Thermoelectric Generator: An Electronic Device for the Reduction of CO_2 Emissions in Commercial Vehicles

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Abstract— Exhaust heat recovery using Thermoelectric Generators (TEG) is investigated as a cost effective approach for Hybrid Commercial Vehicles which use regenerative braking systems. Recent research has shown that conversion of 10% of this waste heat into electricity may result to an increase of fuel efficiency of up to 20%. Particularly, in the case of heavy duty vehicles there is evidence in the literature that assuming certain designs and manufacturing costs, a heat recovery system can increase the total powertrain efficiency by almost 30%. This paper examines the application of TEG in commercial vehicles and it describes the environmental an economic benefits which are expected in view of the new EU policies for Heavy Duty Vehicles CO_2 emissions reduction.

Keywords— *thermoelectric generator, automotive exhaust heat recovery, CO_2 emissions reduction, hybrid heavy duty vehicles*.

I. Introduction

Heavy Duty Vehicles (HDV) – trucks and buses – are responsible for about a quarter of CO_2 emissions from road transport in the EU and for some 6% of total EU emissions. More specifically, HDV employ Internal Combustion (IC) engines, which produce an amount of energy the majority of which is mainly dissipated in the form of heat through the exhaust gases and the coolant and apart from a small percentage that could be mostly useful to be utilized for cabin heating instead of making use of the more energy consuming A/C, this energy could be recovered and used to improve powertrain efficiency. Fig. 1 shows a typical energy flow path of an internal combustion engine in which only 25% of the fuel combustion is utilized for vehicle operation, whereas about 70% of the total fuel energy dissipates to the environment.

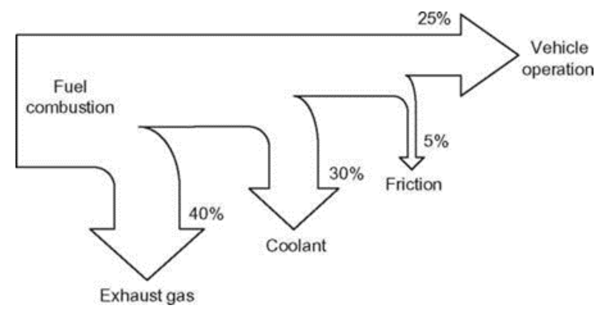

Fig. 1.: *Energy flow of an Internal Combustion engine.*

The two main heat sources which are readily available for the improvement of the overall vehicle powertrain and energy efficiency are: a) the radiator system, which is used to dissipate in the air heat and pump the coolant through the chambers in the heat engine block to avoid overheating, and b) the exhaust gas system of an IC engine, which is used to discharge the expanded exhaust gas through the exhaust manifold [1].

It has been claimed that conversion of even a 10% of this waste heat into electricity by using a Thermoelectric Generator (TEG) may result up to 20% in increase of fuel efficiency [2] and consequently in the reduction of emissions. Consequently, the use of TEGs in the European automotive industry becomes of even greater importance especially in light of the new regulatory targets and measures to be set by the European Commission for fuel savings and CO2 emissions reduction for commercial vehicles.

The present study overviews, in section 2, the EU policies related to CO_2 emissions due to road transport and highlights a technology that may contribute to further reductions by the use of new emerging technologies as the heat recovery from the car exhaust using thermoelectric generators.

Furthermore, in section 3, a synoptic presentation of the state of the art of thermoelectric generators for materials, the principles of thermoelectricity are given. The electrical characteristics of a TEG are presented, in section 4, to show the necessity of using a maximum power tracking system.

Section 5 presents an electronic design to implement maximum power transfer, Finally, section 6 presents the estimated economic benefits of using TEGs for the reduction of gas emissions associated with vehicle operation.

II. EU POLICIES FOR COMMERCIAL VEHICLES CO_2 EMISSIONS

Road transport contributes for about one-fifth to the EU's total emissions of carbon dioxide, the main greenhouse gas. These emissions are still 20.5% higher than in 1990. Transport is the only major sector in the EU where greenhouse gas emissions are still rising. More specifically, Light Duty Vehicles (LDV) – cars and vans – produce around 15% of the EU's emissions of CO_2 whereas Heavy Duty Vehicles (HDV) – trucks and buses – are responsible for about a quarter of CO_2 emissions from road transport in the EU and for some 6% of total EU emissions [3].

