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Novel hybrid system of pulsed HHO generator/TEG waste heat recovery for CO reduction of a gasoline engine

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Abstract

Environmental crisis requires using cleaner energy sources for different sectors including the transportation. Hydrogen can support the transition of the automotive industry from petrol and diesel into a sustainable fuel. It could be the main source of energy or the auxiliary fuel in vehicles. As an auxiliary fuel, it has recently been considered in hydroxyl (HHO) form for reducing the emissions from transportation fleet. In this study, an HHO generator with the optimum power consumption was utilised for HHO injection into the intake manifold of a petrol engine as the case study. High concentration of CO is expected to be produced during idling, so the experiments were designed to inject ultra-low HHO for reducing CO emissions. The results were very promising, and it was shown that the CO emission could be reduced by about 98%. Furthermore, a novel design was developed based on the concept of waste heat recovery (WHR) for powering the HHO unit. Engine was simulated in AVL software to design a thermo-electric generators (TEG) for running the HHO unit. Based on the results, TEG can provide the energy required for HHO unit as the energy output of the TEG was between 91 kJ to 169 kJ for the case study while the energy consumption of the proposed HHO generator was just about

22.5 kJ. The results of this study are recommending a practical solution for bringing HHO injection from laboratory research into the real practice.

Keywords

IC engine, HHO (Brown gas), Hydrogen fuel, Emission reduction, Engine simulation, Driving cycle

Nomenclature

BDUR	Burning duration (degree)
BSFC	Brake specific fuel consumption [gr/kWh]
ISFC	Indicated Specific Fuel Consumption
SGM	Signal generator module
SOC	Start of combustion (degree)
TEG	Thermo-electric generator
PWM	Pulse width modulation
WHR	Waste heat recovery
COFR	CO fraction in engine exhaust gas
DC	Direct current
CAT	Catalyst converter
AC	Air cleaner
MP	Measuring point
RPM	Revolutions per minute
LPH	Liters per hour
COFR	CO Fraction
n	Number
m	Vibe shape
x	Fuel mass burned fraction

a	Vibe parameter
$\propto$	Crank shaft angle (degree)
Subscripts	
EX	Exhaust
Ci	Coolant inlet
Co	Coolant outlet

1. Introduction

Fossil fuel consumption has increased continuously since the start of modern oil industry in 19^{th} century as it becomes the main source of energy to turn the development wheels around the world. As a result, we are facing with the reality of climate change and global warming today due to the vast amount of pollutants releasing into the environment from different sectors including transportation (1-4). Hydrogen as a carbon free fuel, is believed to be a solution to overcome the environmental challenges (5, 6) but this technology still faces some challenges such as cost and safety of hydrogen storage vessels (7, 8). In vehicle applications, it can be the main fuel for running the drive train by means of hydrogen combustion engine or hydrogen fuel cell (9, 10). The benefits of hydrogen fuel can fully be achieved for electrical power generation in fuel cell, but it still needs further development (11-13). Alternatively, it can be used as the auxiliary fuel which can reduce fuel consumption and emissions.

One of the efficient solutions for reduction of emissions in vehicle application is the injection of hydrogen gas into the engine in which hydrogen is produced by gas reforming process and electrolysis of water (14-16). Among the harmful emissions generated by vehicles in transportation systems, CO is of special interest of this paper due to its high concentration during idling and the negative environmental and health effects. CO is produced by internal combustion engines as the result of incomplete combustion of fossil fuels in combustion chamber. To use hydrogen for CO reduction, water should go through an electrochemical process to produce hydroxyl (HHO) or Brown's gas which is a mixture of oxygen and hydrogen (17-19). The convectional water electrolysers produce pure hydrogen in a way that a separator membrane is used to separate hydrogen and oxygen (20, 21). However, the hydroxy gas consists of hydrogen and oxygen will be produced by removing separator membrane which also results in a significant decrease of the overall electrolyser cost. This type of electrolysers are called HHO generator, and they can be used in vehicles to reduce the fuel consumption and emissions. Moreover, HHO generators can be tuned to produce hydrogen and oxygen (Hydroxy) at the right time when needed by the engine(22-24).

El-Kassaby et al., (25) studied the effects of injecting different amounts of hydroxyl gas on engine thermal efficiency. By injecting HHO, thermal efficiency of engine increased by 10% and CO, HC and NOx were reduced by 34%, 18% and 15%, respectively. Karagoz et al., (26) also studied the effects of hydroxyl injection on engine Indicated Specific Fuel Consumption (ISFC) and emissions. Based on the results of their work, the ISFC decreased significantly and THC and CO were reduced. In addition, it was reported that injection of HHO to engine would result in high reduction of (above 80%) for CO emission (27). There are also other reports in literature (28, 29) about HHO injection into the engine confirming the CO and HC reduction in various engine operating conditions.

One of the main challenges for HHO generator in passenger cars application is to provide the required power from the engine. Using the engine power for running the HHO system means extra fuel consumption which is not ideal. Furthermore, the HHO energy consumption could be affected by reduction of electrolysis efficiency due to the formation of bubble layer on the electrodes active surface which increases cells electrical resistance (30, 31). The electrolyser power consumption can be reduced by employment of pulse width modulation (PWM) technologies (32-34)and magnetic field (18, 35-37). In this research, the pulsed power was employed to run the electrlyser to produce HHO. Besides, for overcoming HHO generator power consumption challenge, an innovative approach was proposed to use the exhaust power to run the HHO generator instead of engine from the concept of waste heat recovery (WHR).

Implementing a waste heat recovery (WHR) system on engine would lead to recover a considerable amount of energy due to wasting huge amount of fuel energy through engine exhaust (38). Small scale thermodynamic cycles such as Organic Rankine cycle, Brayton cycle and thermo-electric modules has been studied as the waste heat recovery system for vehicles in literature (39, 40). Using thermo-electric generators (TEG) to run the HHO unit by WHR for our system could be a favorable and promising option due to the simplicity, low cost and light weight (41). Based on the previous reports (42, 43), the TEG efficiency is about 30% showing a great potential to be used in HHO generation during idling condition.

The presented research included the experimental phase, simulation and design work to propose a novel HHO system for reducing CO emissions. High concentration of CO is expected to be produced during idling, so the experiments were designed to inject ultra-low HHO for reducing CO emissions. As the power consumption of HHO system can be a challenge for real world application, thermo-electric generator (TEG) based on the concept of the WHR was proposed for running the HHO system. To evaluate the feasibility of this innovative approach, the mathematical model and engine simulation data from AVL software was used. The applicability of the proposed solution was evaluated for the standard Tehran driving cycle. Finally, a cost analysis was developed, and results were extrapolated to large-scale to evaluate the impact of the proposed system on CO reduction. This work is one of the first studies which is recommending a practical approach to bring HHO injection from laboratory research into the real practice. As the novel solutions without too many modifications in IC engines would be more attractive for automotive industry, this approach was followed in this study to reduce the CO emissions during the idling. The proposed system can help the emission reduction in capital cities where the idling condition is happening frequently due to the exotic traffic jams.

