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Comparative analysis of heat recovery methods from internal combustion engines

M E Filip, G Csaba and D Lelea

University Politehnica Timisoara, Department of Thermal Machines and Transportation, Timisoara, Romania

E-mail: fillip_mihai@yahoo.com

Abstract. This paper discusses different ways of recovering wasted energy from the internal combustion's engine exhaust gas. It is well known that the mechanical work produced by an internal combustion engine is only a small amount related to the fossil fuel it uses. By recovering some of the wasted energy, the internal combustion engine's efficiency can be increased especially in the cold season. The amount of the toxic compounds and greenhouse effect gases that are released in the air can also be decreased by heating up the engine very quickly, lower the engine's load and reduce fuel consumption. The energy is recovered as heat using different types of heat exchangers but can be converted to mechanical energy, electrical energy or even air conditioning power. Because we are referring at vehicle engines, special care must be taken regarding safety in normal operating conditions and also in case of a crash. Some of the methods that combine recovering and storing heat are suitable for hybrid vehicles also. The conclusion of this paper is that the internal combustion engine can take advantage of some heat recovery systems.

1. Internal combustion engines efficiency

The biggest problem with the internal combustion engine is that most of the energy generated by combustion is wasted as heat rather than converted propulsion for the vehicle. The first Lenoir engine that was built in 1860 had 2 horsepower and only 4% efficiency. Four years later, in 1864 the first Otto engine had already 12% efficiency. Today's car engines reach about 40%-45% efficiency and the best efficiency achieved is 54,4% by the low speed diesel marine engine, MAN S80ME-C7. The turbine, the intercooler, the use of high-pressure stratified fuel injection, the recirculation gas valve and the downsizing of the engines all contribute to a better fuel efficiency. Also, the new fuels have better performances than the old ones.

2. Pollution, the main focus

2.1 Fossil-fuel based engines

Every engine that burns fuel will release exhaust gas that is toxic for humans, animals and the environment. If the engine is more efficient it will burn less fuel for the same amount of mechanical work and release less exhaust gas. A warmer engine will also have better efficiency and burn less fuel than a cold one. Exhaust gases produced by an internal combustion engine from diesel, bio-diesel, petrol and other alternate fuels consist in particulate matter, un-burnt hydrocarbons, oxides of nitrogen, carbon monoxide and carbon dioxide. Euro emission norms establish how much an engine can pollute to meet a specific euro standard. The newer cars, if maintained well, produce a smaller quantity of air



pollutants but when we get into this equation a significant number of cars we still have a big air quality problem. The only visible air pollutant is the particulate matter which can also be observed only in certain conditions, especially in case of older diesel engines. Un-burnt hydrocarbons, oxides of nitrogen, carbon monoxide and carbon dioxide are our stealth enemies.

Other small particles can be also produced by tyres, brake discs, brake pads or brake floating shoe. If an engine is not correctly maintained and consumes oil it will release blue smoke which is very harmful for our health. In other cases, like clogged admission or very rich fuel mixture following a cold start even gasoline engines can produce visible smoke. A clean air filter is very important for the car to have enough intake air and burn all the injected fuel. The quantity of air pollutants is also influenced by other factors like traffic, driving style, ambient temperature, air humidity, fuel and oil quality. EU emissions standards are only a starting point for all new passenger cars. [1] Hydrocarbons, N_2O , CO_2 , NO_x , NH_3 , CO and particulate matter have higher concentrations at cold start, until the engine reaches its optimal operating temperature. Since the Euro 3 regulations in 2000, performance has been measured using the New European Driving Cycle test (NEDC; also known as MVEG-B), with a "cold start" procedure that eliminates the use of a 40-second engine warm-up period found in the ECE+EUDC test cycle (also known as MVEG-A). The COMMISSION REGULATION (EC) No 692 / 18 July 2008, implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) [2] describes the COLD START procedure even better and also there are new specific measurements that car manufactures have to make before releasing a new vehicle on the market.