In order to reduce these emissions the European Parliament and the Council of the European Union reached an agreement at the end of 2013, regarding two regulatory proposals that will implement mandatory 2020 CO_2 emission targets for new light-commercial vehicles in the European Union. In more detail:

A. Vans

EU legislation sets CO_2 emission targets for new vans sold on the European market. The law requires that new vans registered in the EU do not emit more than an average of 175 grams of CO_2 per kilometer by 2017. This is 3% less than the 2012 average of 180.2 g CO_2/km. In terms of fuel consumption, the target corresponds to about 6.6 l/100 km of diesel. In 2014, the average van sold in the EU emitted 169.2 g CO_2/km. This is significantly below the 2017 target, which was already reached in 2013, four years ahead of schedule. For 2020, the target is 147 grams of CO_2 per kilometer – 19% less than the 2012 average. This target corresponds to around 5.5 l/100 km of diesel. The legislation affects light commercial vehicles, which means vehicles used to carry goods weighing up to 3.5 tons and which weigh less than 2610 kg when empty. It is worth noting that the targets for 2017 for vans were achieved already in 2013.

B. Heavy Duty Vehicles (HDV)

While CO_2 emissions from new cars and vans are being successfully reduced under recent EU legislation, the HDV strategy, adopted in May 2014, is the EU's first initiative to tackle such emissions from trucks, buses and coaches. The Commission has developed a computer simulation tool, VECTO, to measure CO_2 emissions from new HDV. With the support of this tool the Commission intends in late 2015 to propose legislation which would require CO_2 emissions from new HDVs to be certified, reported and monitored. When this legislation is in force the Commission may consider further measures to curb CO_2 emissions from HDVs. Despite some improvements in fuel consumption efficiency in recent years, these emissions are still rising, mainly due to increasing road freight traffic. Under legislation adopted by the European Commission on 25th July 2011 [3] the automotive industry has a greater incentive to invest in new technologies that reduce CO2 emissions from new cars. The Regulation enables motor manufacturers to receive recognition for CO2 savings achieved by fitting new cars with approved "eco-innovations" which reduce emissions. These savings will help the industry meet the European target of limiting CO2 emissions from new cars to an average of 130 grams/km by 2015 (around one fifth below 2007 levels). Under this Regulation, a technology can qualify as an eco-innovation if it is new to the market, contributes to significant CO_2 savings. The technology should also aim at improving vehicle propulsion or the energy consumption of devices that are mandatory, without compromising vehicle safety. In this normative framework, the Eco-Innovations envisaged by the EU are a specific category of technologies that provide a confirmed contribution in terms of reducing CO_2 emissions, certified by third-party bodies and verified in real life and in the actual road use of the vehicle (consequently outside the official type-approval cycle of the vehicle).

Moreover, the European Commission is working on a comprehensive strategy to reduce CO_2 emissions from HDV in both freight and passenger transport, because despite of considerable improvements in fuel consumption efficiency (i.e. the introduction of turbo-chargers for diesel engines and the development of Hybrid HDVs) in recent years, these emissions are still rising, mainly due to increasing road freight traffic.

In view of all the aforementioned policy developments it is evident that the need for the adoption of automotive technologies that in the past were considered expensive to implement and commercialize, may now be of the utmost importance to consider and the TEG is a very prominent example.

III. OVERVIEW OF THE THERMOELECTRICITY PRINCIPLE

A practical automotive waste heat energy recovery system, using TEGs, consists of four components [4, 5], as shown in Fig. 2:

A) A heat exchanger to transfer heat from the exhaust gases to the hot side of the thermoelectric modules
B) Thermoelectric modules that convert heat to electricity in the appropriate temperature range, i.e. 100^0C up to 300^0C depending on materials used
C) A heat exchanger to remove the heat from the cold side of the thermoelectric modules, and
D) An electrical power conditioning and interface unit to match the power output of the thermoelectric modules to the vehicle battery.

