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POTENTIAL THERMOELECTRIC APPLICATIONS IN DIESEL VEHICLES

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ABSTRACT

Novel thermodynamic cycles developed by BSST provide improvements by factors of approximately 2 in cooling, heating and power generation efficiency of solid-state thermoelectric systems. The currently available BSST technology is being evaluated in automotive development programs for important new applications. Thermoelectric materials are likely to become available that further increase performance by a comparable factor. These major advancements should allow the use of thermoelectric systems in new applications that have the prospect of contributing to emissions reduction, fuel economy, and improved user comfort.

Potential applications of thermoelectrics in diesel vehicles are identified and discussed. As a case in point, the history and status of the Climate Controlled Seat (CCS™) system from Amerigon, the parent of BSST, is presented. CCS is the most successful and highest production volume thermoelectric system in vehicles today. As a second example, the results of recent analyses on electric power generation from vehicle waste heat are discussed. Conclusions are drawn as to the practicality of waste power generation systems that incorporate BSST's thermodynamic cycle and advanced thermoelectric materials.

INTRODUCTION

Increased concerns over vehicle fuel economy and harmful emissions of particulate matter, nitrogen oxides, and chemical refrigerants have amplified the search for new technological advances. Recent research into new materials and assembly methods has made thermoelectric energy conversion-based devices viable options to make enhancements in these areas. This paper discusses how applications of thermoelectric devices in diesel vehicles can impact fuel economy and emissions reduction, with the added benefit of improved user comfort.

Thermoelectric (TE) energy conversion for power generation is based on the "Seebeck effect", where a temperature difference, T_{sh}–T_{sc}, across two dissimilar legs of semiconductor material produces a voltage, ΔV_{oc}, (see Figure 1). This voltage is equal to the Seebeck coefficient of the material, α, times the temperature difference across the device. The dissimilar legs of semiconductor material, one p-type and one n-type, are called a thermoelectric couple. The p- and n-legs are joined by an electrically conducting material at the p-n junction. A thermoelectric module consists of a series of p-n couples, which are connected electrically in series and thermally in parallel. Electrically insulating material separates the electrical connectors from the heat source and sink. When a temperature gradient is applied across the couple, the negatively charged electrons, e^-, in the n-leg and the positively charged holes, h^+, in the p-leg move from the heat source to the heat sink, conducting heat to the cold base. This flow of electrons and holes causes separation in an initially uniform charge carrier distribution, which results in a current flow, I, in the couple [1].

For heating and cooling applications, the "Peltier effect" describes the TE energy conversion, where a temperature difference is created across two dissimilar legs of semiconductor material by flowing an electric current through the legs.

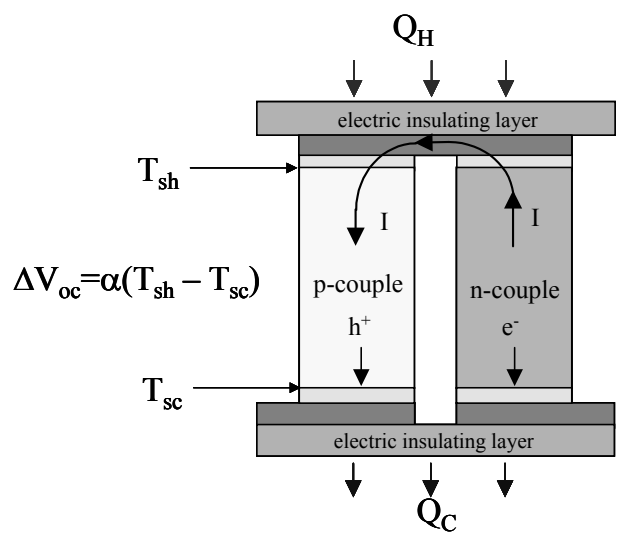

Figure 1. Energy flow through a thermoelectric couple. Q_H and Q_C represent the heat input and output flows respectively [2].