2.2 The copper heat exchanger

The goal is to heat up the engine as soon as possible by using energy that normally is dismissed in the air but we also need to be very careful where do we take that heat from. If we want to recover as much heat as possible we should mount a heat exchanger very close to the engine because the exhaust gas has over $500^{\circ}C$ but at the end of the pipe it has less than $190^{\circ}C$.



Figure 1. The copper heat exchanger used to recover heat from the exhaust gas



Figure 2. The copper heat exchanger mounted just in front of the exhaust pipe

2.3 The catalytic converter

The catalytic converter requires a temperature above 400 °C to efficiently convert harmful exhaust gases into inert gases, such as CO₂ and water vapor. This is why, the first catalytic converters were placed close to the engine to ensure fast heating but this kind of placing caused several problems, such as vapor lock. It occurred a few minutes after the engine is shut off, because the heat from the catalytic converter influences fuel in the fuel lines, which makes it first boil and then aerate. This condition of fuel results in engine failing to start until the engine and fuel in the lines cool down. To resolve this, manufactures moved the catalytic converters to a third of the way back from the engine, and were then placed underneath the vehicle. In the desire to recover as much heat as possible and because it was enough room, we first placed the heat exchanger in front of the catalytic converter which was a very big mistake. We recovered a lot of heat but the catalytic converter failed to heat enough and after four tests the CHECK ENGINE lamp lighted up.

The next step was to re-mount the heat exchanger after the last sensor on the exhaust pipe to ensure the catalytic converter will heat fast enough and no other errors occur, as shown in Figure 3.



Figure 3. The copper heat exchanger correctly mounted after the catalytic converter

2.4 Heat energy recovered, experimental setup

The heat exchanger was filled with water (0,6l at 15°C).

The quantity of heat retrieved by the water is $Q = c \cdot m \cdot (\theta_2 - \theta_1)$ where

$c = 4,2 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ is the water's specific heat;

$m = 0,60 \text{ kg}$ is the water weight;

$\theta_1 = 15^\circ\text{C}$ is the initial water temperature;

$\theta_2 = 100^\circ\text{C}$ is the final water temperature;

With this data the result is $Q = 210 \text{ kJ}$;

Thermal power is thermal energy \div time;

In the first experiment the engine was cold, -9°C .

The water needed 188 s to reach the boil temperature (100°C).

$$Q = 210 \text{ kJ}, \Delta t_1 = 188 \text{ s}, P_1 = \frac{210}{188} = 1,1 \text{ kW}.$$

In the second experiment the engine was operating at optimal temperature (88°C)

The water needed 56 s to reach the boil temperature (100°C).

$$Q = 210 \text{ kJ}, \Delta t_1 = 56 \text{ s}, P_1 = \frac{210}{56} = 3,8 \text{ kW}.$$

All tests were performed at 2500Rpm with the car on an elevator (Dacia Solenza 1.4MPI).

