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THERMOELECTRIC WASTE HEAT RECOVERY AS A RENEWABLE ENERGY SOURCE

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Abstract:

A thermoelectric converter is a solid-state heat engine in which the electron gas serves as the working fluid and converts a flow of heat into electricity. It has no moving components, is silent, totally scalable and extremely reliable. Thermoelectric devices employing radioactive isotopes as a heat source (Radioisotope Powered Thermoelectric Generators, referred to as RTGs) provided the required electrical power. Total reliability of this technology has been demonstrated in applications such as the Voyager space craft's with Voyager. However, employing radioisotopes as sources of heat has remained restricted to specialized applications where the thermoelectric generator's desirable properties listed above outweighed its relatively low conversion efficiency (typically 5%).

The environmental problems associated with global warming, resulted in an upsurge of scientific activity to identify and develop environmentally friendly sources of electrical power. Thermoelectric generation in applications, which employ waste heat as a heat source, is a totally green technology and when heat input is free, as with waste heat, the system's generating power density is of greater importance than its conversion efficiency in determining the system's economic viability.

Keywords: Green energy conversion technology, waste heat recovery, scalable electric power generation, solid state generators, thermoelectric semiconductors, generator on a chip and miniature sensors.

I. INTRODUCTION

Waste heat recovery devices can increase vehicle fuel economy by converting a portion of engine waste heat to useful work. Taking a conventional example, a turbocharger expands hot exhaust gases through a turbine and uses this shaft power to compress engine intake air and boost engine efficiency. Though they are not used in vehicles at present, adsorption and absorption refrigeration systems provide potential pathways to convert engine waste heat into passenger cabin cooling [1, 2], eliminating engine loads associated with traditional vapor-compression systems.

Thermo acoustic devices [3, 4] provide a pathway to convert waste heat to sound and then to cooling or, if combined with a linear motor or piezoelectric generator, electricity. Thermoelectric (TE) devices, the subject of this report, offer an attractive direct conversion path from heat to electricity, with no moving parts [5]. This direct conversion of heat to electricity, combined with recent laboratory advances in efficiency, makes TE devices an interesting candidate for automotive waste heat recovery [6].

While TE generators have the potential to increase vehicle fuel economy by converting a portion of engine waste heat to electricity [7, 8], that electricity can be used in several ways. Conventional vehicles could derive a fuel economy benefit by using the extra electrical power to reduce alternator loads and/or electrically drive accessories such as power steering [9]. Hybrid electric vehicles (HEVs) might also use the extra electrical power to directly assist with vehicle propulsion [10].

A typical engine wastes approximately two-thirds of the fuel's combustion energy as heat. Some waste heat is transferred to the coolant system and/or carried from the engine block by convection and radiation. Although waste heat could potentially be recovered from the coolant system, the relatively low difference in temperature from ambient would result in low TE generator efficiency. This work assumes that the TE generator recovers heat from the engine exhaust, which has the highest temperature and, consequently, the most thermodynamically available waste heat.

In most vehicle applications currently being explored, the TE device employs heat exchangers to carry heat from the exhaust system to the hot side of the device (and isolate the device from peak exhaust system temperatures) as well as to remove heat from the cold side of the device [8, 11]. The cold side commonly uses ethylene glycol as a working fluid, either shared with the engine cooling loop or using its own dedicated radiator.

This report provides a simplified analysis in which the energy conversion efficiencies of the TE device and associated heat exchangers, pumps, and other components are lumped into a single conversion efficiency representative of the entire TE system. In the analysis, four vehicle platforms—a midsize sedan, a midsize sport utility vehicle, a Class 4 truck, and a Class 8 truck—are initially considered.

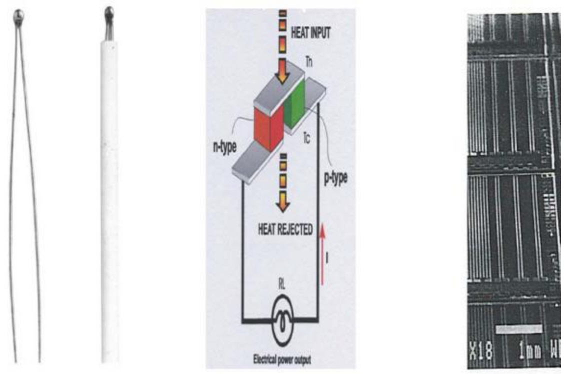

Fig. 1. **Conventional metal alloy Bulk semiconductor Miniature thin thermocouple.**

II. Model

a. *Thermo Electric System model*

A thermoelectric device generates electricity when a temperature gradient is applied across the junctions of two dissimilar metals. The performance of the device, determined by properties of the junction materials, is typically stated using a figure of merit, *ZT*. Yang [6] gives a timeline of advances in thermoelectric materials and their figures of merit. Bulk materials, such as bismuth telluride and lead telluride, which were identified in the 1960s and 1970s, have a *ZT* in the range of 0.5 to 1.0. These materials are most common in current applications, including vehicle waste heat recovery demonstration programs.

