"Simulation of the performance of a thermoelectric generator in a heavy-duty vehicle under realistic driving conditions"

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Abstract

The automotive market is suffering constant changes, either by imposed environmental regulations or by the general publics search for more economical and efficient vehicles. Therefore, brands are obliged to seek and develop alternatives to current technologies, especially to internal combustion engines. This type of engine converts a third of the energy contained in fuel into useful energy for movement, and the remaining is lost in the form of heat, for the exhaust gases and coolant fluid. With the increase in demand and the consequent increase of hybrid vehicles production, it would be a feasible solution to try to recover and convert some of the dissipated thermal energy into electric energy. In this thesis, a TEG (Thermoelectric generator) is proposed for the purposes mentioned in the pre- vious paragraph. Based on the Seebeck effect, this device generates electrical energy through thermal energy. Recurring to an integration between MATLAB, Simulink and ADVISOR with a previously developed numerical model, the exposure of the TEG to the exhaust temperatures and exhaust mass flow rates of a heavy-duty vehicle is simulated. The power generated and its applicability is after analysed. In the end, and despite this promising technology, the amount of power generated (about 1kW - average) proved to be low, specially when compared to the amount of power necessary to run any accessory in this type of vehicles.

Keywords: Thermoelectric generator, Seebeck effect, Heavy duty vehicles, Exhaust gas, Heat recovery

1. Introduction

Despite the ongoing emergence of new fuel solutions for the transport sector, combustion engines remain the primary propulsion system used in on-road vehicles. This situation is expected to continue for the foreseeable future (at least until 2035)[18]. The transport sector is the second largest energy consumer in the EU, responsible for 1/4 of the total greenhouse gases emissions. This situation is caused by the low efficiency of combustion engines (between 20 and 50%) where most of the fuel consumed is wasted by the exhaust gas and coolant system in the form of heat [14, 1].

Different policies and rules have been proposed, by several entities, to decrease greenhouse issues and climate changes in the world. Furthermore, the European Union is aiming to reduce the greenhouse gases emissions by 20% until 2020 [4]. It can be argued that this can be achieved by increasing the use of electric vehicles, which in theory might reduce the consumption of fossil fuels (depending on how the electricity is produced), or in contrast by optimising the combustion engines efficiency. In fact, a lot of work has been done to improve the efficiency of combustion engines. Internally wise through the enhancement of engine components, and externally by developing devices able to improve fuel economy, recovering some of the wasted heat energy, like for example, a thermoelectric generator.

A thermoelectric generator (TEG) is a device able to convert energy obtained from a thermal source into electric energy, by taking advantage of thermoelectricity. The TEG has no moving parts. It can generate electricity without introducing any additional carbon into the atmosphere. TEGs can produce up to 3.5 kW [17] in vehicles. This capacity allows them to replace/eliminate some engine parts, on the one hand reducing the engine load and engine emissions and on the other increasing the fuel economy.

A TEG can directly convert temperature differences into electricity or vice versa. This entire process is possible due to three different effects, Seebeck effect, Peltier effect and Thomson effect. These effects were discovered respectively by Thomson J. Seebeck (1821), Jean C. Peltier (1834) and William Thomson (1854). The Seebeck effect states that a current will be produced in a circuit formed by two or more different metals if junctions between those metals show different temperatures. Peltier effect stresses that the reverse of the Seebeck effect happens if an electric current runs through the junction of two dissimilar conductors, causing this way, depending on the direction of the current, a heater or a cooler. Thomson effect states that heat is absorbed or released along the length of a material rod with ends at different temperatures. This heat is proportional to the the temperature gradient and to the current that flows along the rod.

This type of technology has been used for several years in a variety of applications. Military, medical, aerospace and automotive applications are just a few examples where TEG's have proved their reliability, simplicity and mostly their power generation capacity [2, 6, 9]. This study focuses on TEG's automotive applications, with particular attention to heavy-duty vehicles.

In 1963, Neild et al. [16] tried for the first time to build and apply a TEG in a vehicle. Even though it generated a low amount of power, this technology sparked interest among the leading brands in the automotive industry. Brands like BMW, Nissan, General Motors or Toyota started to explore this technology, in the late-1990s/early-2000s, through several thermoelectric phenomenon studies, prototype design, building and testing. [3, 5].