The thermal efficiency of a thermoelectric device is based on the non-dimensional figure of merit, ZT, of the material and

the temperatures at the hot and cold faces of the device. Until recently, the highest ZT achieved in practice was ~1 for bulk material Bi_2Te_3. This corresponds to a thermal efficiency of ~5% with a hot-side temperature of 400K and a cold-side temperature of 300K. For maximum effectiveness, it is particularly important for the TE material to have a high ZT in an application's operating temperature range. Figure 2 shows ZT for a variety of materials for a range of temperatures. It is clear from this figure that Bi_2Te_3 has a higher figure of merit than other materials at temperatures below 100°C, but it cannot withstand temperatures above 250°C. Likewise, PbTe has a lower maximum ZT than Bi_2Te_3, but it can operate at temperatures up to 600°C with its maximum ZT at ~475°C. A TE device made of PbTe with a hot-side temperature of 750K (corresponding to a ZT = 0.8) and a cold-side temperature of 300K would have a thermal efficiency of ~12%.

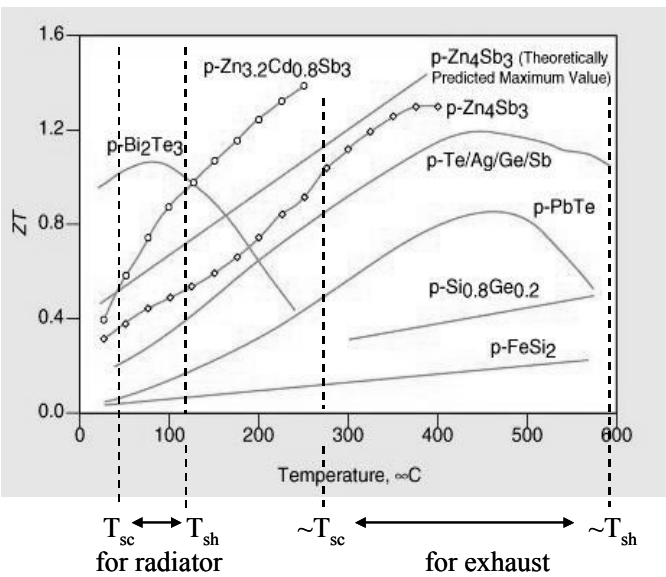

Figure 2. TE non-dimensional figure of merit [2].

Several research groups are currently working on advanced materials that may improve the previous maximum value for ZT by at least a factor of 2. This could push efficiencies closer to the 20-25% range for large temperature differences (>400K). The group at the Massachusetts Institute of Technology (MIT) [3, 4] is pursuing improved thermoelectric figure of merit using quantum well structures. They conservatively estimate that they can achieve intrinsic ZT values of 2.0 at 300K for their material. Meanwhile, the group at Research Triangle Institute (RTI) [5] has reported a ZT of ~2.4 for superlattice thin-film Bi_2Te_3/Sb_2Te_3 at room temperature. In addition, recent developments of novel TE materials such as Zn_4Sb_3-based semiconductors (ZT = 1.4 at 250°C [6]) and skutterudites (ZT = 1.4 at 600°C [7]) may offer higher figures of merit at higher temperatures than previous materials. Such new materials if made affordable and available in production quantities may open new opportunities for thermoelectrics in diesel vehicle applications.

In addition to TE material advances, assembly techniques, which affect the temperature difference across the TE, are also being developed that may improve device efficiency. BSST is developing a novel technique that involves the thermal isolation of each of the thermoelectric couples in the direction of fluid flow [8] (see Figure 3). Individual thermoelectric elements that have been thermally isolated can progressively heat or cool a working fluid to increase system efficiency compared to a standard device. Coefficient of performance (COP) approaches the theoretical maximum of a continuous system by increasing the number of TE elements. COP increases up to 120% over conventional TE devices have been shown theoretically. Experimentally, the thermal isolation technique has shown measured performances ranging from 60 to 90% of the theoretical COP (see Figure 4) and at least 50% greater than the theoretical best COP for conventional TE systems [9]. Experimentation in this area is on-going.

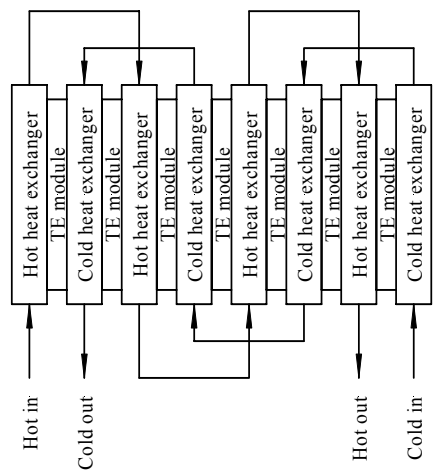

Figure 3. Schematic of thermoelectric heat exchanger using thermal isolation [9].