2. Methodology

2.1. Experimental Set-up

A schematic diagram of the proposed experimental set-up for the engine block used in this study is presented in Fig. 1. The main components of the proposed hybrid hydroxyl gas production and injection system are HHO generator, WHR unit and engine which will be described in following sections.

As shown in Fig.1, HHO gas is injected into the engine air manifold, and it is mixed with inlet air. The injected HHO gas is produced by Hydroxyl production unit in which the power is provided by pulsed DC power supply. However, an innovative approach for powering the HHO unit is proposed and a waste heat recovery unit is studied in simulation phase using data from AVL boost software.

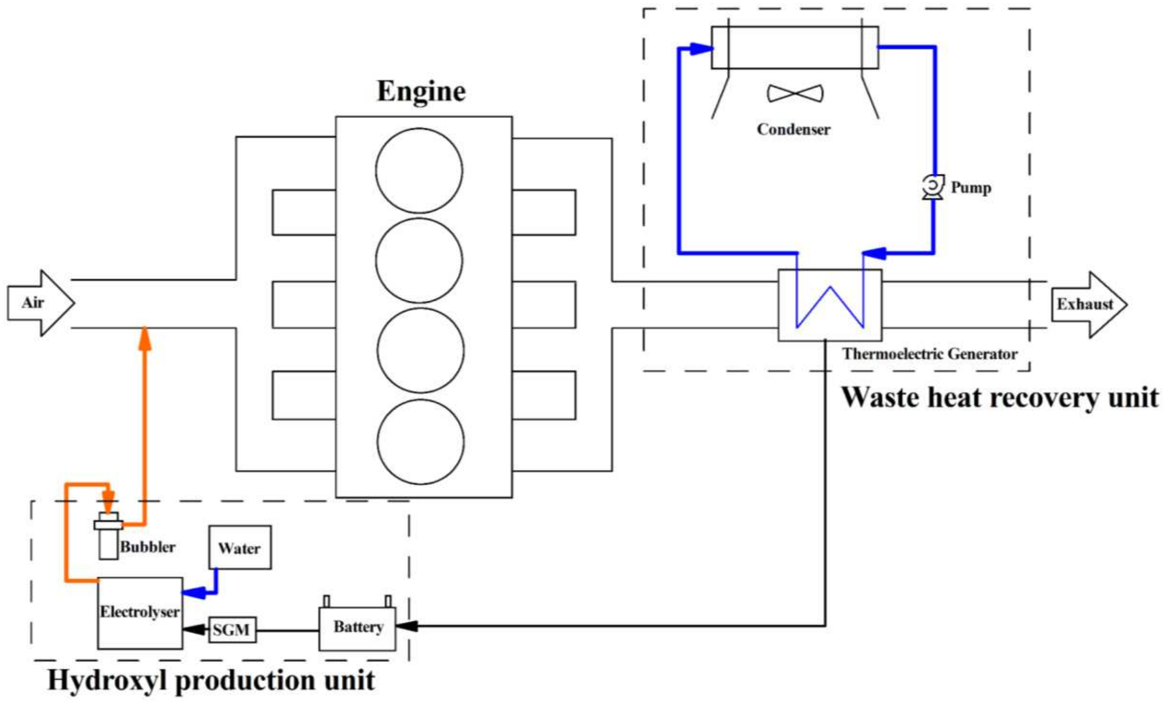

Fig.1 Hybrid hydroxyl gas production and injection system

2.1.1. HHO generator

As shown in Fig. 1, the HHO generator consists of 5 components: battery, signal generator module (SGM), electrolyser, water storage and bubbler. The power provided by battery is converted to pulsed power via SGM (18). There are different techniques recommended in literature to diminish bubbles layer on the electrodes active surfaces such as "Ultrasonic waves", "Magnetic field" and "pulsed power" (44-46). In this research, the pulsed power is chosen for electrolyser to produce HHO gas from water. The detailed analysis of HHO cell was presented in our previous paper (18). The efficiency of a flat plate HHO cell was evaluated by differing different parameters such as electrodes distance, DC power, pulsed power, ultrasonic waves and magnetic field. The results of experiments reported in reference (18) are used in this research to run the HHO on optimum condition. The experimental setup for HHO experiments is shown in Fig 2.

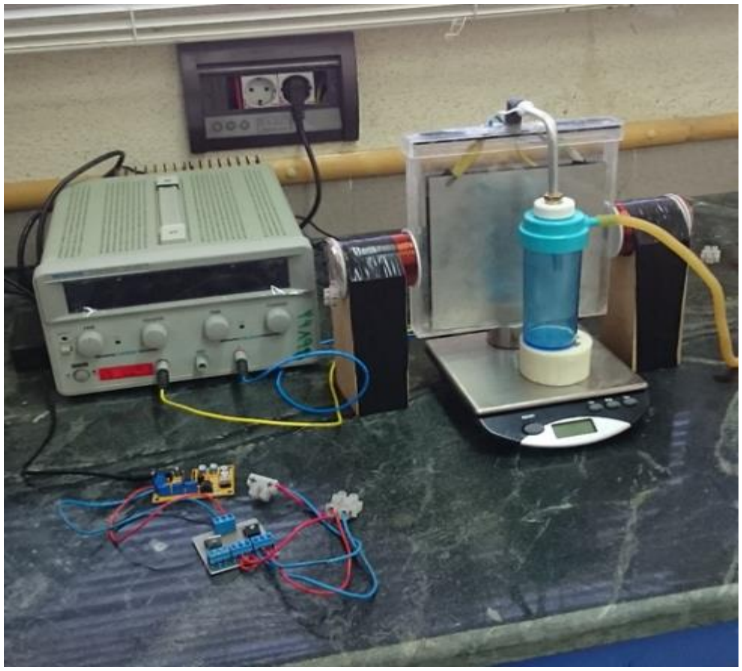

Fig.2 Experimental setup for HHO cell energy analysis tests (18)

2.1.2. Vehicle specification and HHO generator installation

Samand is one of the most common models of passenger cars in Iran cities, a 'domestic national car' manufactured at 2002 for the first time and many are sold in Iran since then. It is also the major vehicles in Taxi fleet in Iran. Based on the statistics published in Iranian media (47), there would be up to 10000 Samand Taxis driving in Iran capital city, Tehran daily. One of the major challenges for Tehran is the air pollution, in which heavy traffic and engine idling is playing a key role. Therefore, finding a solution for reducing CO emissions, which expected to be higher in idling compared to the driving conditions, from Samand tail pipe will help in improving the air quality. That's why Samand car was chosen as the case study for this research, the solution recommended here could be applied in other passenger cars and Taxi fleet in other capital cities with slow traffic and lots of idling events.