The first TEG specially developed for heavy-duty vehicles was designed by Hi-Z Inc in the early-1990s, and it could produce 1 KW [11, 10]. With this Hi-Z Inc project, a very curious and vital fact was obtained. The total output power capacity of a TEG is highly dependent on the engine load, unlike other theories, which attribute this dependence on the engine speed. It can be argued that this may be due to the relationship between the engine load and the exhaust gases temperature variation.

Several studies have been conducted over the years [19, 12, 7] with the primary propose of better understanding this technology and to improve its performance. Several conclusions have been drawn from these studies, such as the massive impact that the thermocouple's shape, its material's properties, the exhaust and the cooling system mass flow rate and temperatures, how heat is transferred from the exhaust gas to the thermocouples or even the vehicle speed, have in TEG's performance.

In 2011 M.A. Karri et al. [13] integrate a TEG numerical model with ADVISOR [8] and they studied the output power generated by the TEG for two different applications, a TEG placed in the exhaust stream of a sports utility vehicle (SUV) and a TEG placed in a stationary, compressed-natural-gas-fueled engine generator. In the case of the vehicle (SUV) all the simulated tests were at constant speed. With this TEG model M.A. Karri et al. [13] were able to produce, for the SUV, about 100 to 450 Watts and they concluded that a significant fraction of the exhaust energy was rejected to the coolant.

More recently Risseh et al. [1] designed and built a TEG for further application on a drivable heavy-duty vehicle with excellent results. It proved that this technology is on the right path to become a great wasted heat recovery solution.

2. Implementation

This study is a follow up to Vale's and Marvo's thesis [18, 14]. Vale, in her thesis has modeled a TEG using MATLAB[15]. Marvo, did an optimisation of the TEG modeled by Vale.

2.1. ADVISOR

ADVISOR [8] is an "ADvanced VehIcle SimulatOR" developed by NREL's to be used with MATLAB® [15] and Simulink®. Used by some well-known brands in the vehicle engineering community, it allows the user to analyse the overall performance of a vehicle.

To perform the vehicles simulations ADVISOR [8] requires some information about the vehicle itself as well as information about the driving cycle. The vehicle frontal area, the vehicle engine type, the vehicle tire dimensions are just some examples of the required information but for this thesis, the exhaust gas system composition and the vehicle engine type are the most important, and they need to be adequately set up. The exhaust gas system used in the simulations has a diesel oxidation catalyst (DOC) installed along its length. In this thesis, the TEG is simulated before and after this exhaust after treatment, and exhaust gases temperatures change according to this location which can probably mean a better or a worse performance of the TEG. Exhaust gases temperature don't affect only TEG's performance but the diesel oxidation catalyst too, so a right balance needs to be achieved.

It's important to refer that models in ADVISOR [8] have some limitations. Models are quasi-static and mostly empirical. This means that, it uses data collected in steady-state tests and corrects them for transient effects ("cannot be used to predict phenomena with a timescale less than a tenth of a second") and that it relies on drivetrain component input/output relationship measured in a laboratory. Another limitation is that in electrical components, ADVISOR [8] deals in power and not in voltage and current. This causes some limitations when analysing the TEG behaviour in a vehicle.

Four different types of files constitute ADVISOR [8], input scripts, output scripts, control scripts and block diagrams.

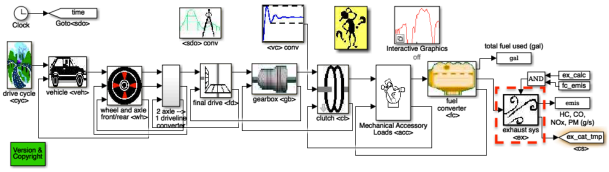

Figure 1: Block diagram - ADVISOR

Figure 1 shows a block diagram extracted from Simulink that represents a vehicle (conventional heavy-duty vehicle in this case). Every single block in this image is a Simulink file that contains all the equations used to compute the outputs. For this study all the values used as inputs for the TEG were extracted from the exhaust system block, as shown in figure 1.