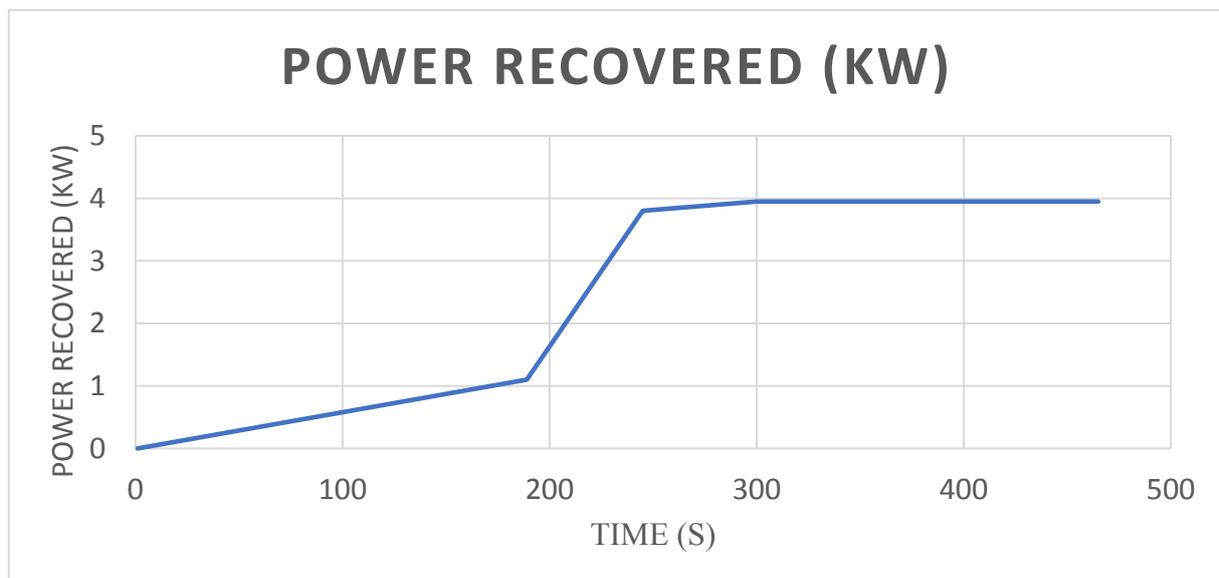


Figure 4. The amount of power recovered using the heat exchanger

2.5 Electric energy recovered, experimental setup

We used 16 pieces of SP1848 TEG, serial wired. The manufacturer gives the following specifications: at temperature difference of 100 degrees: open circuit voltage 4.8V, power current: 669mA.

The hot side was placed directly at the end of the exhaust gas pipe where temperature does not exceed 100°C because we wanted to protect the modules. The cold side was cooled with water blocks using water from the network at 15°C .

When electrical measurements were made, the temperature at the hot side was 92°C and at the cold side 17°C . The difference was 75°C .

As load, we used a H4 bulb, 110W@12v which didn't light up but we obtained the following results: closed circuit voltage 8.74v and closed circuit current 0.16A.