More recently discovered thin-film materials, such as silicon carbon and boron carbon operating on a quantum well principle, have demonstrated a *ZT* of 4 to 5 in the laboratory, but designs that use these materials have yet to be scaled up to practical systems. In addition to higher efficiency, these thin-film designs offer the potential for much lower cost in comparison to bulk designs because less junction material is required; however, they usually have higher manufacturing costs.

The efficiency of a TE device is the amount of electrical power generated for a given amount of heat input, $\eta TE = Pelec / Ph, in.$ This efficiency can be calculated as a function of the hot-side temperature, *Th*, the cold-side temperature, *Tc*, and *ZT*.

$$\eta_{TE} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c/T_h}$$

In a vehicle application, the overall *system* efficiency, $\eta TE\ sys = Pelec / Pexh$, where *Pexh* is the engine exhaust heat, will be less than the *device* efficiency. This difference is due to exhaust line temperature drops (ΔT) between the engine and the TE system, cold- and hot-side heat exchanger effectiveness $\varepsilon < 1$, and parasitic losses due to pumps and electric power conversion devices. Given these losses, it is reasonable to expect that the efficiency of a complete system, $\eta TE\ sys = f(\eta TE, \Delta T, \varepsilon, Ppumps, \ldots)$, might be only half that of the thermoelectric device, ηTE.

To complete a large design space search across multiple vehicle platforms, the current model neglects losses due to heat exchangers, pumps, and so forth. Instead, a simple "black box" TE system model is used to predict the TE system's electrical power output, *Pelec*, as a function of the engine's rate of exhaust heat output, thermoelectric figure- of- merit of the thermocouple material **Z**.

a. Thermoelectric generation, efficiency and figure-of-merit

A thermoelectric converter is a heat engine and like all heat engines it obeys the laws of thermodynamics. If we first consider the converter operating as an ideal generator in which there are no heat losses, the efficiency is defined as the ratio of the electrical power delivered to the load to the heat absorbed at the hot junction. Expressions for the important parameters in thermoelectric generation can readily be derived by considering the simplest generator consisting of a single thermocouple with legs or thermo elements fabricated from n- and p-type semiconductors as shown in Figure 1b [1-2].

The efficiency of the generator is given by:

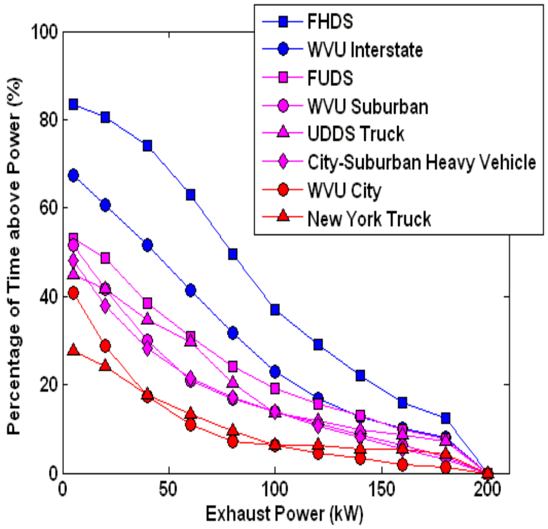

Fig.3. Percentage of time that a Class 8 truck spends above various levels of engine power for various driving cycles.

Where *fv* is the percentage of time spent at exhaust waste heat *P exh*, and *Pexh,0* is the exhaust waste heat produced by idling the engine.

$$P_{elec} = f_v \cdot \max(P_{\max, TE\ sys}, \eta_{TE\ sys} P_{exh}) + (1 - f_v) \cdot \eta_{TE\ sys} P_{exh,0}$$

For a Class 8 truck with $\eta TE\ sys$ = 10%, Figure 9 graphically depicts the equation above with contours of *Pelec* (kW) versus *fv*. The maximum power rating, *Pmax, TE sys*, appears on the left y-axis; consequently, contours of *Pelec* are unobtainable if they occur above a horizontal line drawn to intersect a chosen value of *Pmax, TE sys*. For reference, limits on TE system power output during constant-speed driving are given on the right y-axis.