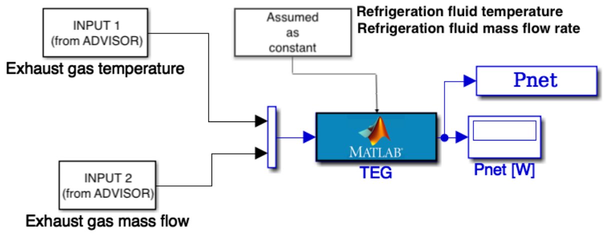

Figure 2: TEG block - ADVISOR

A thermo-electro generator uses temperature gradients to produce electric energy. This represents at least four inputs in a TEG, two temperatures (exhaust gas and coolant fluid) and two mass flow rates (exhaust gas and coolant fluid). For this study, just like Vale [18] and Marvo [14] did, the temperature and mass flow rate for the coolant fluid are considered constant. This means that, the TEG will use for all the calculations values extracted from ADVISOR for the exhaust gas temperature and exhaust gas mass flow rate and will consider coolant fluid temperature and mass flow rate constants. We can observe this in figure 2. TEG in this figure represents a MATLAB [15] function adapted from the numerical code developed by Vale [18] to work side-by-side with Simulink and ADVISOR [8]. In figure 3 it's possible to observe where the TEG is going to be connected in order to get the temperature and mass flow rate values for the exhaust gas.

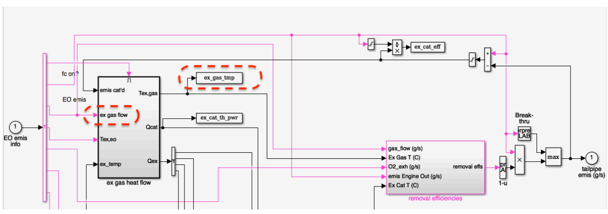

Figure 3: Exhaust system block - ADVISOR

Figure 4 represents the integration of the TEG with the vehicle exhaust system. As referred in the previous paragraph the inputs for this system are the exhaust gas mass flow rate and the exhaust gas temperature, and they are acquired in "real time". It's possible this way to have a real-time calculation for Pnet (our output in this system) that represents the power generated by the TEG. It's also noticeable in this figure 4 that a real-time unit converter for the exhaust gas temperature (to convert C in K) and exhaust gas mass flow rate (to convert g/s to kg/s) is also needed so that Pnet comes in Watts. The switch named "Position" allows the user to choose between different exhaust gas temperatures (at various locations along the exhaust pipe length). Using it makes possible to the user to select between Position 1 (exhaust gas temperature after the Catalyst - After Catalyst) and Position 2 (exhaust gas temperature before the catalyst - Before Catalyst).

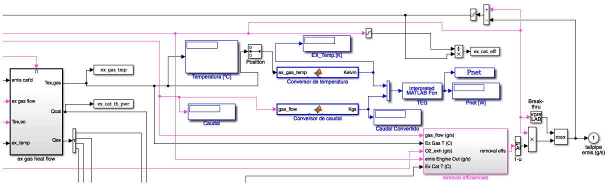

Figure 4: TEG Circuit in ADVISOR

2.2. Study

In this study, two different vehicles are tested in two different cycles. In a first stage, all the results are obtained with the vehicle being tested in a constant velocity cycle while in a second stage the vehicle is exposed to the transient cycle ETC (European Transient Cycle).

Vehicle	Engine	Weight[kg]
A	Turbo Diesel; V= 15.6L ; 397kW	9250
B	Turbo Diesel; V= 15.6L ; 308kW	9250

Table 1: Vehicles description

Three type of fins were tested (Hot side) , Plain Fins, Offset Fins and Triangular fins all in two different configurations (consult images from 5 to 10). All the thermoelectric materials, both p-type and n-type used in this TEG model were previously defined by Vale [18] in her master thesis such as the maximum width, length and height of the TEG. The TEG weight was calculated using SolidWorks, a 3D modeling software used for mechanical design. Using a configuration of 8 layers, 25 thermoelectric modules per layer and 15 thermocouples per thermoelectric module we end up with approximately 9,76kg. With different configuration of 11 layers, 68 thermoelectric modules per layer and 25 thermocouples per thermoelectric module we will end up with approximately 55kg just for the inside components of the TEG. Adding all the electric cables, cooling fluid circuit, cooling fluid, the TEG shell (outside cover protection) and maybe a high capacity battery easily we end up with something between 100 and 200kg. This is the value (200kg) used to represent the TEG weight in all the calculations.

