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# Experimental investigation of cold start emission using preheating system on the exhaust line at the idle conditions on a spark ignition engine

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**Abstract.** In an ideal conditions, three-way catalytic converters have a structure that will convert almost all of the harmful exhaust emissions. However, these conditions are not valid for cold start and idle conditions. Especially in cold weather, people wait for a while at the idle speed even though it is not a good way to warm up the engine. In this period, since the required temperature to reach light-off values are not provided, the emission released to the environment is at the highest level. The effects of preheating of the catalytic converter have been investigated in order to minimize the exhaust gases emitted under cold and idle working conditions and to meet the Euro standards as soon as possible after the emission release starts. In this experimental study, preheating of 1060, 1253 and 1493 Watt energy was applied to the exhaust line before the three-way catalytic converter at the cold start and idle conditions. Preheating was started when the engine started running. In the experiments, temperature and emission values were obtained at the catalytic converter inlet and outlet at idle conditions (1000 rpm) for about 430 seconds. The effects of inlet temperatures of exhaust gases on HC and CO emission behavior and converter conversion efficiency were investigated. When 1060, 1253 and 1493 Watt preheating are applied to the exhaust line, the times for reaching the light-off for HC and CO emissions occur at 395, 295, 220 and 369, 277, 200 seconds, respectively. However, when preheating is not applied, the catalytic converter has not been able to reach the light-off within the specified time. Finally, the EURO VI standard could not be achieved for the specified period without preheating. However, when the preheating load was set to 1493 Watt, EURO VI standards were achieved at the end of 310 and 285 seconds preheating times for both HC and CO emissions.

**Keywords.** Three-way catalytic converter; preheating; exhaust emissions; light-off; cold start; SI engine.

## 1. Introduction

It is foreseen that it will not be possible to pass on completely electric powered vehicles in the near future even though this subject is on the world's agenda. While the total number of vehicles is 1.2 billion today, it is expected that this number will be around 2 billion in 2035 and it is foreseen that only 2.5% of these vehicles are expected to be battery electric, plug-in hybrid, or fuel-cell vehicles [1]. In this sense, efforts are being made to meet the standards that will reduce emissions and fuel consumption without lowering the performance and power values of internal combustion engines. Some of these activities include the development of different internal combustion system models, the use of alternative catalyst and the application of different catalytic converters [2, 3].

It is possible to prevent harmful emissions and to improve the quality of the air with improvements in control technology. For example, today, new model cars emit 95% less HC and CO and about 90% less $NO_x$ than an automobile without emission control. Investigations show that a large proportion (60–80%) of harmful gas emissions occur in the first 300 seconds during which cold working conditions occur and HC and CO oxidation cannot take place efficiently [4]. This time is mainly related to the fact that the vehicles start to work, move and come under a certain load. However, this period has been observed to be more than 800 seconds for idle and intermittent working regimes [5]. This has forced the researchers and manufacturers to adopt different approaches to emission problems during cold start conditions. When these approaches are examined

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in the literature, it is seen that they are generally gathered in two categories. These are active and passive systems. Active systems aim to increase the conversion efficiency by increasing the exhaust gas inlet temperature in cold working conditions with any external source. These are electrically fuel burner systems, heated catalyst, chemically heated catalyst, heat exchanger method, exhaust gas ignition with secondary air injection, etc. On the other hand, passive systems aim to increase conversion efficiency through the design of the exhaust system. These are usually methods such as close coupled catalyst (CCC), making different exhaust manifold designs, using pre-catalysts, using HC traps, air gap insulation, phase change material, variable conductance insulation, etc. [5–8].