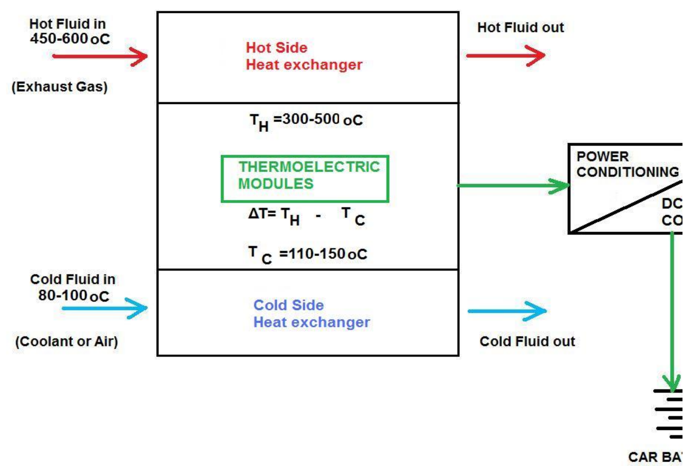

Fig. 2.: *The four general components that should exist in a practical automotive heat recovery system using TEG.*

The heart of a TEG system is obviously, referring to Fig.2, the thermoelectric module. The thermoelectric modules are solid state devices which are commercially available today in a variety of shapes, sizes and power ratings. There are mainly four classes of TEG modules currently available on the market: a)the Bi2Te3 (Bismuth Telluride), which functions up to 320^{o}C, b)the PbTe-BiTe (Lead Telluride-Bismuth Telluride), which functions up to 360^{o}C, c)the Calcium Manganese-Bismuth Telluride, which functions up to 600^{o}C and d)the Calcium Manganese Oxide (CMO), which functions up to 800^{o}C [6].
New materials such as CeFeSb (skutterudite), ZnBe (zinc-beryllium), SiGe (silicon-germanium), SnTe (tin telluride) and new nano-crystalline or nano-wire thermoelectric materials are currently under development to improve the conversion efficiency of TEGs. The BiTe-based bulk thermoelectric material is mostly used in waste heat recovery power generation applications, due to its market availability and wide temperature application range.
Thermoelectric materials are evaluated by a dimensionless figure of merit, ZT, which is defined as a function of materials properties of both N and P type semiconductors and determined by three physical properties, i.e. Seebeck coefficient (α), electrical conductivity (σ), and thermal conductivity (μ) at a temperature T. The following equations hows how these parameters are related to the figure of merit:

$$ZT = \frac{\sigma \alpha^2}{\mu} \mathrm{T}$$

Rowe [7] presents ZT figures of the most popular thermoelectric materials.
Consequently, materials with a high electrical conductivity and Seebeck coefficient together with low thermal conductivity have large values of ZT. Today commercial materials exhibit ZT values of up to 2. There is evidence, however, that further improvements are possible either by introducing new production techniques, i.e. super-lattice, plasma treatment and segmented material using the aforementioned conventional materials or by fabricating nanowires and nanotubes [8].
A typical layout [9] is depicted in Fig. 3.

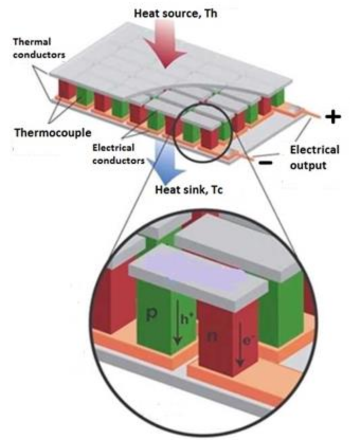

Fig. 3.: *The working principle of a TEG module [9].*

A thermoelectric module is positioned between a heat source and a heat sink. As the heat flows from the heat source through the module and is dissipated into the heat sink, electricity is produced by the module. The thermoelectric module consists of several pairs of p-n thermo-elements. The positive (p-type) and negative (n-type) doped semiconductor elements are connected electrically in series and thermally in parallel. Initially, the conductors in the module possess a uniform distribution of charge carriers. The heat input to the module creates a temperature difference across the p-n thermo-elements.
If the temperature difference across these junctions is maintained, the free carriers (electrons) at the hot end have greater kinetic energy and diffuse to the cold end. However, the accumulation of charge in the cold end results in a back electro-motive force (emf), which eventually resists further flow of charge.