Both engines (A and B) were tested, with and without the TEG installed, for fuel consumption (L/100), emissions (g/Km), exhaust gas mass flow rate (kg/s), exhaust gas temperature (K) and TEG generated power (W). In a first stage, all the tests were performed for a constant speed of approximately 105km/h considering both hot and ambient temperature starts. Two different positions for the TEG were tested, before the catalyst (Before Catalyst) and after the catalyst (After Catalyst). Results for two different configurations per fin type will be presented, one using the standard parameters used by Marvao's [14] (configuration 1) and a second one using part of his optimisation to the TEG. For the second stage of the section, the two best results of each fin type(the configurations with higher Pnet values) are tested in a different driving cycle (ETC). This cycle test simulates realistic driving conditions (transient state).In order to compare all the parameters (fuel consumption (L/100km), emissions (g/Km), exhaust gas mass flow rate (kg/s), exhaust gas temperature (K) and generated power - Pnet (W)) pre and post TEG installation, an initial simulation for both vehicles without the TEG installed was also performed.

Number of layers	9
s (mm)	4.61
h (mm)	13.16
t (mm)	1.00

Figure 5: Plain Fins setup - Configuration 1

Number of layers	11
s (mm)	2.00
h (mm)	19.08
t (mm)	1.00

Figure 6: Plain Fins setup - Configuration 2

3. Results

In this section "Pnet" represents the average generated power by the TEG in Watts [W]; "Fuel consumption" is represented in L/100km; All the emissions are represented in g/Km; "Mass flow" represents the exhaust gas mass flow rate in kg/s;

Number of layers	9
s (mm)	8.20
h (mm)	13.16
t (mm)	1.00

Figure 7: Triangular Fins setup - Configuration 1

Number of layers	15
s (mm)	5.75
h (mm)	8.12
t (mm)	1.00

Figure 8: Triangular Fins setup - Configuration 2

Number of layers	7
s (mm)	5.13
h (mm)	23.60
t (mm)	1.00
l (mm)	50.00

Figure 9: Offset Fins setup - Configuration 1

Number of layers	13
s (mm)	5.13
h (mm)	13.25
t (mm)	1.00
l (mm)	30.12

Figure 10: Offset Fins setup - Configuration 2

"Ex.g.Tem." represents an average value for the exhaust gas temperature right before entering the TEG in Kelvin [K]; "TEG Position" represents the TEG position along the exhaust gas pipe.

3.1. Results without TEG

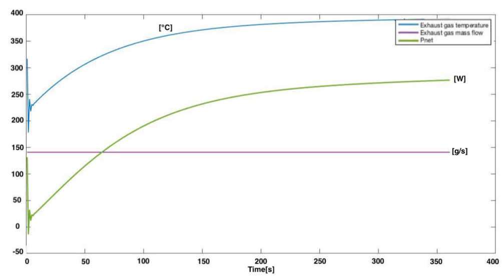

Figure 11: Constant velocity cycle with cold start. Green - Pnet[W]; Blue - Exhaust gas temperature[C]; Purple - Exhaust gas mass flow rate[g/s]

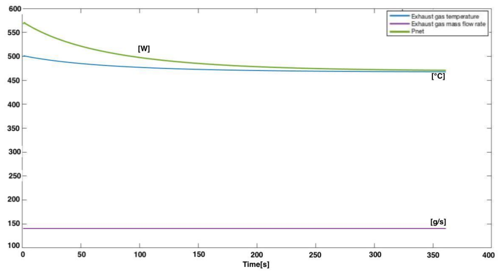

Figure 12: Constant velocity cycle with hot start. Green - Pnet[W]; Blue - Exhaust gas temperature[C]; Purple - Exhaust gas mass flow rate[g/s]

Vehicle	Start	Fuel Consumption	Nox	HC	CO	Ex.mass flow	Ex.gas temperature
A	Ambient	39.9	34.111	1.35	0.825	0.139	693.19
	Hot	37	28.011	0.07	0.069	0.139	730.96
B	Ambient	35.8	24.1	1.043	0.763	0.125	647.91
	Hot	33.3	20.359	0.054	0.058	0.125	684.97

Figure 13: Vehicles emissions and fuel consumptions before TEG considering 9250kg