Mahadevan and Subramanian [6] used a telescopic pipe between the engine and catalytic converter, pre-catalyst (20% and 40% of the volume of main catalytic converter), and hot air injection into the exhaust gas. When the catalytic converter was close to the engine, its efficiency increased and the light-off temperature period was shortened. With hot air injection, CO and HC light-off times have reduced about 65%. Chen *et al* [9] studied cold-start emissions of an SI engine using different percentages of ethanol-gasoline blended fuel. The percentages of ethanol in the blended fuel were 5, 10, 20, 30 and 40. As a result, HC and CO emissions were reduced by more than 20% ethanol contribution. However, when 40% ethanol was used for blended fuel, there was instability in the idling condition. Therefore, the percentage of ethanol addition was determined to be 20%–30% for the best cold-start emission. Tyagi and Ranjan [10] studied the effect of heating the catalytic converter on emission characteristic of automotive vehicles in its starting phase of combustion. As a result, the emission characteristic of hydrocarbons has been reduced from 800 to 15 ppm, CO from 4 to 0.07(V/V%) and $NO_x$ from 1200 to 115 ppm. Roy *et al* [11] studied the emissions of the 4-cylinder direct injection diesel engine at cold start idling (800, 1000 and 1200 rpm) conditions. They used biodiesel-diesel blends, biodiesel-diesel-ethanol blends and biodiesel-diesel-DEE (diethyl ether) blends for emissions analysis. Test results showed that the CO and $NO_x$ emissions decrease, but HC emissions increase. Mianzarasvand *et al* [12] numerically examined the effects of catalytic converter heating on emission characteristics in cold operating conditions in a motorcycle engine. Three different heating temperatures (700, 800 and 1000 K), different heating positions (inlet and mid-section) and three different heating durations (20, 25, 35s) were analyzed. As a result, using the heater at the inlet of the converter was more effective than the other position. Moreover, minimum heating temperature was found 450 K for light-off temperature. As a consequence, the heaters had to be operated 35 seconds before starting the engine to ensure better CO conversion efficiency.

Gumus [13] designed and tested an example of an advanced experimental thermal energy storage system for preheating internal combustion engines to reduce cold-start emissions. The results showed that CO and HC emissions decrease about 64% and 15%, with the effect of preheating the engine at cold start and warming-up period. Kim *et al* [14] developed a control module and an algorithm for the Unburned Exhaust Gas Ignition (UEGI) technology. Results show that Clouse Coupled Converter (CCC) reaches the light-off temperature faster compared with the baseline exhaust system. Therefore, HC and CO emissions were reduced during cold start. As a result, about 20% of HC emission in the cold transient phase was reduced when UEGI was applied to the exhaust system. Borland and Zhao [15] attempted to investigate the thermal and chemical processes associated with secondary air injection inside the exhaust system in order to maximize the simultaneous benefit of improving catalyst light-off performance and reducing converter emissions. It was found that proper design and optimization of secondary air injection can significantly improve catalyst light-off characteristics and reduce converter HC emissions. Cheng *et al* [16] investigated the temperature change before and after catalytic converter using the EC 15- mode test process. In-cylinder pressure measurements, air-fuel ratio and also inlet manifold pressure data were recorded. As a result, A/F ratio should be stoichiometric and stable combustion must be ensured to reduce HC emissions. Hayes *et al* [17] has modeled the catalytic converter on a one-to-one basis. Numerical simulations were done using the COMSOL Multiphysics 4.1 program and verifying the experimental data from the literature. In general, the effect of cell density and flow angle on diffuser angle to heat, mass transfer and velocity were investigated. The numerical solutions were made separately for the flow with the cold flow and the chemical reactions and the single-stage CO reduction reaction was defined as the chemical reaction. Zeng and Hohn [18] studied the performance of three-way catalytic converters with exhaust mixture from natural gas-fueled engines. A comprehensive and thermodynamically consistent surface reaction mechanism describing the surface reactions in the TWC was built by compiling elementary step reaction kinetics involving $CH_4$, CO, formaldehyde, NO, $NH_3$ and $N_2O$ from literature sources. The model predicted the major trends in conversion/formation of all species in the TWC over a wide range of air to fuel ratios.