A four-cylinder gasoline engine (XU7) is used in Samand and technical specifications of this engine is presented in Table 1. During the experimental phase, the effects of HHO injection on CO emission are analyzed. As shown in Fig. 3, HHO is injected into the air manifold and Testo 310 gas analyzer is used to measure CO emission during the idling.

Table.1 Technical specification of XU7 engine

Parameter	Unit	Values
Fuel type	-	Gasoline
Number of cylinders	-	4
Bore	mm	78.6
Stroke	mm	85
Displacement volume	cc	1700
Compression ratio	-	11
Maximum power	kW	82.12
Maximum speed	RPM	6700
Maximum torque	Nm	150.75

Fig.3 HHO gas injection location in vehicle

2.1.3. Waste heat recovery unit

TEG is a small-scale power producer which can be installed in vehicles to recover the waste heat. The hot side of TEG should be in contact with flue gas in engine exhaust pipe and the cold side should be cooled by an integrated cooling system. In design and simulation phase, TEG system is studied as the waste heat recovery unit. The power required by HHO generator is proposed to be provided by this unit. Engine simulation results from AVL software and the experimental data from literature (41) were used to predict TEG unit power output under various conditions.

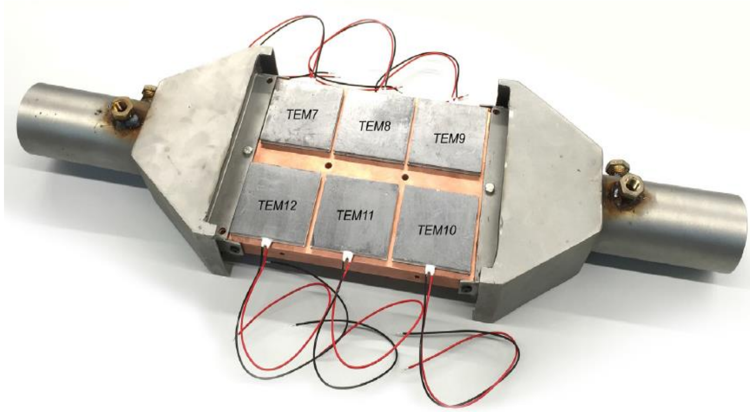

Fig.4 TEG unit for the WHR system (41)

2.2. Engine simulation

In addition to the experimental phase, the XU7 engine is modeled in AVL boost software to study the WHR system. AVL boost software is a 1D software to run thermodynamic and numerical analysis of the engine. It can deliver an advance model for accurate prediction of engine performance and tailpipe emissions. AVL BOOST software is used to design and analysis engine by many researchers and manufacturers around the world. The block diagram of XU7 model in AVL software is shown in Fig. 5. As shown, TEG block is also added in this simulation. Vibe combustion model (48) is employed to model engine combustion mechanism. Furthermore, Woschni heat transfer model is chosen for modeling of gas mixture and cylinder walls heat transfer.

There are prior studies in literature on mathematical modelling of hydrogen gas injection to gasoline engines (49, 50) and the functional parameters of engine such as power, torque and BSFC are used to validate the mathematical model in literature (49, 51), so the same approach was followed in this research.

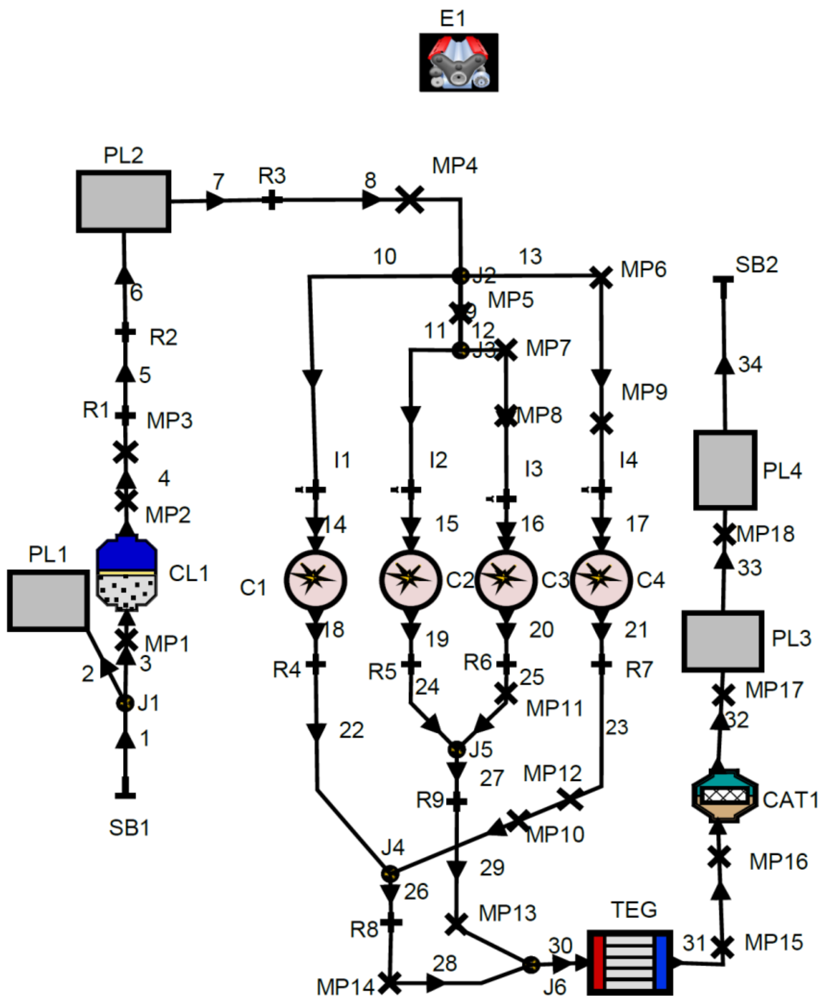

Fig.5 XU7 engine model in AVL boost

2.2.1. Combustion model

Vibe single zone model was selected for the combustion analysis in this study and fuel mass burned fraction (x) during combustion is expressed as follow (52):

$$x = 1 - \exp\left[-a\left(\frac{\propto - SOC}{BDUR}\right)^{m+1}\right] \quad (1)$$

SOC, BDUR, $\propto$, m and a are the start of the combustion, burn duration, crankshaft angle, Vibe shape and Vibe parameter, respectively. Vibe shape parameter indicates the position of the brunt for the combustion position and Vibe parameter (a) is set to be 6.908. The values of other parameters are represented in Table 2. Also, Woschni model has been used for modelling of the heat transfer between gas and cylinder walls (52).