3.2. Results for configuration 1 (constant velocity)

As we can see from the tables, the best results for this type of fins were obtained using a hot start, and the TEG positioned after the catalyst, obtaining this way higher temperatures for the exhaust gas. Considering that the exhaust gas mass flow rate has the same value for all the simulations (same value per vehicle), it is noticeable the influence of the temperature gradient between the exhaust gas and the coolant fluid in Pnet. Clearly, the best results in this section were obtained for configurations where the temperature difference between the exhaust gases and coolant fluid was bigger. Its possible to notice as well that the vehicle B, with less engine power (308kW) generates less Pnet than Vehicle A (397kW). This happens because not only the exhaust gas temperatures for vehicle B are lower when compared with vehicle A, but, at the same time, vehicle B has lower values of exhaust gas mass flow rate. The best Pnet value in this section for both vehicles was obtained using offset fins and an After Catalyst position.

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	346.14	40.00	34.73	1.15	0.68	140.10	704.49	Before Catalyst
	183.29	40.00	34.73	1.15	0.68	140.10	599.44	After Catalyst
Hot	439.95	37.00	28.15	0.07	0.07	140.28	746.25	Before Catalyst
	448.99	37.10	28.15	0.07	0.07	140.28	749.91	After Catalyst

Figure 14: Plain Fins Setup - Configuration 1 results - Vehicle A(TEG weight included)

3.3. Results for configuration 2 (constant velocity)

Reading across the results it's possible to notice that the Pnet values obtained with configuration 2 are higher when compared with configuration 1,

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	287.97	35.90	24.39	0.94	0.66	126.35	685.38	Before Catalyst
	163.07	35.90	24.39	0.94	0.66	126.35	593.34	After Catalyst
Hot	363.08	33.40	20.56	0.05	0.06	126.35	723.92	Before Catalyst
	380.56	33.40	20.56	0.05	0.06	126.35	731.86	After Catalyst

Figure 15: Plain Fins Setup - Configuration 1 results - Vehicle B(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	345.66	40.00	34.73	1.15	0.68	140.10	704.49	Before Catalyst
	194.63	40.00	34.73	1.15	0.68	140.10	599.44	After Catalyst
Hot	261.45	37.10	28.15	0.07	0.07	140.10	749.90	Before Catalyst
	246.80	37.10	28.15	0.07	0.07	140.10	749.90	After Catalyst

Figure 16: Triangular Fins Setup - Configuration 1 results - Vehicle A(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	129.37	35.90	24.87	0.82	0.55	126.22	685.37	Before Catalyst
	96.39	35.90	24.87	0.82	0.55	126.22	593.34	After Catalyst
Hot	155.38	33.40	20.90	0.05	0.06	126.22	723.91	Before Catalyst
	164.72	33.40	20.87	0.05	0.06	126.22	731.86	After Catalyst

Figure 17: Triangular Fins Setup - Configuration 1 results - Vehicle B(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	399.70	40.00	34.73	1.15	0.68	140.10	704.49	Before Catalyst
	211.75	40.00	34.73	1.15	0.68	140.10	599.44	After Catalyst
Hot	510.03	37.10	28.15	0.07	0.07	140.10	749.90	Before Catalyst
	520.76	37.10	28.15	0.07	0.07	140.10	749.90	After Catalyst

Figure 18: Offset Fins Setup - Configuration 1 results - Vehicle A(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	349.66	35.90	24.87	0.82	0.55	126.22	685.37	Before Catalyst
	197.59	35.90	24.87	0.82	0.55	126.22	593.34	After Catalyst
Hot	356.83	33.40	20.59	0.05	0.06	126.22	689.93	Before Catalyst
	359.89	33.40	20.59	0.05	0.06	126.22	705.10	After Catalyst

Figure 19: Offset Fins Setup - Configuration 1 results - Vehicle B(TEG weight included)

mainly because the optimisation that Marvo's [14] developed for his thesis increments the number of layers, the number of thermoelectric modules per layer just like the number of thermocouples per thermoelectric module. As expected, the same results were obtained regarding the exhaust gas mass flow rate, exhaust gas temperatures and emissions but, overall, with better results for the amount of power generated (Pnet). Once again, the best results for Pnet for vehicle A and B were obtained with the offset fins configuration.

