

Waste Heat Recovery for Light-Duty Truck Application Using ThermoAcoustic Converter Technology

Dipankar Sahoo
 Tenneco Inc.

Adam Kotrba
 Tenneco Inc

Tom Steiner
 Etalim Inc

Greg Swift
 Los Alamos National Laboratory

ABSTRACT

Nearly a third of the fuel energy is wasted through the exhaust of a vehicle. An efficient waste heat recovery process will undoubtedly lead to improved fuel efficiency and reduced greenhouse gas (GHG) emissions. Currently, there are multiple waste heat recovery technologies that are being investigated in the auto industry. One innovative waste heat recovery approach uses Thermoacoustic Converter (TAC) technology. Thermoacoustics is the field of physics related to the interaction of acoustic waves (sonic power) with heat flows. As in a heat engine, the TAC produces electric power where a temperature differential exists, which can be generated with engine exhaust (hot side) and coolant (cold side). Essentially, the TAC converts exhaust waste heat into electricity in two steps: 1) the exhaust waste heat is converted to acoustic energy (mechanical) and 2) the acoustic energy is converted to electrical energy. The converted electrical energy can be used to offload the alternator, supplying power for auxiliary loads as well as battery charging. In the event of excess electrical energy, it can be returned to the drivetrain through a motor connected to the front end accessory drive (FEAD). With the increasing demand for clean energy, TAC could be an attractive alternative for reducing fuel consumption and CO₂ emissions. Such a technology will become more attractive as electric power loads on a vehicle increase through hybridization and the increased usage of infotainment systems, media, and connected vehicles.

In this paper, the fundamental principle of TAC technology is described and the TAC waste heat recovery vehicular integration with exhaust is presented. Numerical simulations are performed on light-duty gasoline pick-up truck engine exhausts over the US certification cycles to assess the performance and potential of TAC technology. Finally, some of the technical challenges are presented as well, acknowledging technology maturity and risks.

CITATION: Sahoo, D., Kotrba, A., Steiner, T., and Swift, G., "Waste Heat Recovery for Light-Duty Truck Application Using ThermoAcoustic Converter Technology," *SAE Int. J. Engines* 10(2):2017, doi:10.4271/2017-01-0153.

INTRODUCTION

It is well known that nearly a third of the fuel energy is wasted through the exhaust of the vehicle. The vehicles operated by internal combustion engines can have efficiencies of 25-40% depending on the drive cycle. And, now with GHG emissions concerns and effects on climate change, regulations are adopted to improve fuel economies over time, as targeted in the US to be on average 54.5 mpg by 2025¹. Future regulations across most mobile markets will continue to focus on reducing GHG emissions, which requires increasing the efficiency of the engines and/or moving to costlier hybrid drivetrains². Hence, the automobile industry world-wide is undertaking significant research and development efforts to improve the ICE fuel efficiency and reduce

the vehicular GHG emissions. WHR technologies provide an excellent opportunity to achieve both objectives and recent technological advancements have made such technology more viable and cost effective³. There are two primary sources of waste heat from the engine: 1) engine exhaust and 2) coolant. Other sources are also present although with a smaller quantity of waste heat, namely EGR and CAC. The exhaust heat available is regarded as medium grade while the coolant heat is regarded as low grade⁴, although both the primary sources have similar energy content. However, the exhaust waste heat recovery is more attractive due to its higher temperature and exergy. It inevitably results in higher thermal efficiency when coupled to the ICE engine⁵.

Most of the WHR research to date has been using Organic Rankine Cycle (ORC) or Thermo Electric Generator (TEG) systems. A third alternative discussed in this paper is based on thermoacoustic physics called Thermo Acoustic Converter (TAC) technology. TAC technology provides significant advantages in terms of higher efficiency and lower mechanical complexity. Besides the study performed by Karlsson et. al.⁶, there are other relevant instances of thermoacoustic technology use within the field of automotive waste heat recovery for e.g. A DOE project performed by Keolian⁷ and a VW led effort by Fritzsche et. al.⁸ It is worth noting that although the basic underlying thermoacoustic principles are similar in both studies, the operating parameters and electricity generation processes are fundamentally different.

The purpose of this paper is to provide a deeper understanding of the TAC technology and potential power outputs when integrated within the exhaust of a light-duty gasoline truck. An introduction to thermoacoustics is provided followed by the principle of operation, an overview of the employed numerical model, and finally results for a couple of light-duty gasoline engines varying in size.

INTRODUCTION TO THERMOACOUSTICS

Thermoacoustics is the science and engineering of engines and refrigerators that rely on a combination of thermodynamics and acoustics^{9,10}. Sound waves in a gas are often thought of as coupled oscillations of pressure and motion, but oscillating temperature occurs as well. In small passages, there are steep lateral gradients in that oscillating temperature, because the passage walls' solid heat capacity enforces an isothermal boundary condition on the gas, leading to large oscillating lateral heat flows. Together, these oscillating thermodynamic phenomena can be harnessed to create sealed, pressurized heat engines with an efficiency that can be comparable to that of ICEs. Furthermore, the virtues of thermoacoustic engines include the possibilities of no rubbing or moving parts and no exotic materials.