Table.2 Combustion parameters

Parameter	Unit	Value					
		1000RPM	2000RPM	4000RPM	6000RPM	6500RPM	7000RPM
m		2.4	2.28	1.62	1.26	1.2	1.17
SOC	deg	5	-5	-5	-7	-5	-6
BDUR	deg	40	42	46	50	51	52

3. Validation

As explained before, the functional parameters of engine such as power, torque and BSFC are used to validate the AVL model of gasoline engines in literature (49, 51). Therefore, engine power output and engine BSFC from experimental data were used in this study to validate the AVL model and data from experiment and simulation were compared (53). Figure 6 shows the amount of engine power obtained in experiments and AVL model. As shown in this figure, the engine power in various RPMs are accurately predicted by AVL software. Engine BSFC variation at different RPMs obtained from AVL model and experimental tests are presented in Figure 7. The maximum error for BSFC by comparing the experimental results with AVL model was approximately 6%. As indicated in Figure 6 and 7, a good agreement between experiment and simulation was achieved with the maximum error of about 8%.

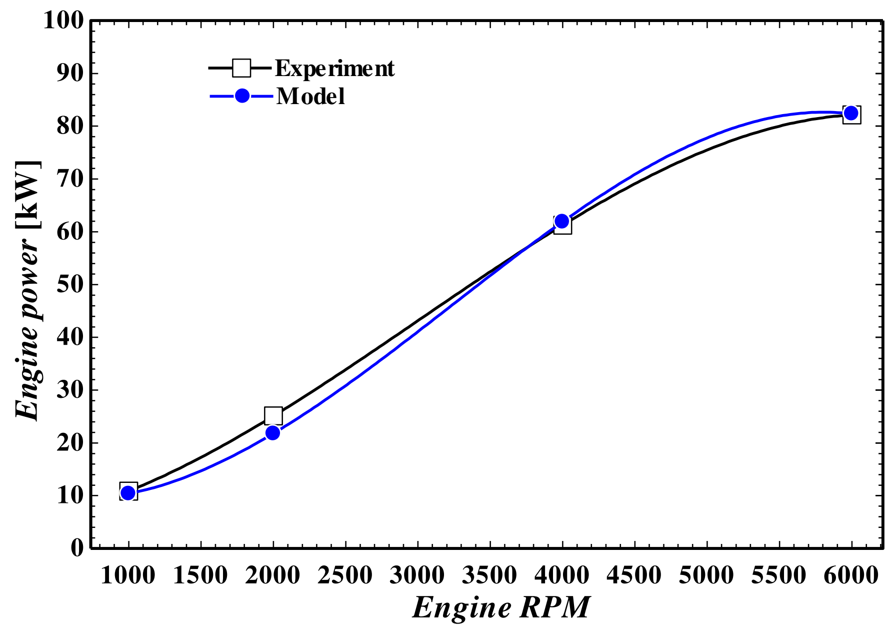

Fig.6 Comparison of Engine power in AVL model and experimental data in various RPMs

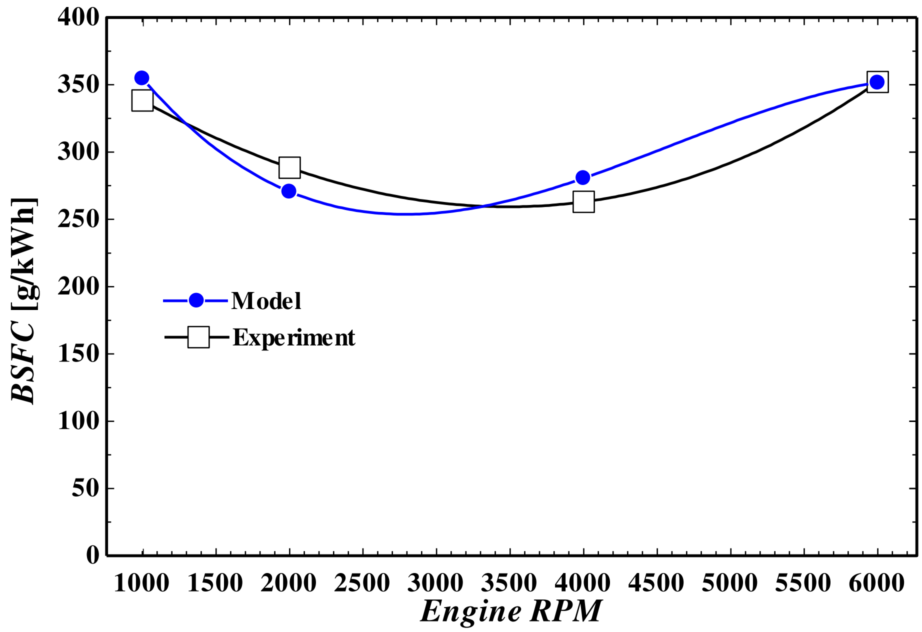

Fig.7 Comparison of Engine BSFC in AVL model and experimental data in various RPMs

4. Results and discussion

4.1. Ultra-low HHO gas injection into the engine

The retrofitting of HHO generator was performed by analyzing the effect of different parameters such as DC, pulsed DC, Magnetic field and Ultrasonic waves on HHO cell power consumption and the required surface area and the results were presented in (18). Table 3 shows HHO cell power consumption and required electrode surface area for 1 LPH of HHO production when various technologies are tested. Based on the results of the experiments, minimum power consumption and maximum required surface belongs to pulsed DC technology.

Table.3 Power consumption and required surface area of HHO cell for 1 LPH gas production (18)

Technology	Power consumption [W]	Required surface area [m^2]
DC	12.72	0.005428
DC+Magnetic field	12.68	0.00532
DC+Ultrasonic waves	12.17	0.005154
Pulsed DC (300kHz)	6.894	0.02942

Based on the results of the energy analysis (18), pulsed DC was selected and effects of HHO injection on CO emission was evaluated. A convectional 6 cell HHO cell was employed to inject HHO into the intake manifold during engine idling condition at the rate of 0.126 LPM which is the maximum production rate of HHO generator, and each test is repeated three times. Prior to data collection, engine was run for a while to pass the cold start condition and to achieve the steady-state operation. According to the results, engine CO emission decreased from 2303ppm to just 52ppm when HHO gas is injected. It is about 98% reduction of CO in idle condition proving a high potential for using this technology in vehicles. It is specially highly important for mega cities such as Tehran where the idling condition is happening frequently due to the exotic traffic jams.