Gong *et al* [19] experimentally investigated the effects of the length of the gas flow path from the exhaust outlet, the ignition timing and engine idle speed condition on the catalytic converter conversion efficiency and light-off behavior. As a result, the reduction of the gas flow path length increases the inlet temperature of the catalytic converter, and then light-off time reduced. It is understood that retarding the ignition time and increasing idle speed, the light-off time of HC and CO emissions could be reduced. Smieszek *et al* [20] used phase-transitional thermal accumulator in order to heating the catalytic converter. By this way, they aimed to reduce cold-start exhaust emissions. For catalytic conversion efficiencies, they showed efficiency increases with the additional heating at lower temperatures. Pellegrino *et al* [21] studied DOC (Diesel oxidation catalyst) recently. DOC is similar to a three-way catalytic converter in gasoline engines. They performed both experimental tests and numerical simulations. They also worked on the light-off behavior of the electrically heated catalyst. They conducted their experiments and simulations for FTP-75 cycle. The results were consistent with each other for the duration of 2600 sec. Leahey *et al* [22] investigated the effects of inductive heating of the catalytic converter for diesel engine cold-start emissions. In the experiments, a passenger car and a heavy duty vehicle were used. The heating loads were 1300 W and 2600 W for inductive heating of the catalytic converter. Coppage and Bell [23] studied on a commercial electrically heated catalytic converter with secondary air injection. With this configuration, maximum CO and HC conversion efficiencies were obtained. They showed that electric heating was ineffective in reducing NOx emissions. Ning and Yan [24] used a 15-equations reaction model to model the chemical reactions inside the catalytic converter. They modeled the cold start emissions and temperature control for the electrically heated catalytic converter. In order to control the cold start catalytic converter temperature, they tried to achieve fast light-off by using bang-bang controllers and an active disturbance rejection controller. Bhaskar *et al* [25] studied the electrically heating catalytic converter with different materials. Also, in another study, Bashkar and Sendilvelan [26] tried different materials for electric heater for EHC (Electrically heating catalytic) catalytic converter with various air injection configurations. CO and HC emissions were reduced reasonably. Schifter *et al* [27] studied the ethanol content in gasoline and emission conversion strategies. They concluded as the amount of ethanol content increases, total hydrocarbon emissions increase and - aromatic compounds decrease. For the high ethanol content (85 ethanol including fuel), the air–fuel mixture was too lean, making the reduction reactions necessary for NOx emission control in the catalytic converter impossible.

In general, the literature shows that between 60% and 80% of total emissions occur under cold working conditions. It has been observed that there has been an increase in efforts to reduce the light-off time (the time at which the catalytic converter reaches 50% conversion efficiency) so that these emissions can be minimized. For this reason, different studies are being carried out in different ways to ensure that the catalytic converters can reach the light-off temperature as soon as possible. These studies are expected to increase further to meet restrictive emission standards such as EURO, TIER, LEV, BS.

When the literature studies are investigated, the studies mostly focus on heating the converter or oxidation catalysts directly and increasing the conversion efficiency by providing a secondary air intake. It can be said that there are quite a few experimental studies investigating the effects of heating exhaust gas on temperature and emission behavior, for both cold-start and idle conditions, prior to catalytic converters or oxidation catalysts. While some of these studies were carried out in cold operating conditions under the load, some of them were carried out for the idle condition after the engine warmed up. In addition, it is seen that no comparison is made in terms of emission standards after the studies.

Emission standards require less harmful emissions in a shorter time. For this situation, either the emission must be reduced with the measures taken in the cylinder or different heating systems that will be active in cold and idle working conditions must be integrated. This study was carried out by heating the exhaust line with the help of electric resistance heaters before the catalytic converter in a gasoline engine under cold start (first running state, when the engine is at its most unstable) and no-load idle conditions. Then the temperature values, emission values, conversion efficiencies, light-off temperature and time were experimentally investigated. In addition, emission values obtained with different preheating loads were given by comparing them with the EURO VI standard.

## 2. Experimental set-up and procedure

### 2.1 *Experimental set-up*

Experiments were carried out at Internal Combustion Engines and Automotive Laboratory of Mechanical Engineering Department of Gazi University. The schematic view of the experimental set-up is shown in Figure 1.