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	566.22	40.00	34.73	1.15	0.68	140.11	704.49	Before Catalyst
	298.60	40.00	34.73	1.15	0.68	140.11	599.45	After Catalyst
Hot	723.18	37.10	28.15	0.07	0.07	140.11	746.26	Before Catalyst ←
	738.40	37.10	28.15	0.07	0.07	140.11	749.91	After Catalyst ←

Figure 20: Plain Fins Setup - Configuration 2 results - Vehicle A(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	497.04	35.90	24.87	0.82	0.55	126.22	685.38	Before Catalyst
	279.28	35.90	24.87	0.82	0.55	126.22	593.34	After Catalyst
Hot	631.08	33.40	20.87	0.05	0.06	126.22	723.91	Before Catalyst
	662.63	33.40	20.87	0.05	0.06	126.22	731.86	After Catalyst

Figure 21: Plain Fins Setup - Configuration 2 results - Vehicle B(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	271.47	40.00	34.73	1.16	0.68	140.10	704.49	Before Catalyst
	132.26	40.00	34.73	1.15	0.68	140.10	599.44	After Catalyst
Hot	359.17	37.10	28.15	0.07	0.07	140.10	746.25	Before Catalyst ←
	367.97	37.10	28.15	0.07	0.07	140.10	749.90	After Catalyst ←

Figure 22: Triangular Fins Setup - Configuration 2 results - Vehicle A(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	239.45	35.90	24.87	0.82	0.55	126.22	685.37	Before Catalyst
	126.89	35.90	24.87	0.82	0.55	126.22	593.34	After Catalyst
Hot	313.71	33.40	20.87	0.05	0.06	126.22	723.91	Before Catalyst
	331.91	33.40	20.87	0.05	0.06	126.22	731.86	After Catalyst

Figure 23: Triangular Fins Setup - Configuration 2 results - Vehicle B(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	579.01	40.00	34.73	1.15	0.68	140.10	704.49	Before Catalyst
	306.15	40.00	34.73	1.15	0.68	140.10	599.44	After Catalyst
Hot	739.34	37.10	28.15	0.07	0.07	140.10	746.25	Before Catalyst ←
	754.92	37.10	28.15	0.07	0.07	140.10	749.90	After Catalyst ←

Figure 24: Offset Fins Setup - Configuration 2 results - Vehicle A(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Ambient	498.60	35.90	24.87	0.82	0.55	126.22	685.37	Before Catalyst
	281.16	35.90	24.87	0.82	0.55	126.22	593.34	After Catalyst
Hot	632.62	33.40	20.87	0.05	0.06	126.22	693.81	Before Catalyst
	664.25	33.40	20.87	0.05	0.06	126.22	731.86	After Catalyst

Figure 25: Offset Fins Setup - Configuration 2 results - Vehicle B(TEG weight included)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Hot	542.89	28.30	61.08	0.63	0.05	60.24	758.49	Before Catalyst
Hot	666.60	28.30	61.08	0.63	0.05	60.24	801.56	After Catalyst

Figure 26: ETC cycle Vehicle A (Plain Fins)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Hot	300.07	28.30	61.08	0.63	0.05	60,24	758,49	Before Catalyst
Hot	379.76	28.30	61.08	0.63	0.05	60,24	801,56	After Catalyst

Figure 27: ETC cycle Vehicle A (Triangular Fins)

Start	Pnet	Fuel Consump.	Nox	HC	CO	Mass flow rate	Ex.g.Tem.	TEG Position
Hot	470.80	28.30	61.08	0.63	0.05	60.24	758.49	Before Catalyst
Hot	575.52	28.30	61.08	0.63	0.05	60.24	801.56	After Catalyst

Figure 28: ETC cycle Vehicle A (Offset Fins)