4.2. Thermoelectric generator analysis and engine simulation

Next, the TEG system is analysed for the WHR application to deliver the electrical power of the HHO generator unit. The proposed WHR system can provide an integrated HHO production and injection system which is not consuming the useful power of engine. The other privilege of this system is that no change needs to be made to engine electrical systems for WHR system and HHO unit installations. The performance data of a thermoelectric generator was extracted from (41). Then, linear regression was used to develop a formula for thermoelectric generator power output as the function of the exhaust mass flow rate ($\dot{m}_{EX}$) and exhaust temperature (T_{EX}) as shown in Eq. 2. To obtain the desired power output (P) of the TEG for each temperature and flow rate, the inlet and outlet coolant temperature (T_{ci} and T_{co}) should be tuned accordingly and the relevant equations are shown by Eq.3 and 4.

$$P\ [W] = -33.22 + 0.02147T_{EX} + 3.427\dot{m}_{EX} \quad (2)$$

$$T_{ci}\,[K] = 235.3 + 0.1076T_{EX} + 0.05616\dot{m}_{EX} \quad (3)$$

$$T_{co}[K] = 226.2666 + 0.1221T_{EX} + 0.06488\dot{m}_{EX} \quad (4)$$

As shown, a strong correlation was achieved for Eqs. 2-4 with R values of 98.37%, 91.93% and 92.14%, respectively.

From Eqs. 2-4, engine exhaust gas temperature and mass flow rate are needed to calculate thermoelectric power output. Therefore, engine was modeled in AVL boost software and analysed at various operating conditions to find out those parameters. The AVL output exhaust mass flow rate and temperature at 3 different bmeps and 4 different rpms are presented in Fig. 8 and 9. The bmep was changed in the range of 2-4 bars which is the normal range for the engine during city driving condition. As can be seen in Fig. 8, the exhaust flow rate was not changing considerably at different bmeps, however, the exhaust gas temperature was different at various bmeps because the mass flow rate of the is different in different bmeps. The presented data was used in Eqs. 2-4 to develop the feasibility study of using a TEG for running the HHO unit.