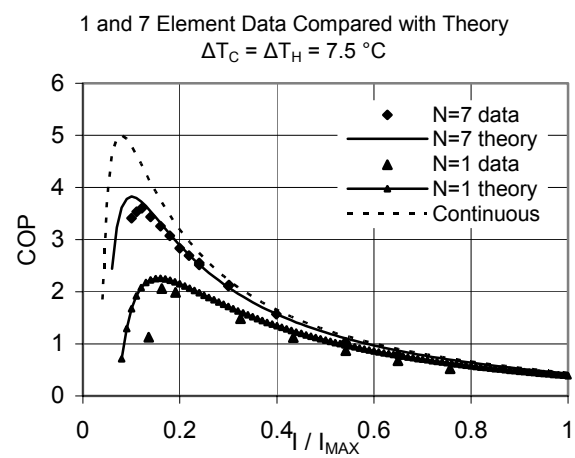

Figure 4. Efficiency improvement for one and seven TE elements at a total temperature difference of 15°C. One element represents a system without thermal isolation [9].

To improve the performance of TE devices further, BSST is also developing high-power density thermoelectrics, which will be discussed further in a later paper. Increased power density will reduce the amount of TE material for a particular application, thus reducing the device's weight and potential cost.

Figure 5 shows the potential of TE energy conversion in HVAC applications. The horizontal band represents the COP for the refrigerant used in a typical automotive HVAC system (R134a), while vertical lines represent the ranges of ZT for current technology, prototype technology at RTI and MIT, and potential future technology. The BSST curve represents the combination of these materials with the thermal isolation technique described above with a cold-side temperature of 280K and a temperature difference across the TE of 30K. The combination of material and assembly advances is expected to allow the development of solid-state systems with performances competitive with those of current two-phase HVAC systems [8]. Similarly competitive performance is also expected when using this combination in power generation applications.

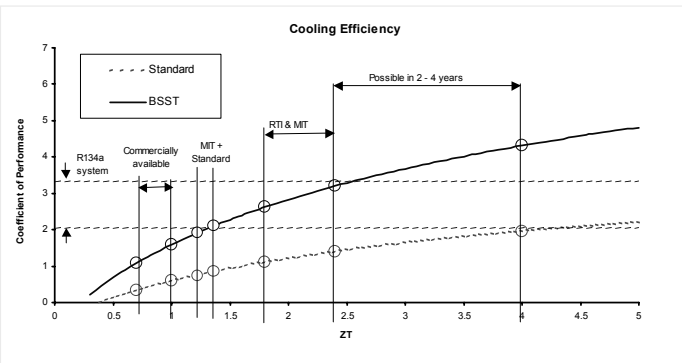

Figure 5. Potential of thermoelectric energy conversion [8].

CLIMATE CONTROL APPLICATIONS

When a person enters a vehicle, one of the primary factors in overall drive enjoyment is user comfort. The comfort level of the user can be affected by a variety of items, including the temperature of the user's environment, which directly affects the user's body temperature. By controlling the temperature for specific parts of the body, the body as a whole can be made to feel cold or hot. For instance, cooling the face will often make the whole body feel cool. When full vehicle HVAC is either cost and/or power prohibitive, a TE-driven face cooling device could be developed that can provide effective cooling and heating of a driver's face that can be low cost and operate at a maximum of 200 watts.

It is not uncommon for today's luxury model automobiles to include the option of heated seats, in which resistive wire or carbon fiber devices provide targeted heating to an occupant's bottom. This strategic heating can provide a level of comfort to the occupant without heating the entire inside cabin of a vehicle or it can provide an extra level of comfort in addition to a standard heating system. It does not, however, address the issue of cooling the occupant.

Using thermoelectric technology, the Climate Control Seat (CCS™) system (see Figure 6) made by Amerigon introduces a unique active temperature management system that offers strategic localized heating and cooling in one package.