IV. ELECTRICAL CHARACTERISTICS OF A TEG MODULE

The voltages produced by each thermocouple, inside a TEG, are in series, thus from an electrical equivalent circuit point of view they can be simplified to a single DC voltage source. Also, a TEG module shows an internal resistance, which is distributed within each thermocouple and the associated solder connections. Consequently, a TEG module may be electrically modeled as a voltage source in series with an internal resistance,

$$R_{Int} = \sum_{1}^{n} R$$

where R is the internal electrical resistance of each one of the n thermocouples that connected in series constitute a TEG module as shown in Fig. 4.

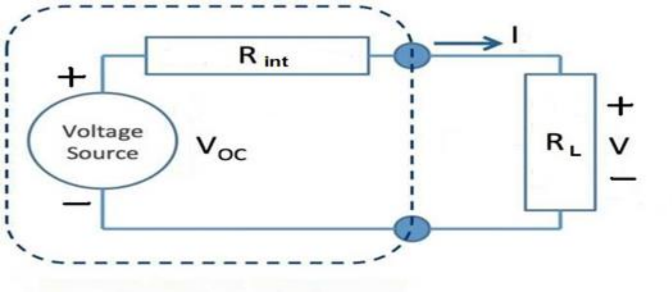

Fig. 4.: *Equivalent circuit of a TEG module connected to a resistive load.*

For a constant temperature difference across the TEG module both the open-circuit voltage and the internal resistance are constant and therefore each one of the output electrical I-V characteristics is linear for a given ΔT.

The following Fig.5 represents the generic electrical behavior of a TEG module and it is obviously valid in the case when TEGs are connected in series and in parallel in order to achieve the required output voltage and output current respectively.

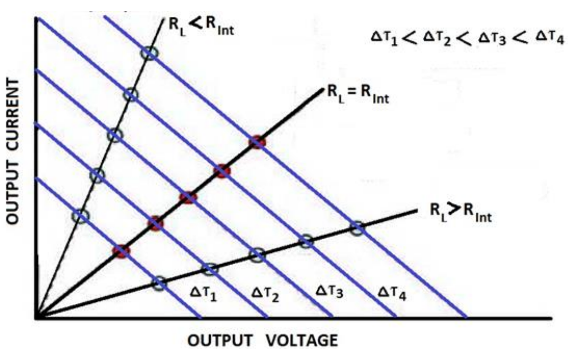

Fig. 5.: *I-V characteristics of a TEG as a function of ΔT.*

It is apparent that there is a high linearity in all I-V lines and almost the same slope. This implies that the internal resistance, $R_{int} \cong |\Delta V \,/\, \Delta I|$, of the TEG system remains constant irrespective of the varying temperature difference and the value of an external resistive load R_L [10].

Fig. 6 shows the I-V characteristic curve of a commercial TEG module (GM250-449-10-12 by European Thermodynamics Ltd), which consists of 449 thermocouples when $\Delta T=220^0C$ [11].

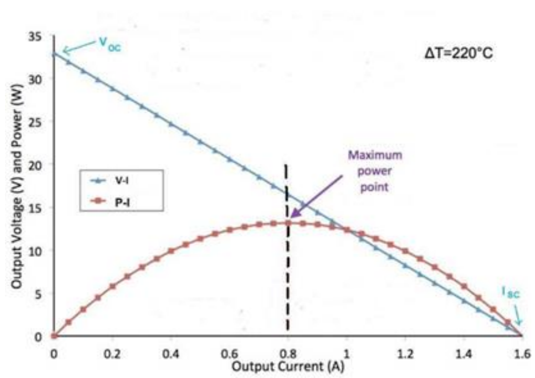

Fig. 6.: *V-I and P-I characteristics of a commercial TEG module [11].*

The blue straight line represents the I-V output characteristic, while the red curve is the corresponding output power curve of the TEG module.

It is interesting to note that the maximum power point lies at the point when $I = I_{SC}/2$ and $V= V_{OC}/2$ and is achieved when the equivalent electrical load resistance, R_L, in the external circuit connected to the TEG exactly equals the internal electrical resistance R_{int} of the TEG, as stated by the theorem of maximum power transfer.

In general, in applications where ΔT is not constant an alternative electronic system is required that will continuously trace the Maximum Power Point (MPP), namely MPP Tracker (MPPT). The MPPT tracks the MPP and consequently drives a buck-boost converter in order to maintain the operating point of the TEG at $V_{OC}/2$ independently of the actual value of ΔT, so that the maximum possible electrical power which can be produced at a given ΔT is delivered to the load as discussed in the following section.