3.4. ETC cycle (transient state)

In this section, the two best configurations per fin type from the two sections above are tested using a cycle that simulates realistic driving conditions. All the selected configurations for the ETC cycle are marked with "←" in the results tables above. Figures 26 to 28 show the results for this ETC cycle, for all three types of fins configurations, using the hot start option (best results in sections above) and both positions before and after the exhaust gas treatment system (catalyst). Again, the generated power displayed on this tables is an average value. Its noticeable that the best results using realistic driving conditions were obtained using the TEG positioned after the exhaust gas treatment system in the exhaust pipe (After Catalyst) just like in the sections above. Although, the best fin type for this cycle test is now the plain type. We can notice as well, using the graphs, that using the After Catalyst configuration, the Pnet line, besides representing higher values, is more stable when compared with the Before Catalyst configuration. In Figure 29, which represent the TEG installed before the catalyst, its noticeable this instability or the constant variation of the exhaust gas temperature mainly when compared with figure 30, that represents the TEG installed after the catalyst. This happens because although the temperature of the exhaust gas before the catalyst is very dependent on the engine regime, the temperature of the exhaust gas after the catalyst is somehow affected by the temperature of the catalyst interior and so, the exhaust gas temperature will increase by the moment it passes trough the catalyst. It's safe to say that the catalyst is acting like an accumulator, accumulating heat while the engine is running at higher regimes and loosing that heat to the exhaust gas when the engine is running at lower regimes. It's possible to confirm this phenomenon using figures 31 and 32. This explains why the TEG, when installed after the catalyst is always able to generate more power [W] in Urban Streets and Rural Roads when compared to an installation of the TEG before the catalyst (figure 33). Although, the TEG installation before the catalyst proves to be better in cycles where a constant speed is used. This type of cycle tend to simulate what happens when a vehicle is driven in motorways, for example. As we can see on figure 34 with constant speed, the temperature gradient (between exhaust gas before and after the catalyst temperatures) converge to a slightly higher temperature of the exhaust gas before the exhaust gas treatment system. Once again, this means that the software ADVISOR is not taking into account the exothermic reaction that occurs inside the catalyst which releases heat to the exhaust gas.

4. Conclusions

The primary objective of this master thesis was to integrate Vale's [18] numerical code with ADVISOR [8] and MATLAB [15] and figure it out the best position for the TEG along the exhaust pipe. This

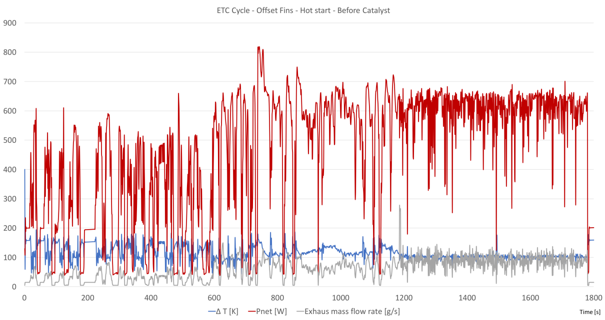

Figure 29: Exhaust mass flow rate [g/s] (Grey) vs Exhaust gas/Coolant Temperature Gradient [K](blue) vs Pnet [W](red) - Offset Fins - Before Catalyst - Hot start - Vehicle A

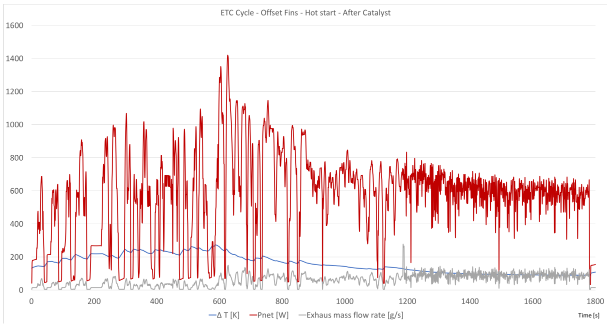

Figure 30: Exhaust mass flow rate [g/s] (Grey) vs Exhaust gas/Coolant Temperature Gradient [K](blue) vs Pnet [W](red) - Offset Fins - After Catalyst - Hot start - Vehicle A

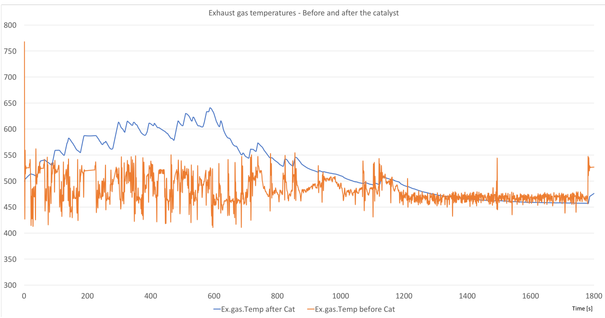

Figure 31: ETC cycle test - Exhaust gas temperature after the catalyst (Blue) vs Exhaust gas temperature before the catalyst (orange)

