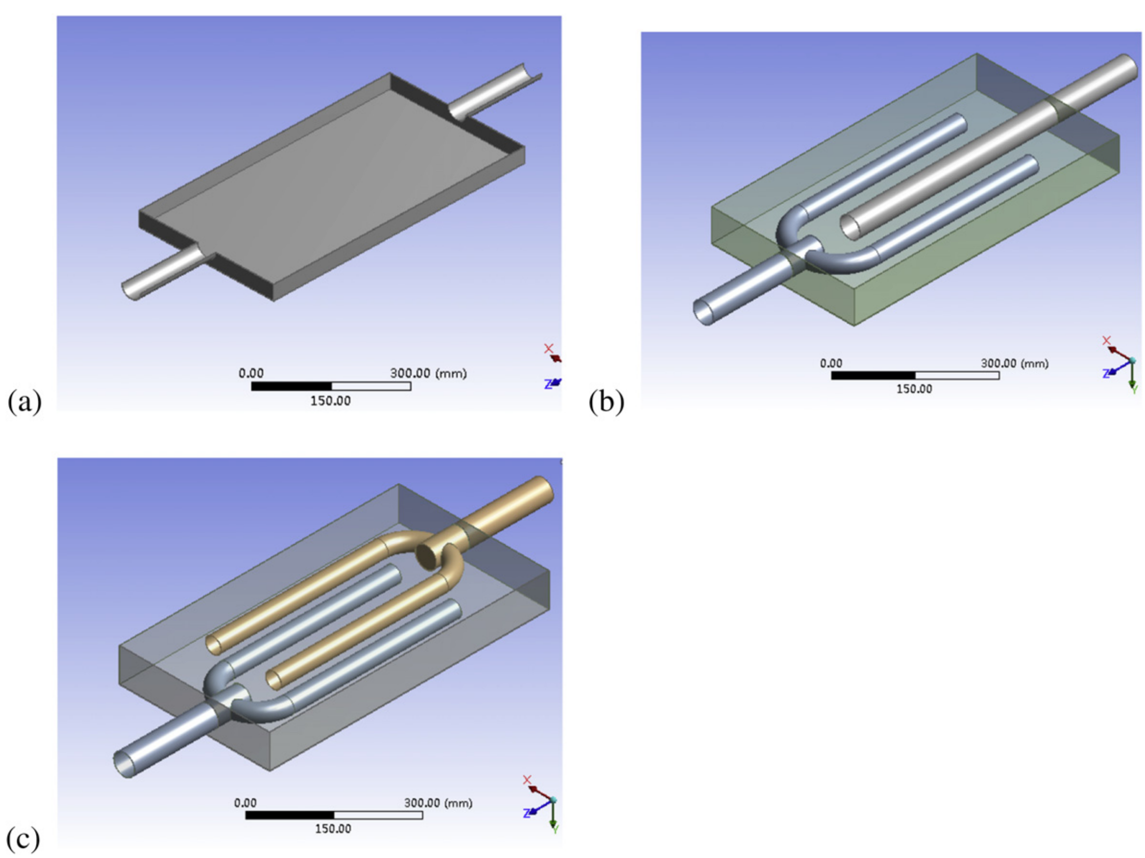

Fig. 1. Three internal structures: (a) Empty cavity, (b) 1-inlet 2-outlet, (c) 2-inlet 2-outlet.