The 1.6 L, 4-cylinder, 4-strok, spark ignition, multi-port injection and water-cooled SI engine are mounted on NETFREN brand electrical dynamometer. Experiments were carried out on this engine. Engine specifications are listed in Table 1.

A Capelec Cap 3200 brand emission analyzer was used to measure emissions. Specifications of emission analyzer are shown in Table 2. Temperatures were measured with Elimko brand K type thermocouples before and after the catalytic converter and transferred to the computer by the data collector.

The electrical resistance is located at 1.2 m from the exhaust manifold as shown in Figure 1. The total capacity of electrical resistance is 6 kW (3 resistance $\times$ 2kW) for 220 Voltage. The thermal power was adjusted for different values by using a voltage adjustable regulator. In this way, desired inlet temperatures can be obtained before the catalytic converter.

### 2.2 *Experimental procedure*

All experiments were carried out at the idle speed (nearly 1000 rpm) and cold start condition (the first time the engine

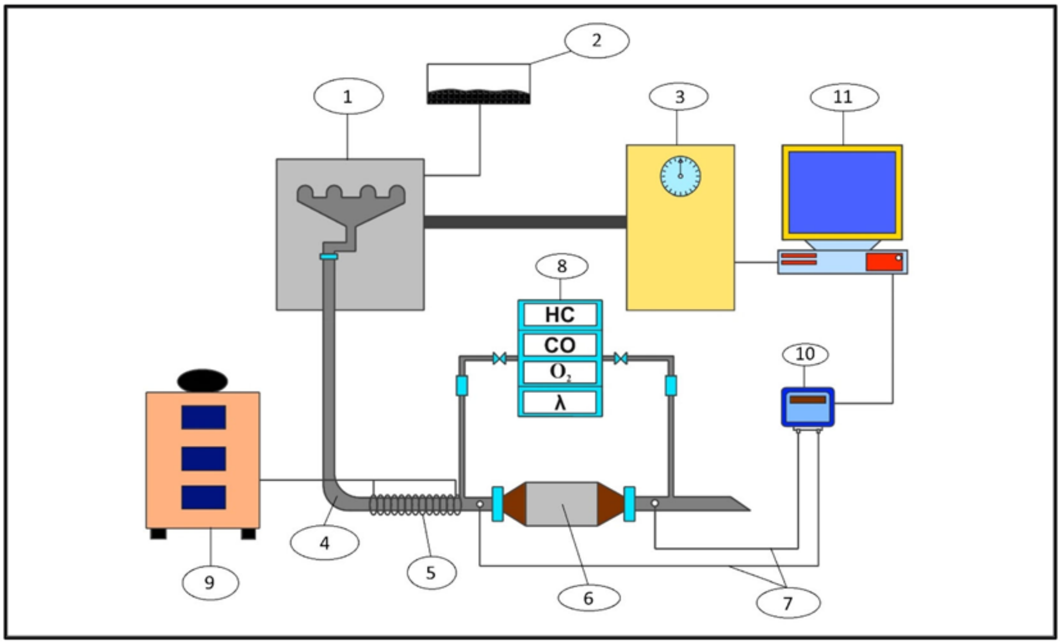


**Figure 1.** Schematic view of the experimental set-up. 1. Engine, 2. Fuel tank, 3. Dynamometer, 4. Exhaust Line, 5. Resistance, 6. Three-way catalytic converter 7. Thermocouples 8. Exhaust Gas Analyzer, 9. Voltage Adjustable Regulator (Three-phase variac), 10. Data logger 11. Computer.