V. POWER CONDITIONING FOR TEGs

In the previous section it was explained that for any fixed thermal condition, the electrical power produced by a TEG varies depending on the electrical load connected at the TEG's terminals and that the maximum power is achieved in the centre of the V-I line, when the voltage is half of the open-circuit voltage V_{OC} or likewise when the current drawn is half of the short-circuit current I_{SC}.

In the design of such systems the major challenge is the connection of the TEG to the load through the appropriate electronic circuits that will provide the maximum power available to the load. This in principle requires the measurement of parameters like output current and voltage of the TEG through use of sensors, and the use of a MPPT controller that drives a DC-DC (buck-boost) converter [12]. The buck/boost converter illustrated in Fig. 7 combines the buck and boost topologies so that the DC voltage output level can be either higher or lower than the DC input voltage level, depending on the duty cycle calculated by the controller. The inductor and capacitors are chosen so as to remove any undesirable AC voltage ripples. Transistor Q is selected so that it can withstand the maximum current through it and the maximum reverse voltage across it when it does not conduct.

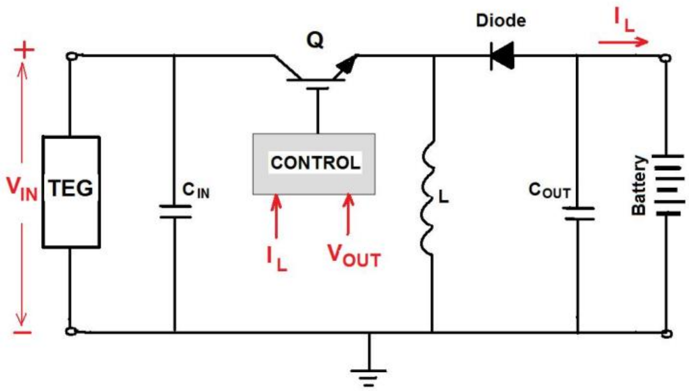

Fig. 7.: *Buck/Boost converter topology*

The most important part in the case of TEGs is the selection of the appropriate MPPT controller algorithm, given that the associated electronic network topology (i.e. DC/DC converter) is usually standardized according to application.

The Perturb and Observe (P&O) algorithm is one of the most commonly used techniques due to its simplicity [13] as to the hardware implementation, despite the computational load involved, thanks to the new families of advanced microcontrollers.

The basic operating principle requires continuously perturbing the electrical operating point and comparing it to the previous value. In this method the operating point moves along the parabola-shaped Power-Voltage curve of the TEG, shown in Fig. 6, and the maximum value corresponds to maximum power extracted.

VI. ECONOMIC BENEFITS

The benefits of using an Exhaust Heat Recovery (HER) system on fuel cost and emissions reduction, have been estimated in Europe: a) for passenger cars [14] and b) for HDV [15].

Assuming that most truck engines today run at around 1500 rpm at cruising speed of 100 Km/h, the exhaust temperature has a mean value of 440°C. Under these conditions, a TEG-HER system for diesel engines, [16] incorporating new thermoelectric materials (i.e. p-type tetrahedrites and n-type magnesium silicide) applied to class 8b trucks (combination tracks, e.g. tractor-trailer, van, bulk tanker, etc) is expected to recover about 4% of fuel energy. This is equivalent to approximately 20% of fuel saving [17]. The cost of a TEG-EHR system for HDVs it has been identified that it can range from 1160 Euros per kilowatt (a target cost by Renault Trucks Joint Company-Volvo Group) [18] to 3600 Euros per kilowatt, [19]. Therefore, an approximate cost of 4000 Euros per kilowatt will be used for the following cost analysis for HDVs, assuming that a 4 kilowatt TEG-EHR system will be installed. Consequently, the total cost is assumed to be the same, i.e. a total cost of 16,000 Euros.

With a fixed fuel price of 1.15 Euro/lt and an annual mileage of 100000 Km, Avaritsioti [15] estimated that the saving on fuel cost from Hybrid trucks equipped with an EHR system is expected to pay-back the cost increase in 5.5 years, whereas a conventional truck equipped with an EHR system, will pay-back in 1 year when a 20% fuel efficiency is assumed.