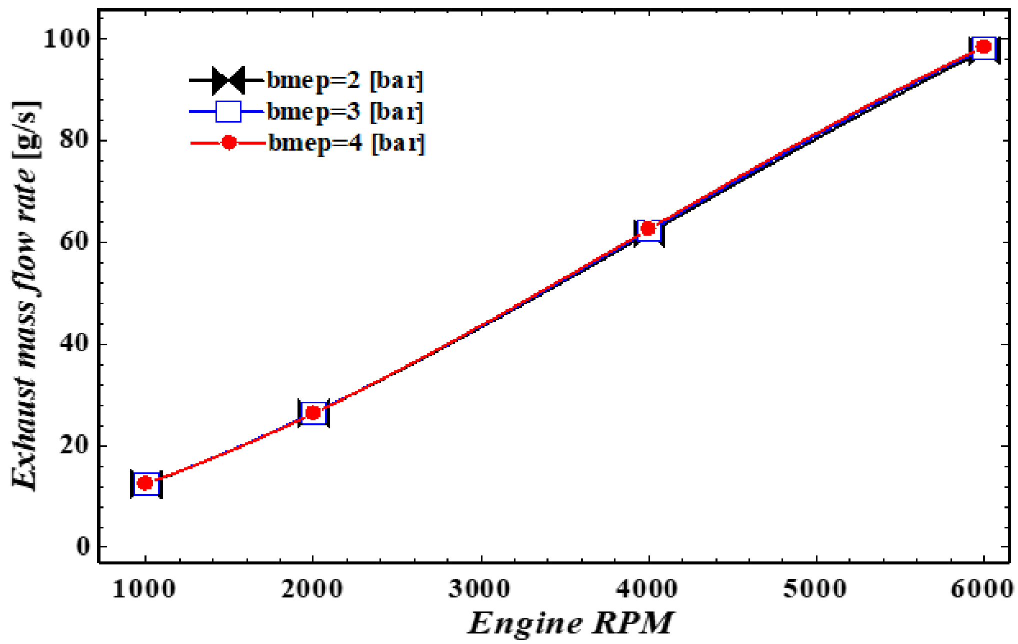

Fig.8 Engine exhaust mass flow rate in various engine RPMs and bmeps

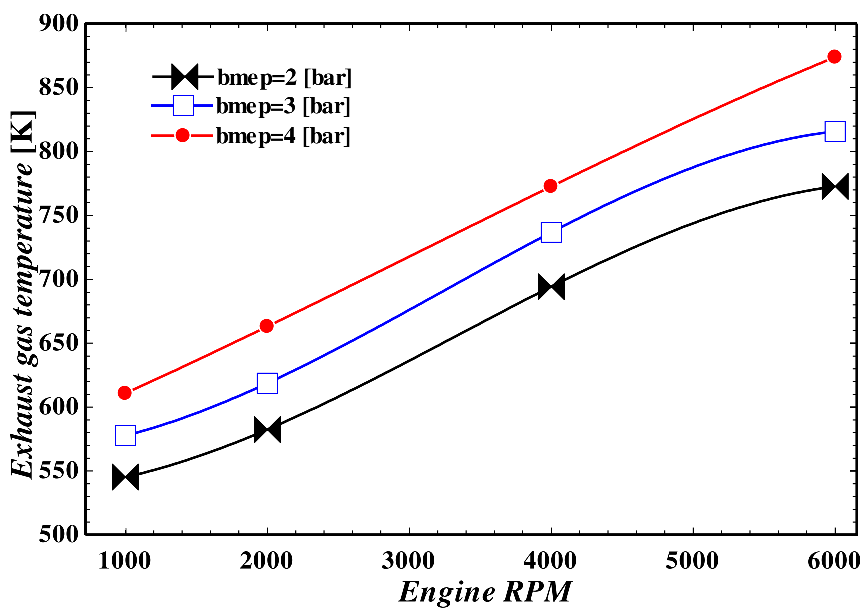

Fig.9 Engine exhaust gas temperature in various engine RPMs and bmeps

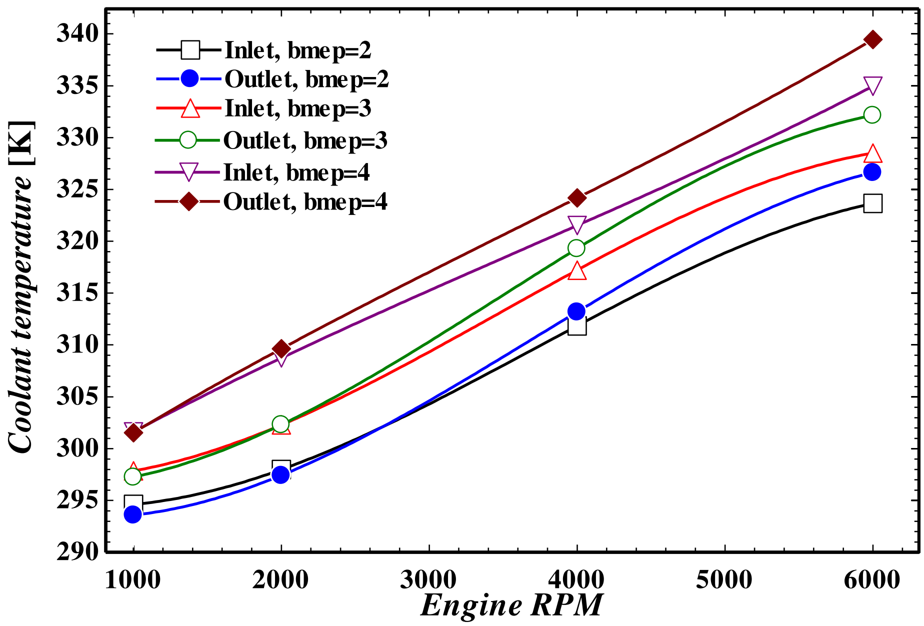

Fig.10 TEG coolant temperature in various engine RPMs

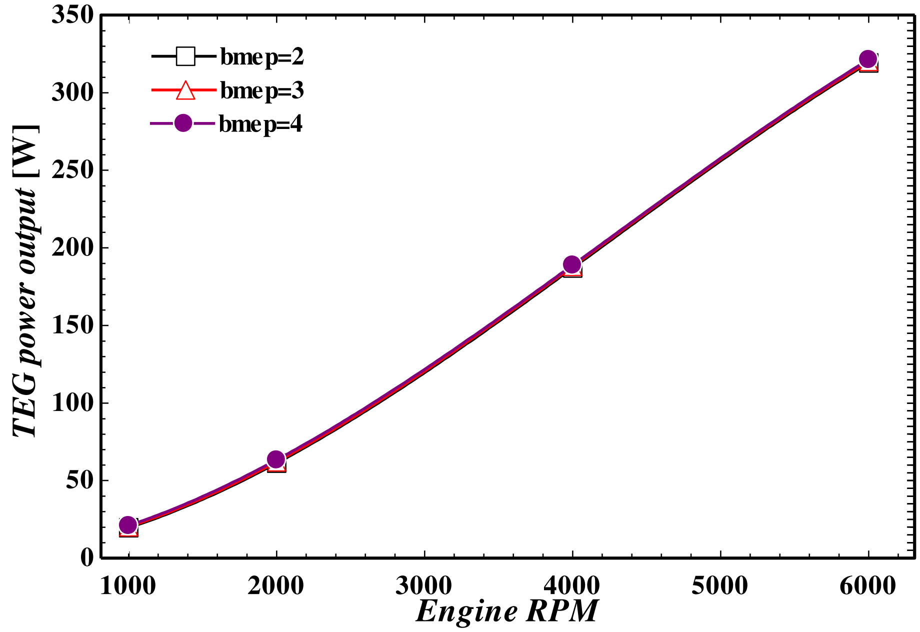

Fig.11 TEG power output in various engine RPMs

The power output and coolant temperature of TEG in various RPMs and bmeps are presented in Figure 10 and 11. As shown in Figure 11 that the power output of TEG is independent from bmep. The data from Figure 10 can be used for designing TEG cooling system, for example, by coupling engine coolant system to TEG for any future study.

4.3. Energy and cost analysis

By using the data presented in Figs. 10 and 11 and Eq. 2, the thermoelectric power production in various engine operating conditions was calculated and presented in Figure 12. As shown, TEG power output is changing between 20W and 320W in different conditions.

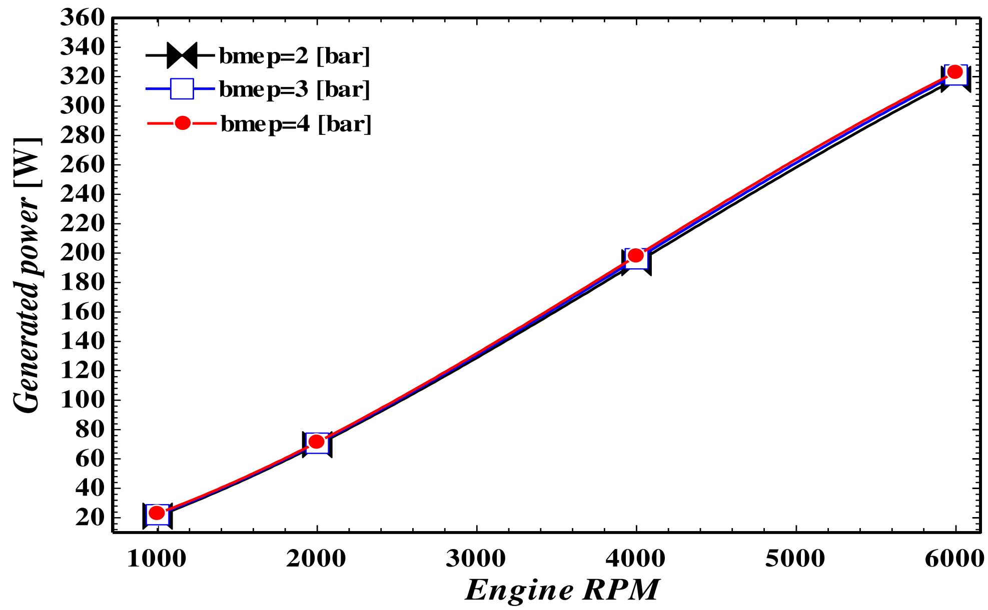

Fig.12 Thermoelectric generator power output in various engine conditions

Based on Tehran standard driving cycle (54) presented in Fig 13., the average speed of a vehicle is approximately 34.1 km/h in which the engine RPM is in the range of 2000-3000 RPM. Using the data from AVL simulation and Eq.2, it means that the average power production from TEG could be between 70W and 130W. As shown in Figure 13, vehicle is traveling approximately 1299 s of whole city travel time during Tehran standard driving cycle at velocity of 34.1 km/h.