**Table 1.** Engine specifications.

| Engine parameters | Specifications |
|---|---|
| Manufacturer and Type | Toyota 1.6, gasoline 4 stroke |
| Number of Valve | 4 |
| Type | In line 4 cylinder, MPFI |
| Bore x Stroke | 80 mm × 77 mm |
| Displacement Volume | 1599 cc |
| Compression Ratio | 9.5:1 |
| Power | 103 HP |
| Max. Torque | 137 Nm @ 3200 rpm |
| Max. Power | 103 HP @ 6000 rpm |
| Cooling | Water Cooling |

**Table 2.** Specifications of Capelec Cap 3200 emission analyzer.

| Parameter | Measurements range | Accuracy |
|---|---|---|
| HC (ppm) | 0–20000 ppm | ±1 ppm |
| $CO_2$ (% vol.) | 0–20% | ±0.1% |
| CO (% vol.) | 0–15% | ±0.001% |
| $O_2$ (% vol.) | 0–21.7% | ±0.01% |
| $NO_x$ (ppm) | 0–5000ppm | ±1 ppm |

is started) without any load. The engine coolant and lubrication temperatures were monitored digitally and the tests were repeated at least every 12 hours for the test setup to return to "cold start" conditions again. During the experiments, data were recorded for periods of 10 seconds for approximately 430 seconds during which the exhaust gases reached the light-off temperature and the conversion efficiency became steady-state condition. Equation (1.1) was used to calculate the conversion efficiency of the catalytic converter.

$$(\eta_{cat})_i = \frac{(\dot{m}_{in})_i - (\dot{m}_{out})_i}{(\dot{m}_{in})_i} \tag{1.1}$$

Initially, experiments were started under engine cold running conditions without preheating. Emission and temperature values were measured before and after the catalytic converter without preheating and the engine was allowed to return to cold running conditions for 12 hours. After the reference emission and temperature parameters were obtained, resistance heaters were commissioned from the first moment the engine started. Then, under cold operating conditions, when the engine was idle and unloaded, different preheating loads were applied to the electrical resistance, and the emission and temperature values were operated in intermittent regime until the desired time (usually until the EURO standard was met). The resistance which can operate in 6 kW power with 220 V voltage difference was preheated by using three different input voltages, 220 V, 250 V and 280 V, but only part of thermal energy was available as useful heating. As a result of the calculations made, it has been observed that the thermal energy transfer from the resistors to the exhaust gas was about 17.6%. The amount of energy transferred to the exhaust gas for the 220, 250 and 280 voltage differences was calculated as 1060 W, 1252 W and 1493 W. The remaining thermal energy was spread to the environment by convection and radiation. Preheating was started in idle and no-load condition when the engine started running and then HC, CO and temperature measurements were taken at 10 second intervals. Temperature measurements were done by thermocouples before and after the catalytic converter. Experiments were repeated at least three times under the same engine operating conditions, mean values of CO, HC and temperature were taken and results were evaluated according to these mean values.

## 3. Results and discussion

Emission behaviors and emission conversion efficiencies are related to the working temperature. Significant reductions in catalytic converter efficiency are observed at low temperatures. It is observed that the converter efficiency is very close to zero during the cold start and engine warm-up period. Therefore, alternative methods are needed to reach the light-off temperature (usually between 250–300 °C) as quickly as possible in order to increase the efficiency of the converter. Preheating of the exhaust line before the catalytic converter is one of the methods that can be used. The figure of varying temperature, HC, and CO emissions, based on various preheating conditions are given below.

### 3.1 *Temperature variation of before and after TWC*

The change in gas temperature over time at three different energy loads before TWC is shown in Figure 2. (Legends in the figures represent the amount of energy supplied to the exhaust line before the catalytic converter and the measuring point; for example, 1060 W (After TWC) means 1060 W net energy is supplied to the line before TWC and the measuring point is after the catalytic converter). The positions of the thermocouples to measure the exhaust gas temperatures are given in Figure 1. Thermocouples positioned 5 cm before and after TWC are located at the centerline of the exhaust line. When 1060 W energy is applied, it is seen that the output temperature is less than the input temperature up to 270 seconds. For this period, it can be said that heat was transferred from the exhaust gas to the catalytic monolith. The catalysts need the activation energy to initiate chemical reactions. As the catalysts became active and chemical reactions began, the direction of heat transfer changed from monolith to exhaust gas. As a result of chemical reactions, the reaction heat was released and the exhaust gas outlet temperature reached 370 °C while the inlet temperature reached 300 °C for constant 1060 W. When the energy applied was increased to 1253 W, the starting time of the chemical reactions was approximately 185 seconds, and when the energy was increased to 1493 W, it is seen that this time was reduced to 160 seconds. As a result, with the increasing energy application, it was seen that the catalyst activation time in cold working conditions dropped from 270 seconds to 160 seconds. Here, the electric resistance heater applied along the line contributes to the heating of the intake manifold, and then the inlet volume of the catalytic converter, together with the line through which the exhaust gas passes. This caused a sudden increase in temperature due to the increased energy input, and the time it took for activation energy to be provided rapidly decreased.