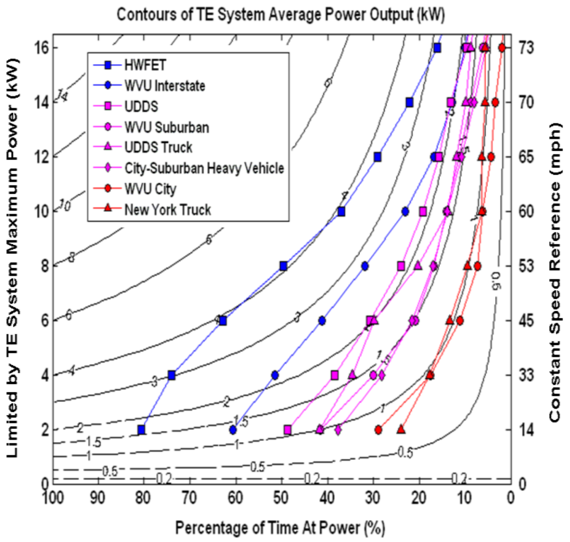

Figure 9. Contour lines showing average electrical power

III.WORKING

The generated emf of the synchro transmitter is applied as input to the stator coils of control transformer. The rotor shaft is connected to the load whose position has to be maintained at the desired value. Depending on the current position of the rotor and the applied emf on the stator, an emf is induced on the rotor winding. This emf can be measured and used to drive a motor so that the position of the load is corrected.

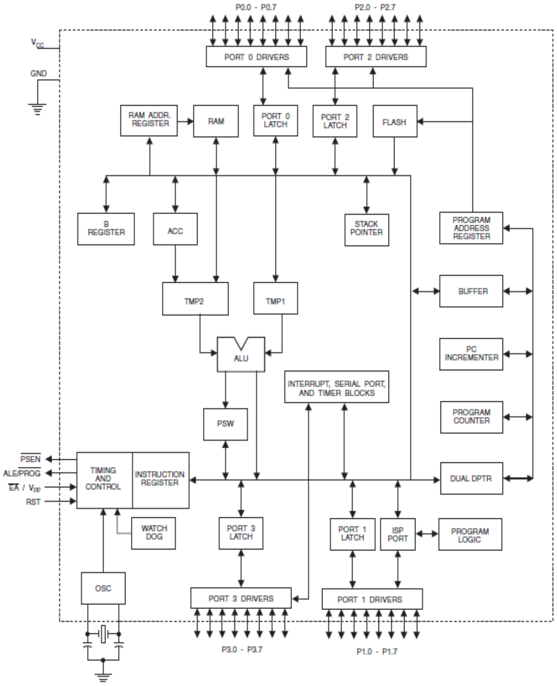

Fig.4. Circuit Diagram

IV.EXPERIMENTAL RESULTS

TEMPORAL/TIMING PERFORMANCE:

Contrary to spatial performance, temporal performance is a feature where smaller is better. Specifically, the range is the pixel response time of an LCD, or how quickly a sub-pixel's brightness changes from one level to another. For LCD monitors, this is measured in black to black gray to gray. These different types of measurements make comparison difficult Further, this number is almost never published in sales advertising.

COLOR PERFORMANCE:

There are many terms to describe color performance of an LCD. They include color gamut which is the range of colors that can be displayed and color depth which is the color resolution or the resolution or fineness with which the color range is divided. Although color gamut can be expressed as three pairs of numbers, the XY coordinates within color space of the reddest red, greenest green, and bluest blue, it is usually expressed as a ratio of the total area within color space that a display can show relative to some standard such as saying that a display was "120% of NTSC". NTSC is the National Television Standards Committee, the old standard definition TV specification.

SPATIAL PERFORMANCE

LCD comes in only one size for a variety of applications and a variety of resolutions within each of those applications. LCD spatial performance is also sometimes described in terms of a "dot pitch". The size (or spatial range) of an LCD is always described in terms of the diagonal distance from one corner to its opposite. This is an historical remnant from the early days of CRT television when CRT screens were manufactured on the bottoms of glass bottles, a direct extension of cathode ray tubes used in oscilloscopes. The diameter of the bottle determined the size of the screen. Later, when televisions went to a squarer format, the square screens were measured diagonally to compare with the older round screens.

Fig.5. LCD Display

V. CONCLUSION

Vast quantities of untapped natural heat is available together with huge amount of waste heat, most of which is below 100C and is discharged into the environment. Thermoelectric generation is an environmentally friendly technology which can convert this unused heat, and in particular lower temperature heat, into electricity.

This technology has been successfully demonstrated on a laboratory scale and in prototype commercial systems. Collaboration between University and Industry has resulted in research and development in this area of thermoelectric technology progressing rapidly. In the near future thermoelectric waste heat recovery will make a significant contribution, over a wide range of applications, in reducing fossil fuel consumption and global warming.

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