By considering this vehicle running time and its engine RPM range, the TEG energy output can be calculated and it ranges from 91 kJ to 169 kJ.

Also, it can be found from Fig. 13 that during the Tehran standard driving cycle, each vehicle is in idling condition for over 15% of the travel time in city [67], i.e., the amount of time in which a vehicle is in idle condition in Tehran standard driving cycle is about 234 s. By using the amount of power required for running the HHO unit from Table 1, the overall energy consumption of a convectional HHO generator with DC technology is about 22.5 kJ. Therefore, the produced energy by TEG would be more than enough for running the HHO generator. During city travel, the produced power by TEG can be stored in a battery unit and it can be used for HHO generation when engine is on idling condition.

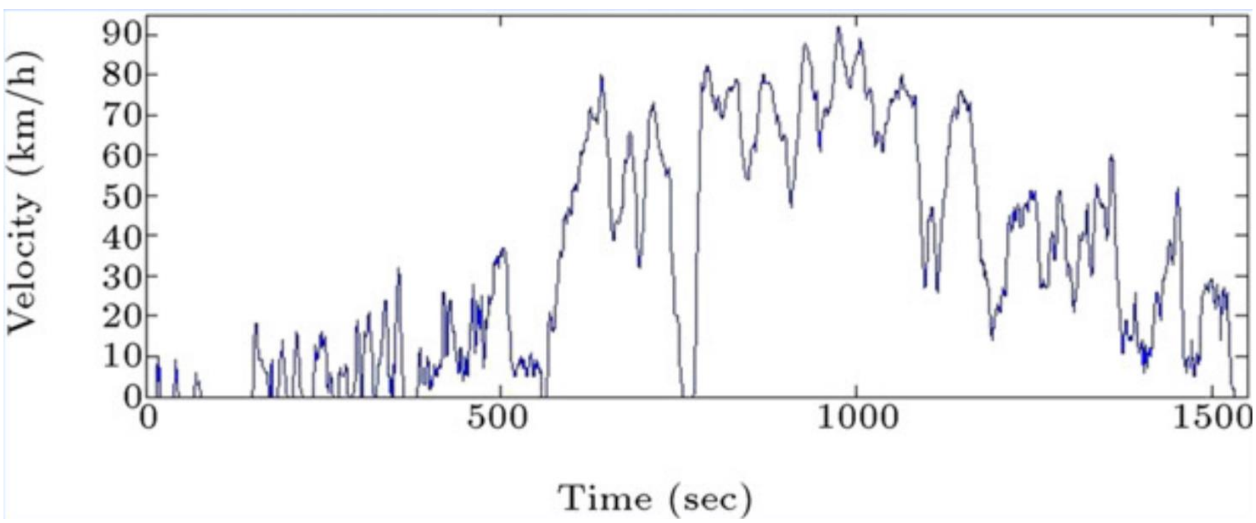

Fig.13 Tehran standard driving cycle (54)

To develop a simple cost analysis, the components cost and weight of HHO generator is given in Table 5. The power consumption of HHO generator can be reduced by using different techniques as presented in Table 4. In our case study, the energy consumption and total cost of

HHO generator cells were calculated based on the data provided in Table 4. It should be noted that the dimension of electrodes which are used for each cell equals to 15 cm*15 cm.

Table.4 Energy consumption and number of HHO cells

Technology	Energy consumption [J]	Required number of cells
DC	22502	1
DC+Magnetic field	22431	1
DC+Ultrasonic waves	21528	1
Pulsed DC (300kHz)	12196	10

From Table 4, it can be found that the lowest amount of energy consumption belongs to Pulsed DC technology. Pulsed DC technology for HHO generator system needs more cells and electrode area which results in increase of HHO generator cost. However, the extra cost of the pulsed technology is negligible compared to the vehicle cost, so the energy consumption is the key parameter in this case. Therefore, pulsed DC was chosen for the analysis due to the low energy consumption and negligible cost increment.

Table.5 Cost, weight and occupied volume of each component of hybrid HHO injection system (55)

Component	Cost [$]	Weight [kg]	Occupied volume [cm^3]
TEG	400	7	4546.56
Water pump	9	0.15	502.4
Condenser	100	2	19200
Battery	50	2	12800
SGM	10	0.4	520
Water storage	5	2.5	4000
HHO generator	150	1	5000
Bubbler	5	0.2	339.12
Total	729	15.25	46908.08

The total cost, weight and occupied volume of the proposed hybrid HHO generator for Samand is presented in Table 5.

By adding such an HHO injection system, nearly 15.25 kg weight would be added to the vehicle and the total price of system will be approximately 9% of the vehicle cost. In addition, nearly 47 liters of volume is occupied by hybrid HHO generator in the vehicle. However, the system is very efficient for CO reduction as discussed previously. In addition, by installing this integrated HHO gas production and injection system on vehicle, no modification is required in vehicle engine and electrical systems.

4.6. Environmental impact in large scale for Tehran city

People living in Tehran in average are spending more than 50 min of their time in heavy traffic (56). According to the results of AVL simulation, the mass flow rate of exhaust gas for XU7 engine in idling condition is approximately 10 gr/s. Considering the CO fraction of 2303 ppm obtained from experimental phase, CO emission rate of an XU7 engine would be about 76 gr/day. By installing an HHO injection system, CO emission from XU7 engine would decrease to just 1.7 g/day as shown in Figure 14. While the HHO was usually produced by DC power supply for engine research applications in previous studies, the proposed ultra-low HHO by pulsed power technology in this research with different thermo-physical properties (57-59) has showed a high potential in CO reduction.