Thermoacoustic engines are classified as either standing-wave or traveling-wave^{9,10}. Standing-wave engines historically arose from fortuitous observations of heat-driven self-sustained oscillators over a century ago, explained by Rayleigh, who wrote in 1877 "if heat be given to the air at the moment of greatest condensation [i.e., density] or be taken from it at the moment of greatest rarefaction, the vibration is encouraged¹¹." Traveling-wave engines are descendants of Stirling engines¹², originally developed in the early 19th century as an alternative to steam engines. In both engines, the production of work occurs in a porous medium, in which the oscillating motion of the gas along a temperature gradient in the pores causes an oscillating heat flow into and out of the gas, which in turn causes oscillating thermal expansion and contraction. Paraphrasing Rayleigh, if the thermal expansion occurs while the pressure is high and the thermal contraction while the pressure is low, the gas does net work on the wave surrounding it during every cycle of the oscillation. The wave then carries that acoustic power elsewhere, where it can force the oscillation of a piston, generate electricity, or be put to other beneficial use.

The porous medium is called a stack in standing-wave engines and a regenerator in traveling-wave engines. Standing-wave engine stacks rely on deliberately imperfect thermal contact to achieve the necessary time phasing between pressure and expansion, and are thus inherently irreversible. Traveling-wave engine regenerators are inherently more efficient, because they rely on good thermal contact. Traveling-wave engines are applied within the proposed TAC technology and are the focus of this study. The required time phasing and the good thermal contact imply that acoustic power flows into the cold end of the regenerator and is amplified within the regenerator across its thermal gradient, so larger acoustic power flows out of the hot end^{9, 10}. Ideally, the ratio of these two powers is the ratio of the absolute temperatures at the ends of the regenerator, and real engines often come close to that ideal. In the regenerator, the oscillating pressure amplitude is typically on the order of 10% of the mean pressure, and the gas motion amplitude is typically on the order of 10% of the regenerator length. Power scales as the product of the oscillating pressure amplitude, the gas motion amplitude, the frequency, and the cross-sectional area.

Unlike an internal-combustion engine, a thermoacoustic engine needs two heat exchangers to maintain the temperature gradient across the regenerator. The hot heat exchanger carries steady heat from an external heat source, delivering it to the thermoacoustic working gas near the hot face of the regenerator in a pulsatile fashion. Similarly, the cold heat exchanger absorbs waste heat from the gas near the cold end of the regenerator in a pulsatile fashion, and carries it away for steady disposal to the ambient environment. The temperatures of those two heat exchangers, T_h and T_c , respectively, set the scale of efficiency for thermoacoustic engines via the Carnot efficiency $1 - T_c/T_h$. In research thermoacoustic engines, the efficiency typically falls between 10% and 25% of the Carnot efficiency for standing waves when practical details of the entire apparatus are taken into account, and between 20% and 50% for traveling waves, with the highest efficiency reported to date being 49% of Carnot¹³.

To minimize the amount of hardware at the hot temperature, a short thermal buffer tube is used adjacent to the hot heat exchanger in a traveling-wave thermoacoustic engine. This is simply an unobstructed tube through which acoustic power can flow, but with careful attention to flow straightening at the ends, so the oscillating gas motion within it is thermally stratified.

Thus, the thermodynamic heart of a traveling-wave engine, the thermal module, comprises in series a cold heat exchanger, a regenerator, a hot heat exchanger, and a thermal buffer tube as shown in [Figure 1\(c\)](#). This thermal module receives steady heat at the hot heat exchanger and receives acoustic power at the cold heat exchanger, yielding amplified acoustic power flowing out of the thermal buffer tube and waste heat at the cold heat exchanger.

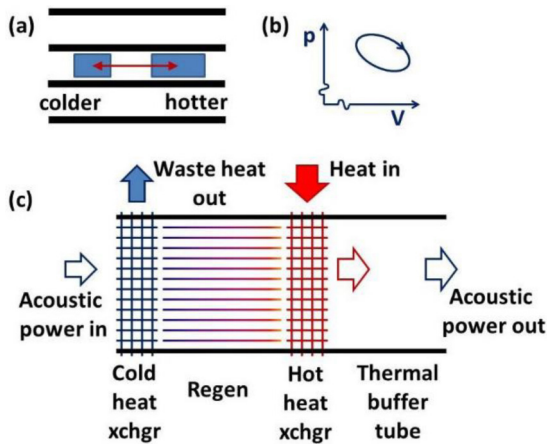


Figure 1. Some details in the heart of a traveling-wave thermoacoustic engine. (a) Oscillating flow in the microscopic pores of the regenerator carries a typical parcel of gas back and forth along the temperature gradient, heating and cooling it, causing thermal expansion and contraction. (b) The acoustic wave must ensure the proper phasing between that motion and the oscillating pressure, to make the thermal expansion occur mostly at high pressure and the thermal contraction to occur mostly at low pressure, causing that parcel of gas to do net $p dV$ work during each cycle. (c) In the thermal module, the regenerator is in between two heat exchangers to maintain the temperature gradient, and the $p dV$ work of all the parcels in the regenerator causes the acoustic power out of right side of the module to be greater than the acoustic power into the left side. The thermal buffer tube carries the output acoustic power from the hot temperature back to the cold temperature.