The energy recovered this way is only 1,4W

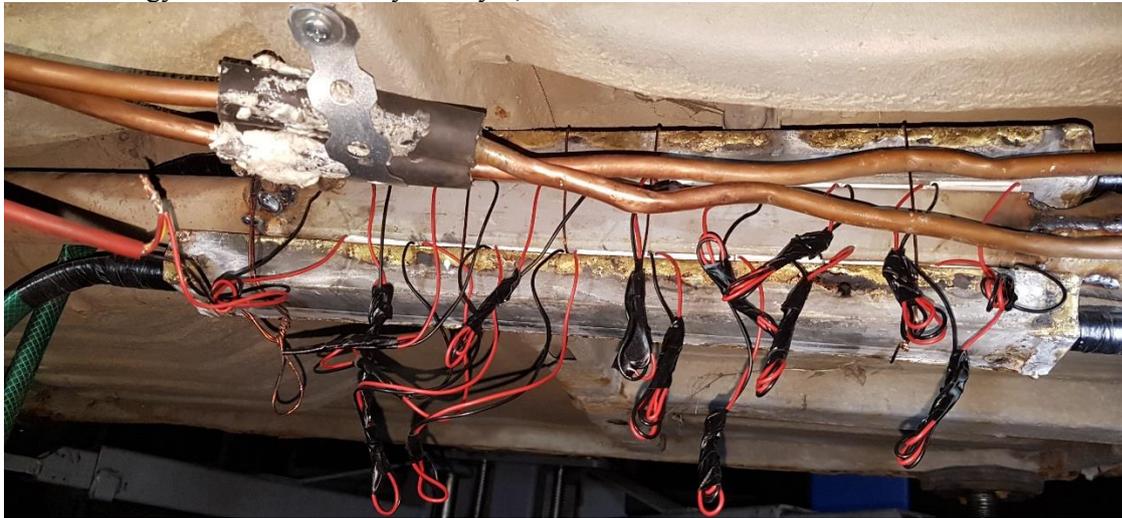


Figure 5. SP1848 Thermoelectric generator setup

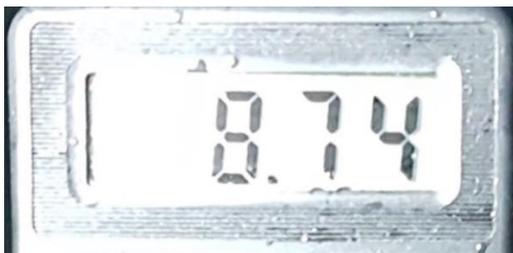


Figure 6. Closed circuit obtained voltage (V)



Figure 7. Closed circuit obtained current (A)

3. Other means of recovering wasted energy from different producers

3.1 Alphabet EnergyPowerModule- γ TM [3]

Alphabet Energy Power Module- γ TM claims to produce up to 850W of electricity from exhaust gas, which is the best performance of any similar product found on the market. There are no independent tests to confirm this. We tried to contact them several times for more information using their website contact form, e-mail and the phone numbers provided on their website but nobody ever answered us.



Figure 8. Alphabet EnergyPowerModule

3.2 BMW turbosteamer [4]

This concept uses the principle of a thermal power plant, using a steam turbine. The steam circuit claims to produce 14 hp (10 kW) and 20 Nm of torque at peak (for a 1.8 Straight-4 engine), yielding an estimated 15% gain in fuel efficiency. BMW has been the pioneer of this concept as early as 2000 under the direction of Dr. Raymond Freymann, and while they were designing this system to fit to most current BMW models, the technology didn't reach production.

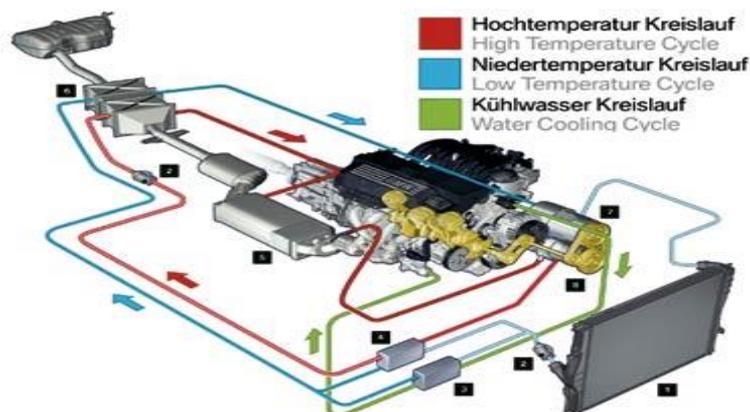


Figure 9. BMW Turbosteamer concept

4. Emission tests setup and results

4.1. Test setup

On the modified Dacia Solenza we have ran a series of tests at different engine temperatures, starting with the engine cold at -9°C . The exhaust gas analysis varies a lot when the engine is cold or when the engine is warm. It even smells very different from a cold engine to a warm one. At this moment the only thing we do with the recovered heat is to heat up the engine faster by warming up the coolant, the oil and the intake air. This reduces the time of heating up the engine to 90°C to 412 seconds. Without the heat recovery system, the engine needed 785 seconds to reach 90°C and only reached 57°C in 412 seconds. The engine also needed 278 seconds to reach 57°C if the heat recovery system was working.

It can also provide heat for the cabin and windows defrost quicker but during the tests all the ventilators and cabin heat were turned off. The car was parked outside in cold weather, -12°C . The ambient temperature in the garage where the tests were performed was $+14^{\circ}\text{C}$. The engine was in idle mode except when performing the test because some tests required the engine to be accelerated to about 2500Rpm.