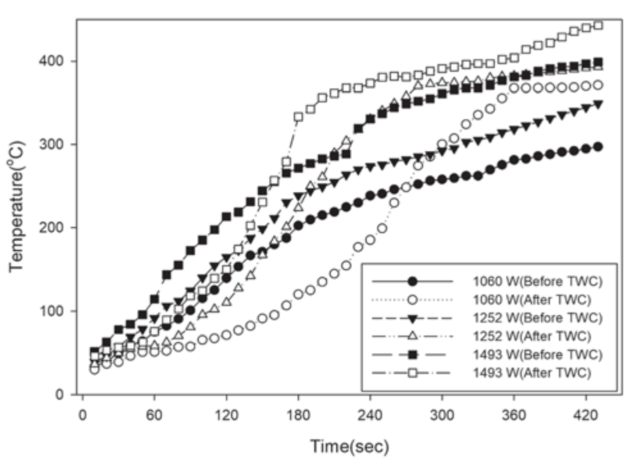


**Figure 2.** Temperature variation of before and after TWC at idle speed.

### 3.2 *HC emission variation and conversion efficiency of TWC*

Hydrocarbon emissions consist of unburned or partially burnt hydrocarbon fuels. During the normal combustion process, the fuel is separated from the cylinder by unburned or by partial burned due to compression leaks, carbon residues, oil layer, etc. in the cylinder. Although hydrocarbons from the exhaust of internal combustion engines are grouped into many classes, the most common ones are the total hydrocarbon (THC) and non-methane form.

The hydrocarbon emission change of TWC over time were given in Figure 3. First of all, when the figure was examined for reference values where the heaters were not active; As the temperature could not rise due to both cold running conditions, and the distance between the engine and the catalytic converter, it was seen that HC emissions at the catalytic converter inlet decreased from 504 ppm to 431 ppm after 430 seconds (This value was also recorded after 430 seconds, but was not given because it remained almost constant).

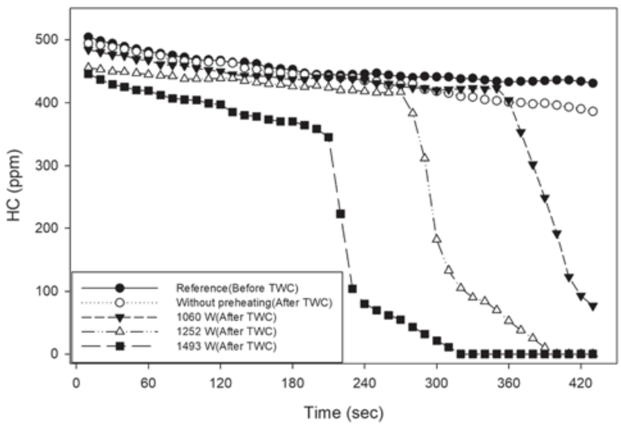


**Figure 3.** HC emission variation of TWC at idle speed.

However, when preheating the exhaust line before the catalytic converter, there was a sudden tendency for HC emissions (ppm) to drop with increasing inlet temperature and chemical reactions. For 1060 W preheat load, HC emission measured as 484 ppm at the first second and then suddenly started to decrease within 360 seconds. After that, reached the light-off temperature at 395th seconds, and was measured at the level of 210 ppm. At the end of 430th second, HC emission value was determined as 77 ppm. When the energy applied rising to 1252 W, HC emission measured as 456 ppm at the first second and then suddenly started to decrease within 280th seconds. After that, reached the light-off temperature at 295th seconds, and HC emission was measured at the level of 220 ppm. And finally, at the 400th second, HC emission value was determined as 0 ppm. When the energy applied is 1493 W, HC emission measured as 446 ppm at the first second and then suddenly started to decrease within 210th seconds. After that, reached the light-off temperature at 220th seconds, and HC emission was measured at the level of 223 ppm. And finally, at the 320th second, HC emission value was determined as 0 ppm.