Surrounding that thermal module, acoustic ductwork can connect to whatever else is needed, such as a linear alternator to convert some of the acoustic power to electricity and send the rest back to the cold heat exchanger. Careful choice of length and varying cross-sectional area of that ductwork creates the acoustic wave needed to make the parts work together as desired. Some applications have called for short toroidal ductwork paths, with net acoustic power delivered to side branches^{14,15}. Other applications, such as for WHR in light-duty engines as discussed, call for a longer path and a series extraction of net power to allow for packaging flexibility.

The principal engineering challenge of traveling-wave thermoacoustic engines is to generate high efficiency at a low system cost that is also lightweight and easy to package, despite the need for high-pressure heat exchangers and a linear alternator. The desire for a small package size pushes the design into high frequency and high pressure, which leads to working gas options with high thermal conductivity and high speed of sound, suggesting either helium or hydrogen.

PRINCIPLE OF OPERATION

Etalim has designed and built a 1 kW thermoacoustic converter consisting of two components, a thermal module and a generator module connected together by acoustic ducts. The thermal module contains the regenerator between hot and cold heat exchangers, with a thermal buffer tube abutting the hot heat exchanger, and functions as an acoustic amplifier of sound power flowing from the cold to the hot side of the regenerator. The generator module consists of a pair of back to back linear alternators connected to flexures that form the dividing walls between a pair of largely planar compression chambers

and a shared expansion chamber. The generator module converts the oscillating linear motion directly to electricity without first converting the reciprocating motion to rotary motion. The generator module contains no sliding parts or seals and thus does not require any lubrication and does not suffer from any wear¹⁶.

The motion of the flexure walls produces high intensity sound waves in the pressurized helium gas (working fluid) hermetically sealed within the TAC. This acoustic power travels from the compression chambers through a tuned acoustic duct to the cold side of the thermal module, where it is amplified by flowing through to the hot side. This amplified power is then returned to the generator module through a second tuned acoustic duct to the shared expansion chamber which is on the other side of the moving flexures¹⁶. The power delivered to the flexures is greater than that needed on the compression sides to produce the starting acoustic power and the extra power is converted to electricity through motion of the pair of attached electro-magnetic linear alternators.

In order to achieve reasonable output power density with a very limited stroke of the flexures and compatible with infinite fatigue life, the TAC operates at a relatively high pressure and frequency. This high frequency has the additional advantage that the tuned acoustic ducts connecting the thermal module and generator module are relatively short allowing for a compact arrangement. The length of the ducts must be chosen to match its operating frequency, as well as to provide the correct phasing of the acoustic power at both modules.

A 1 kW TAC system as outlined above has been built and successfully operated using both electrical heaters and a natural gas burner to deliver heat to the hot heat exchanger in the thermal module, while the cold heat exchanger is kept cool with a circulating fluid. Its target market is combined heat and power (CHP) generator systems for residential applications, providing both heat and electricity from natural gas.

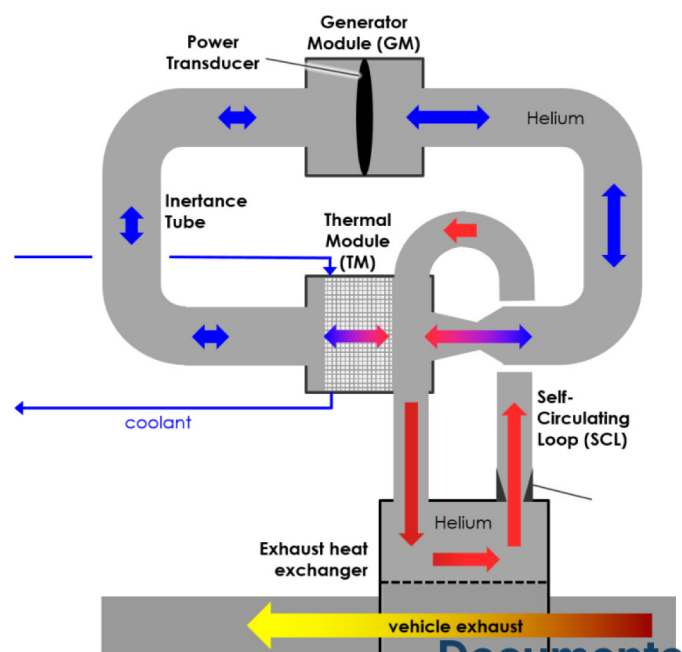


Figure 2. Vehicular integration of a TAC system.