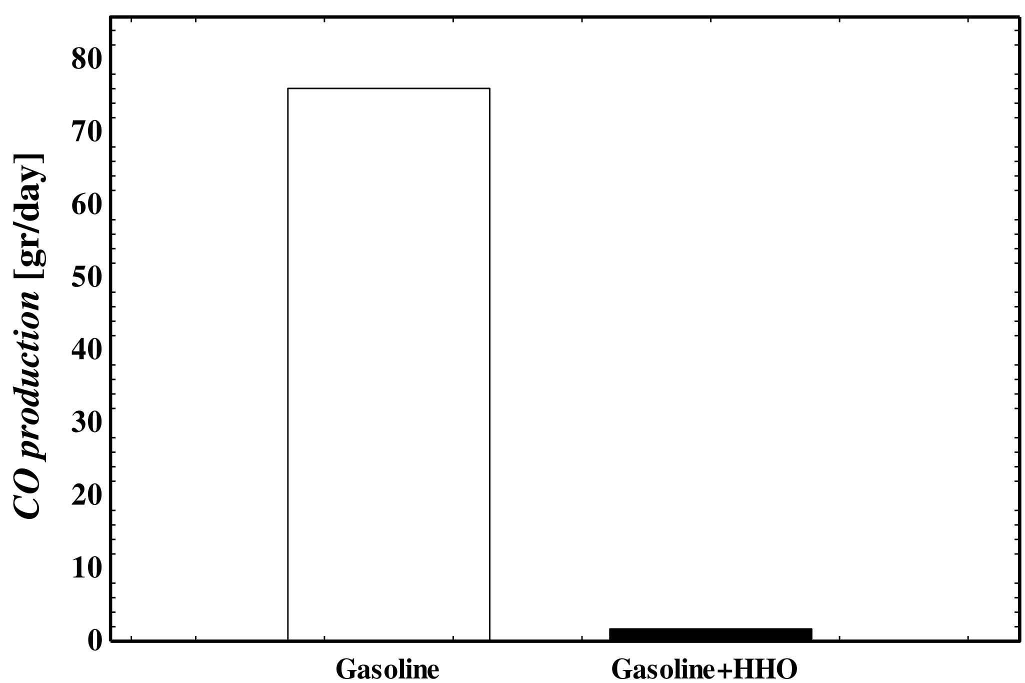

Fig.14 CO emissions of XU7 engine in idling condition

The large-scale impact of this retrofit on CO emission rate based on the numbers of Samand XU7 vehicles driving in Tehran is huge as demonstrated in Figure 15. As shown, by installing proposed HHO production system on Samand vehicles in Tehran, CO emission rate would decrease between approximately 25 ton/year and 280 ton/year depending on the number of Samand cars in Tehran. Furthermore, the CO reduction rate was calculated using equation below:

$$CO_{reduction}[\frac{ton}{year}] = n_{vehicles} n_{days} \dot{m}_{ex} (COFR_{Gasoline} - COFR_{HHO}) \quad (5)$$

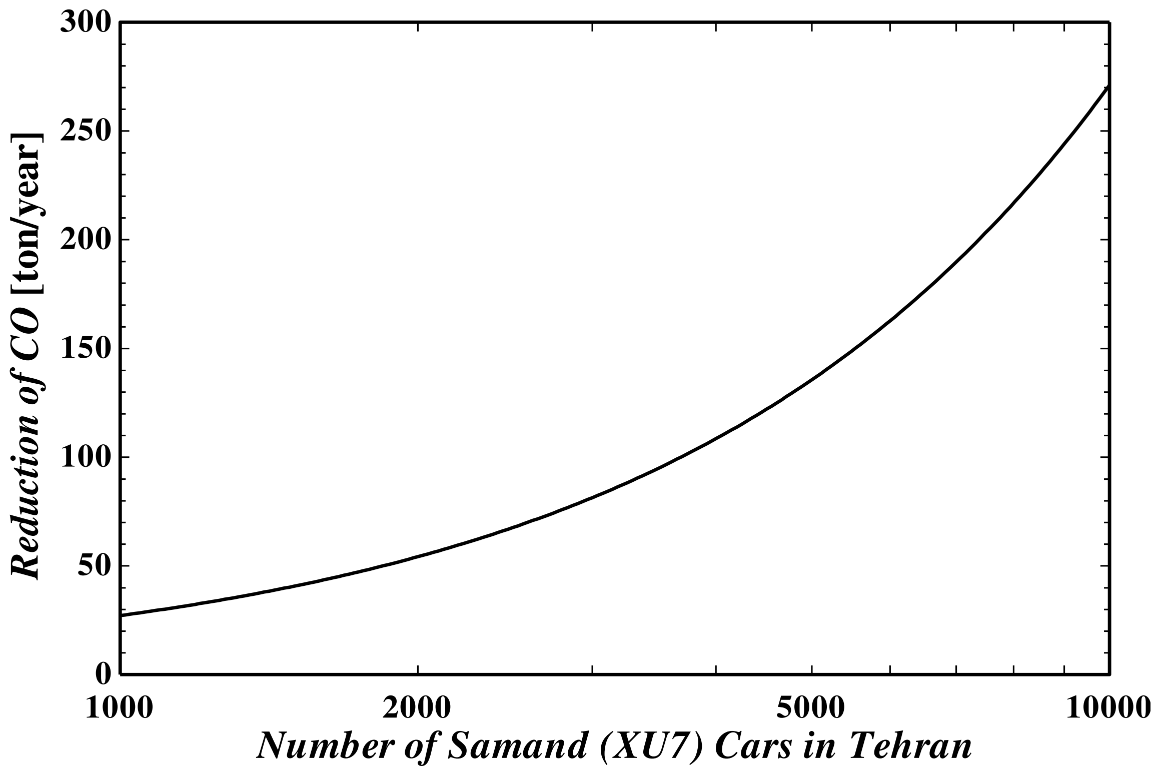

Fig.15 CO emission reduction in large-scale by installing the proposed HHO injection system on Samand vehicles in Tehran

5. Conclusion

The presented research included the experimental phase, simulation and design of a novel HHO system for reducing the emissions. It proposed an innovative solution by powering the HHO with TEG to address the gap between the laboratory research and the real practice for HHO application in passenger cars. Ultra-low concentrations of the HHO gas at the rate of 0.126 LPM were injected into the intake manifold of a case study petrol car (Samand XU7) during the idling and CO emission was reduced by about 98%. The power supply for the HHO system was a pulsed DC power supply as it showed the optimum power consumption based on the energy analysis. In addition, by considering HHO generator power consumption, a small-scale waste heat recovery system by employing the TEG was designed to run the pulsed DC power supply based on Tehran driving cycle. The engine simulation results from AVL software with mathematical modeling showed that Thermo-electric generator (TEG) can power up the HHO unit for our case study. Based on the results for Tehran standard driving cycle, the energy output of the TEG was between 91 kJ to 169 kJ while the energy consumption of the proposed HHO generator was just about 22.5 kJ. So, the proposed system is well capable of providing the power for HHO injection during the idling and power consumption challenge of HHO generator unit could be overcome by the proposed novel application of TEG systems. Extrapolation of the results for large-scale application showed that HHO production system on Samand vehicles in Tehran, would decrease the CO emissions between approximately 25 ton/year and 280 ton/year depending on the number of Samand cars driving in Tehran. Similar analogous effects should be expected for similar Taxi fleets especially in other capital cities where the idling condition is happening frequently due to the exotic traffic jams.

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