Time (s)	0	278	412
Engine Temp. $^{\circ}\text{C}$	-9	57	93
CO %	1,76	0,11	0,01
CO ₂ %	11,3	12,4	13,4
HC ppm	295	159	28
O ₂ %	3,08	2,92	0,48
Lambda	1,091	1,15	1,023
COcorr %	2,02	0,13	0,01
AFR	16,13	17,02	15,1

Figure 10a. Measured values, engine COLD START, with the heat recovery system

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Engine Temp	-9	57	93
CO %	1,76	0,11	0,01
CO ₂ %	11,3	12,4	13,4
HC ppm	295	159	28
O ₂ %	3,08	2,92	0,48
Lambda	1,091	1,15	1,023
COcorr %	2,02	0,13	0,01
AFR	16,13	17,02	15,1

Figure 11a. Measured values, engine COLD START, without the heat recovery system

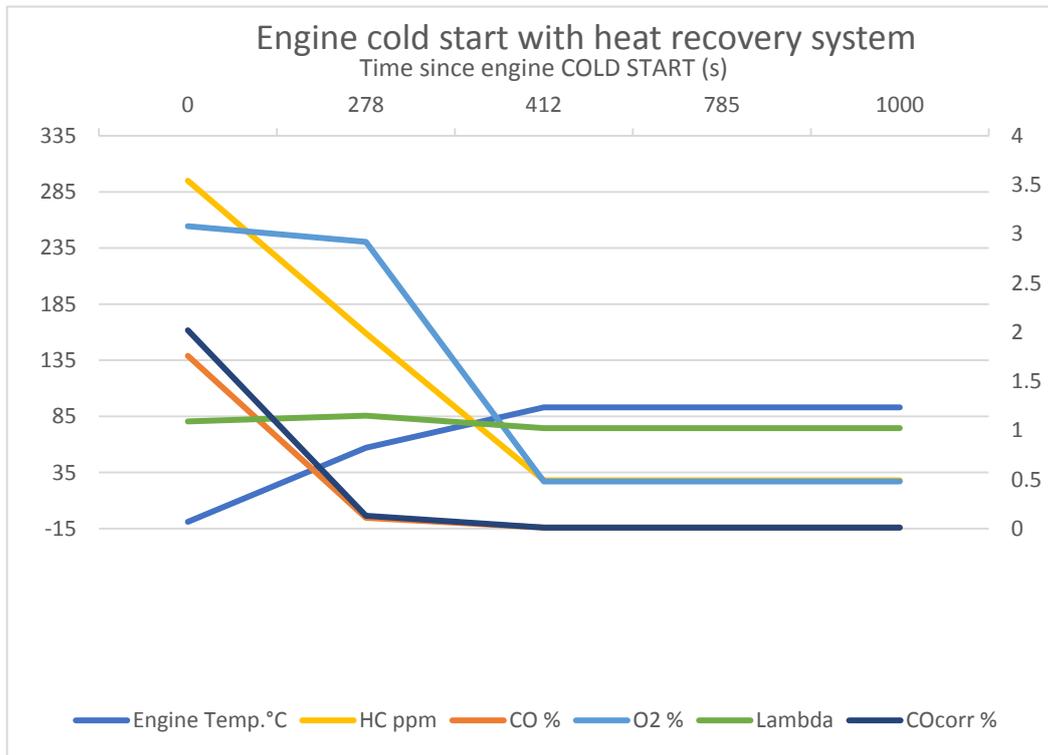


Figure 10b. Measured values, engine COLD START, with the heat recovery system

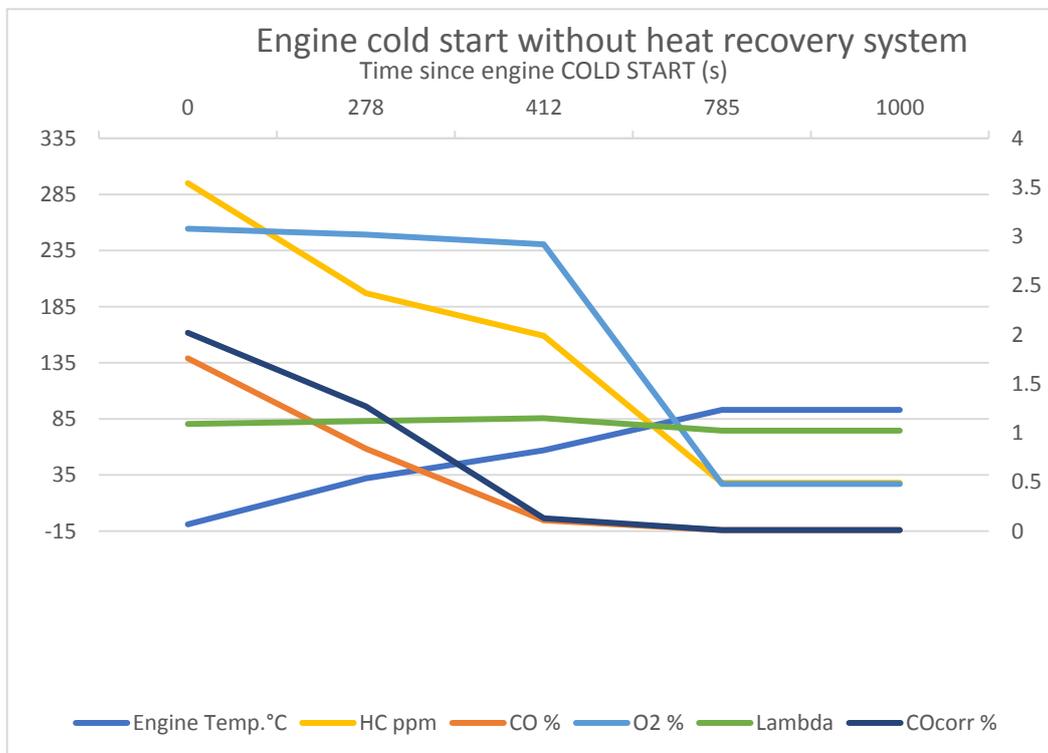


Figure 11b. Measured values, engine COLD START, without the heat recovery system

4.2 Test results

As shown in the results above, using the heat recovery system can almost halve the time the engine reaches the optimal operating temperature.

4.2.1 Hydrocarbon Emissions. The test vehicle's Hydrocarbon Emissions are almost linear and go from 295 ppm when the engine is very cold down to 28ppm which is less than one tenth when the engine reaches its optimal operating temperature. Hydrocarbons contribute to ground-level ozone formation leading to risk of damage to the human respiratory system. Some kinds of hydrocarbons, in addition, are both carcinogenic and indirect greenhouse gases.

4.2.2 Carbon monoxide. Carbon monoxide reduces the blood's oxygen-carrying capacity which can reduce the availability of oxygen to key organs. Extreme levels of exposure, such as might occur due to blocked flues in domestic boilers, can be fatal. At lower concentrations CO may pose a health risk, particularly to those suffering from heart disease. The test reveals that CO is very high when the engine is cold and decreases more than 170 times when the engine reaches its optimal operating temperature. The heat recovery system can help to obtain optimal values in half of the time required by normal operation.

5. Conclusions and future experiments

Internal combustion engines waste a lot of power as heat they give to the environment. If we could convert in usable energy only 1/3 of the wasted energy this could mean more than 30% increase in the overall engine efficiency. The large automotive companies didn't invest enough in research when it comes to fuel efficiency but invested a lot more in car electronics. The built recovery system helps to decrease fuel consumption and exhaust gas and is very effective on internal combustion engines and hybrid systems. The fuel exchanger has only 2kg and does not affect the weight of the car or the air flow in the exhaust system.

In the next experiment we will use a heat storage solution to heat up the engine even faster. We found a very good insulator, aerogel, that is commercially available but can be purchased only in large quantities.

References

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