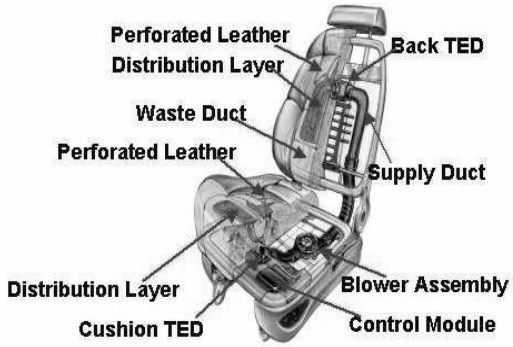

Figure 6. Typical CCS system [10]

The CCS system utilizes two TE assemblies (see Figure 7), one placed in the seat cushion underneath the occupant's bottom and one placed behind the occupant's back, to provide spot heating or cooling where it is most appreciated by the user. Each TE assembly is comprised of a single commercially available 40 x 40 mm TE module. As discussed above, when current is supplied to the TE devices, heat moves from one side of the TE to the other causing one side to heat up while the other side cools down. A change of direction of the current (switching polarity) will switch which side heats up and cools down. Blowing air across an active face of the TE device provides conditioned air that is then channeled to the two strategic areas of the seat. The CCS channels and components are shown in Figure 8.

Figure 7. Thermoelectric assembly [10]

Figure 8. CCS components [10]

The CCS system increases the perceived performance of standard HVAC systems, allowing standard air conditioning and heating system usage to be reduced. Decreasing the use of standard systems, improves fuel economy by reducing the engine load required to drive the HVAC system. If HVAC systems can be replaced by the CCS, greenhouse gas emissions caused by the use of R134a, the standard HVAC refrigerant, can be eliminated. In addition, the weight of the vehicle will be reduced by eliminating the ducts, mechanical drives, and long conduit and supply lines required for standard HVAC systems. This weight reduction translates directly into improved fuel economy.

The CCS system, which will be standard on the 2004 Cadillac Escalade, is also available in vehicle platforms made by Lincoln, Lexus, Ford, Toyota, and Infiniti. Figure 9 shows the progress that the CCS system has made in its penetration into the automotive community.

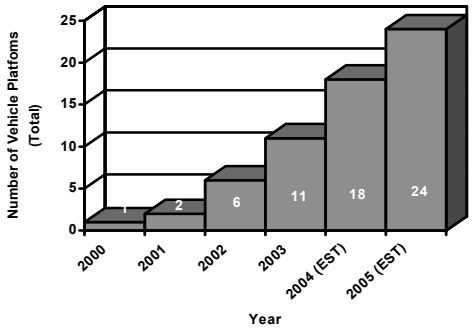

Figure 9. Current and projected CCS vehicle platforms.

There are other heating/cooling examples of TE's being used to improve user comfort in automobiles. Small TE-driven coolers, which can be plugged into a vehicle's cigarette lighter for power, are available in many novelty retail stores. Another current in-vehicle TE application is the heated/cooled cup holder.

WASTE HEAT GENERATOR

In standard diesel-powered vehicles, up to 65% of the fuel chemical energy used to provide vehicle propulsion is lost as waste heat. Most of this waste heat is rejected in relatively equal proportions through the cooling (radiator) and exhaust systems. If some of this wasted heat can be converted into electrical energy and stored in an auxiliary battery or a hybrid electric vehicle battery pack, the efficiency of the vehicle can be improved.

A typical automotive alternator provides up to 1–2 kW of power for a vehicle's auxiliary equipment. Efficiencies for the alternator, a belt-driven device that runs directly off the vehicle's engine, vary from 60% at low engine speeds down to 30% at higher engine speeds. Coupled with the low efficiency of the engine itself, the overall efficiency of the energy producing process of the alternator may be as low as 10-15%. Thus, to produce 1 kW of power from the alternator may require as much as 10 kW of fuel chemical energy. If a waste heat recovery device could supply enough power to support the auxiliary power requirements of the conventional vehicle, then the alternator could be removed from the vehicle with the associated improvements in overall vehicle efficiency. In addition, replacing a maintenance-intensive alternator with a solid-state and rugged waste heat recovery device would also be a significant benefit for the user.