VII. CONCLUSION

Regulatory requirements along with the need for increased energy efficiency in the automotive industry have led to an exploration of methods of enhancement of current vehicle powertrain technologies. In view of this, energy recovery techniques that extract heat from an automotive exhaust pipe and turn the heat directly into electricity by using thermoelectric power generation have been reviewed.

The TEG power system can achieve relatively high conversion efficiency, it has the ability to easily adapt to changes in the driving cycle and it exhibits an extremely high degree of reliability in comparison with other methodologies, i.e. the Rankin Cycle System.

With regard to future CO_2 regulations, a large market opportunity for TEG modules with a high efficiency can be expected.

Disclaimer

The opinions expressed in this paper are those of the author and should in no way be considered to represent an official opinion of the European Commission.

REFERENCES

[1] Frobenius F., Gaiser G., Rusche U., Weller B. Thermoelectric generators for the integration into automotive exhaust systems for passenger cars and commercial vehicles. Journal of Electronic Materials 2016; 45(3): 1433-40.

[2] Saidur R., Rezaei M., Muammil W., Hassan M., Paria S., Hasanuzzaman M. Technologies to recover exhaust heat from internal combustion engines. Renewable and Sustainable Energy Reviews 2012; 16: 5649-65.

[3] http://ec.europa.eu/clima/policies/transport/vehicles

[4] Karpe S. Thermoelectric power generation using waste heat of automobile. International Journal of Current Engineering and Technology 2016; Special Issue 4: 144-148.

[5] Poshekhonov R., Osipkov A., Makeev M. Modelling of physical processes of energy conversion in automobile thermoelectric generators. Global Journal of Pure and Applied Mathematics 2016; 12(1): 677-690.

[6] Rowe DM. Thermoelectric generators as alternative sources of low power. Renewable Energy 1994;5: 1470-78.

[7] Rowe D.M. Thermoelectrics, an environmentally-friendly source of electrical power. Renew. Energy 1999;16: 1251-56.

[8] Zheng X., Liu C., Yan Y., Wang Q. A review of thermoelectric research- Recent developments and potentials for sustainable and renewable energy applications. Renewable and Sustainable Energy Reviews 2014; 32: 486-503.

[9] Sandiz-Rosato J. E., Weinstein J. S., and Stevens J. R. On the Thomson effect in thermoelectric power devices. International Journal of Thermal Sciences 2013; 66: 1-7.

[10] Carmo P. J., Antunes J., Silva F. M., Ribeiro F. J., Goncalves M. L., Correia H. J. Characterization of thermoelectric generators by measuring the load dependence behaviour. Measurement 2011;44: 2194-99.

[11] Montecucco A., Siviter J., Knox A. The effect of temperature mismatch on thermoelectric generators electrically connected in series and parallel. Applied Energy 2014; 123: 47-54.

[12] Gao J., Sun K., Ni L., Chen M., Kang Z., Zhang L., Xing Y., Zhang J. A thermoelectric generation system and its power electronic stage. Journal of Electronic Materials 2012; 41 (6):1043-50.

[13] Laird I. Steady state reliability of maximum power point tracking algorithms used with a thermoelectric generator. Proc. IEEE International Symposium on Circuits and Systems (ISCAS),ISBN:978-1-4673-5760-9, 2013;1316-19.

[14] Gbegbaje-Das E., 2013. Life cycle CO2 assessment of low carbon cars 2020-2030. Final report for the low carbon vehicle partnership, PE INTERNATIONAL.

[15] Avaritsioti E., 2016. Environmental and economic benefits of car exhaust heat recovery. Proc. 6th European Transport Research Conference, April 18-21 Warsaw, Poland; 1-8.

[16] Fulton L. and Miller M., 2015. Strategies for transitioning to low-carbon emission trucks in the United States. A white paper from the sustainable transportation energy pathways program at UC Davis and the National Center for sustainable transportation.

[17] Harrop P., 2015. Thermoelectric energy harvesting comes center stage. (http://www.idtechex.com/research/articles/thermoelectric-energy-harvesting-comes-center-stage-00008354.asp).

[18] Al-Alawi M. and Bradley T., 2013. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. Applied Energy 103, 488-506.

[19] Peng Z., Wang T., He Y., Yang X. and Lu L., 2013. Analysis of environmental and economic benefits of integrated exhaust energy recovery for vehicles. Applied Energy 105, 238-243.