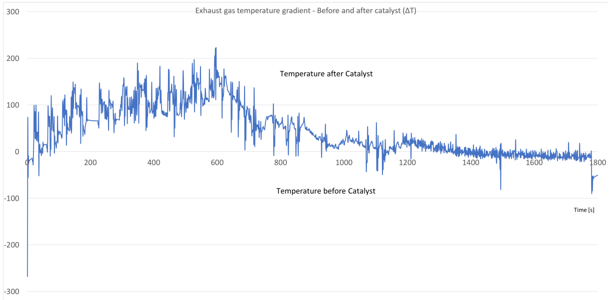

Figure 32: ETC cycle test - Exhaust gas temperature gradient [K] (between before and after catalyst temperatures)

	Plain					
	After Catalyst			Before Catalyst		
	Urbano	Rural	Motorway	Urbano	Rural	Motorway
Pnet [W]	587,88	784,42	629,41	374,68	616,85	637,64

	Triangular					
	After Catalyst			Before Catalyst		
	Urbano	Rural	Motorway	Urbano	Rural	Motorway
Pnet [W]	359,25	446,82	334,35	219,34	341,59	339,51

	Offset					
	After Catalyst			Before Catalyst		
	Urbano	Rural	Motorway	Urbano	Rural	Motorway
Pnet [W]	449,39	695,42	583,64	280,29	542,59	590,14

Figure 33: ETC cycle test - Driving conditions and Pnet

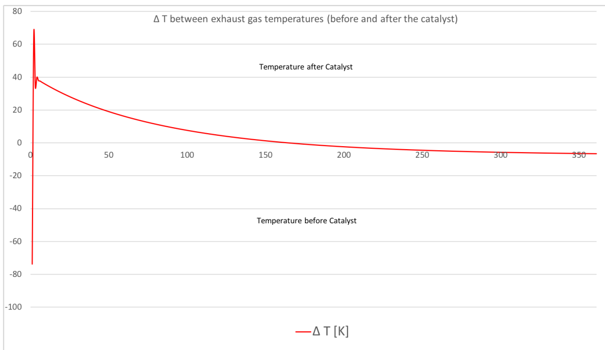

Figure 34: Constant velocity cycle test - Temperature gradient between exhaust gas before catalyst temperature and after catalyst temperature

objective was hit. The TEG is an excellent system to recover some of the wasted energy in a thermal engine, and somehow that energy can be used to power accessories in a vehicle or even help/replace some vehicle parts like the alternator usually used to charge the batteries in a vehicle. The elimination of the alternator in a vehicle could represent savings in fuel consumptions because we are reducing this way the number of accessories that are using power produced directly by the engine. Maybe, both alternator and TEG can be used simultaneously to improve the efficiency in a hybrid car. The type of fins to be used in a TEG and the best position for a TEG installation can change from vehicle to vehicle and specifically with the type of cycle where the vehicle is going to be driven, although the plain type of fins and an installation of a TEG system after the catalyst appears to be the best solution for a daily use. On the overall, the results obtained for the Pnet in all the simulations were good, but there are things to improve in this promising technology. TEG simulated in this master thesis was able to produce 1.4KW in some simulations (bear in mind that the Pnet results showed in tables in section 4 represents an average value). This amount of power was generated in Risseh et al. [1] experiments using two physical TEGs combined, installed in a drivable heavy-duty vehicle.This proves that the model tested in this master thesis has potential when compared with other studies. It's important to say that this model still needs some changes to represent a real transient state and that the results from this master thesis can change in those conditions. Although the amount of power generated by the TEG model used in this thesis is significant for this type of technology, it's still not enough to be used to supply energy to almost any accessory in a heavy-duty vehicle. For example, the power generated by the alternator in the vehicle tested in this master thesis can achieve 7,45KW, and the power used by the air conditioner compressor can achieve 3,72KW (these values were extracted from ADVISOR [8]). It's important to refer that the tested vehicle didn't have a diesel particulate filter (DPF) installed, and besides the fact soot emission are not represented in results tables it can or can not affect the TEG efficiency depending on its position in the exhaust pipe. More companies are now investing in electric and hybrid technology and with this new thermoelectric materials are being designed. This represents a better ZT, an improved TEG efficiency and more available power.

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