A waste heat recovery device could also be a supplemental source of power in a hybrid electric vehicle. By returning a portion of the required electric power to a storage device (as is done in regenerative braking systems), vehicle efficiencies would be improved by reducing the load on the main power source.

A recent study by the author [2] evaluated the potential of a TE waste heat recovery system based on automotive cooling system waste heat. A numerical model was developed for an integrated TE radiator (see Figure 10) that was optimized using hybrid genetic algorithms. The optimal designs were then evaluated using dynamic models that could analyze the transient effects of changing air and fluid temperatures and flow rates over standard driving cycles. Using these distinctive evaluation techniques, the study showed that significant amounts of net power (TE power minus pump and fan power) could be recovered from an automotive cooling system. Figure 11 shows that a maximum of over 2 kW of net power can be recovered with 150 seconds of sustained recovery of over 1 kW when using advanced thermoelectrics in aggressive driving cycles. By replacing the alternator with the integrated TE radiator, overall vehicle efficiency was shown to improve by as much as 3.3% for standard driving cycles. Using BSST's thermal isolation cycle in the study, which was not used originally, could potentially double the above results.

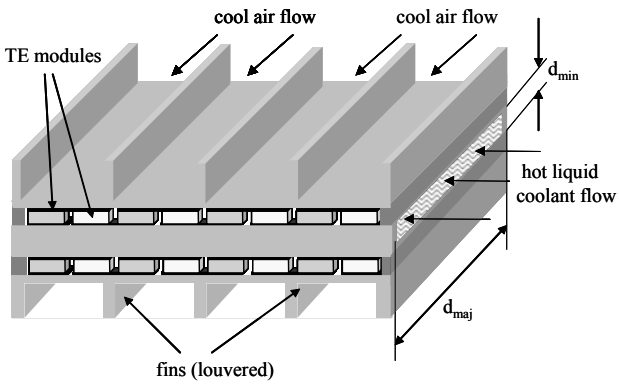

Figure 10. Schematic showing layout of sub-section of integrated TE cross-flow heat exchanger [2].

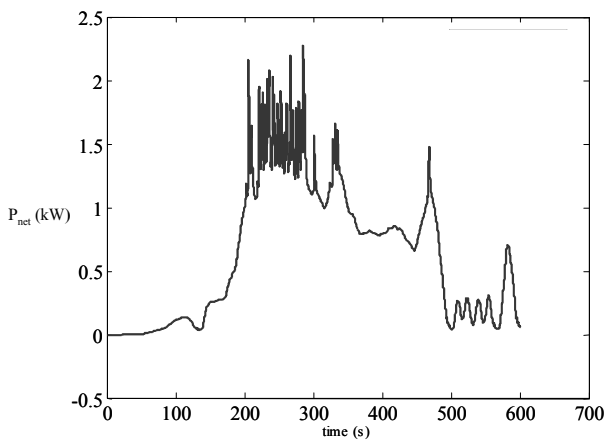

Figure 11. Transient net power for the US06 drive cycle using RTI TE's with T_{amb}=300K and $T_{f,max}$=395K [2].

Researchers have been studying TE waste heat recovery systems in vehicles since as early as 1968 [11]. Most of these studies have involved recovering waste heat from the exhaust system due to the higher quality of the energy (i.e. higher temperatures). The operating fluid in a radiator reaches a maximum temperature of only 120°C, while exhaust system temperatures can go up to 900°C in the catalytic converter due to its exothermic chemical reactions. Thus, the potential for a larger temperature difference across the TE device lies in the exhaust system. This is particularly true for diesel vehicles, which have higher temperatures on average in the exhaust system when compared to similar spark-ignition systems due to the higher compression ratios required for combustion.

One study [12] suggested integrating TE's into a muffler assembly for a heavy-duty diesel engine powered truck. Another study [13] predicted that enough power could be generated by placing a TE waste heat recovery system between the exhaust manifold and exhaust tube to displace a 1 kW alternator when using a low-power diesel engine. A recent modeling study conducted by the National Renewable Energy Laboratory (NREL) [14, 15] predicted TE power outputs up to 5-6 kW from heavy-duty vehicle exhaust waste heat.

Despite previous research, many challenges still remain to make automotive TE waste heat recovery a practical and cost-effective means of improving vehicle fuel efficiency. The costs of such systems will come down as production volumes increase. Production volumes for TE's are already increasing, as discussed previously relating to the CCS system.

In addition, heat transfer issues remain a major concern. Despite the available temperature differences between hot and cold thermal reservoirs for the cooling and exhaust systems, it is not always easy to maintain all of this temperature difference across the TE's. The radiator is an established heat exchanger that will provide a relatively consistent cold side temperature for the TE. In contrast, no current sub-system in automobiles provides consistent airflow along the underside of the car to reject the heat from the exhaust effectively to ambient. Therefore, although higher temperatures for the TE's available in the exhaust may be better, the effectiveness of heat transfer on the cold side may be inadequate to provide high efficiencies. One option is to develop a heat exchanger similar to the radiator. However, such a system is liable to increase engine backpressure. Engine backpressure might also be increased if internal fins are introduced into the exhaust gas flow stream to extract more heat from the system. In another option, an additional coolant flow loop can be created to provide consistent cold-side temperatures. This method would introduce extra complexity into the system, including additional pumps, tubing, and control systems. Neither option is perfect. Both options would have to be evaluated along with different locations within the exhaust system for optimal waste heat recovery potential.

In addition to these concerns, other systems-level considerations must include the effect on road load caused by the additional weight and aerodynamic drag created by the new TE device. These effects were incorporated into the radiator-based study discussed above. The 3.3% efficiency gain cited from that study is a net efficiency gain, which includes the efficiency losses caused by slight increases in drag and weight.

Despite these challenges, the previous research combined with the promising material and assembly developments discussed above suggest that TE waste heat power generation shows significant promise for increasing fuel economy for future diesel vehicles.

EMISSIONS REDUCTION APPLICATIONS

Oxidation catalytic converters eliminate up to 97% of the carbon monoxide and hydrocarbon emissions created during driving. Their performance is limited, however, by their operating temperature. Most catalytic converters do not become fully functional until their operating temperature reaches catalyst "light-off", usually around 300°C. This operating temperature is usually attained in normal vehicle operation after a minute or two. The emissions from this "cold-start" period amount to between 60% and 80% of all vehicle emissions.

Thermoelectric devices could be used to quickly raise the operating temperature of the catalytic converter, greatly reducing cold-start emissions. In addition, these TE devices could be used as temperature control devices to maintain the

optimal operation temperature for the catalytic converter. The problem of temperature control is more apparent in hybrid electric vehicles, where the internal combustion engine is often turned on and off to conserve fuel. This cycling of the engine may result in the catalytic converter never reaching light-off, especially in urban driving. Maintaining a more uniform temperature may also reduce the stress on the converter, extending its lifetime. Other methods exist for providing temperature control for the catalytic converter, but this thermoelectrics configuration could become particularly attractive if these same devices are already being used to recover waste heat from the catalytic converter. A device could be constructed to serve two purposes and provide the benefit of both increased fuel economy and reduced engine emissions.

In addition to catalytic converter limitations, cold-start emissions can also be caused by the obstruction of the fuel filter, due to solidified fuel at low temperatures. This is particularly a problem in diesel vehicles since the solidification temperature of diesel fuel is higher than that of gasoline. In one study [16], researchers designed a device comprised of thermoelectrics, eutectic compound, and a hot wire resistor that when attached to the outside of the fuel filter melts the paraffin (solidified fuel) quickly, helping to remove the fuel filter obstruction and prevent cold-start emissions.

Particulate trap regeneration may be another application in which TE devices may be useful in diesel vehicles. In this application, thermoelectrics can actively raise the temperature of the particles in the trap to around 500°C to allow the particles to ignite, regenerating the trap. Without this periodic regeneration, the particulate trap gets clogged with unburned soot, reducing its functionality.

CONCLUSION

This paper summarizes many potential applications for thermoelectrics in diesel vehicles. These applications show promise in improving fuel economy and user comfort as well as in reducing engine and HVAC emissions. The advanced assembly techniques being developed by BSST, when used in conjunction with advanced thermoelectric materials, can provide thermal efficiencies and coefficients of performance that show potential to be competitive with or exceed the performance of current HVAC and power generation systems. Combined with the solid-state ruggedness of the devices, thermoelectrics have the potential of making a significant impact on the diesel vehicle industry for years to come.

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