The hydrocarbon emission conversion efficiency of TWC over time were given in Figure 4. This figure shows that when preheating was not applied, the HC emission conversion efficiency did not increase much in the first 280 seconds and is approximately 2%, and after 430 seconds this value reaches approximately 10%.

However, when the exhaust line preheating before the catalytic converter, there was a sudden trend of increase in HC conversion efficiency with increasing inlet temperature and chemical reactions. For the 1060 W preheat load, HC conversion efficiency reached 50% (light-off) at 395 seconds, and then suddenly began to increase the conversion efficiency. And finally, HC conversion efficiency was determined to be 82% at the end of 430 seconds. When a preheating load of 1252 W and 1493 W was applied, the times for HC emissions to reach 50% conversion efficiency (light-off) were determined as 295 and 220 seconds, respectively. The times to reach 100% conversion efficiency for these heating loads were 400 seconds and 320 seconds.

Furthermore, when the obtained data were evaluated, it was observed that the temperature for reaching the light-off for the measurements made at the catalytic converter inlet was approximately 290 °C. The sudden jump in both emission and efficiency values in figures 4 and 5 were entirely related to the light-off time and temperature. In the catalytic converter, after reaching light-off temperature, emission values decrease in a very short time and efficiency values increase. As a result, it can be said that with the increased **preheating power, not only** the exhaust line but also the intake manifold and the catalytic converter inlet were heated, and hence HC emission emissions were further reduced.

### 3.3 *CO emission variation and conversion efficiency of TWC*

The carbon monoxide emission change of TWC over time were given in Figure 5. First of all, when the figure was examined for reference values where the heaters were not

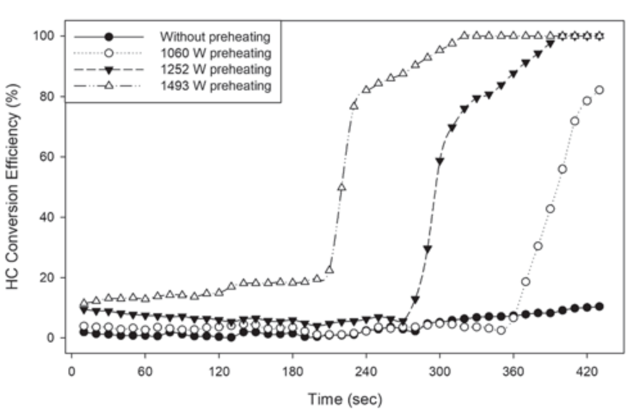


**Figure 4.** HC conversion efficiency of TWC at idle speed.

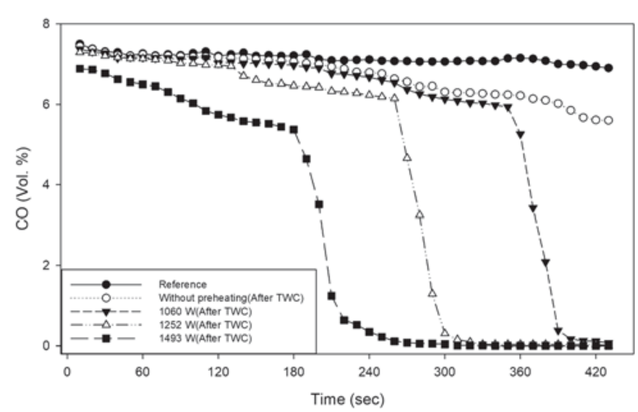


**Figure 5.** CO emission variation of TWC at idle speed.

active; As the temperature could not rise due to both cold running conditions, and the distance between the engine and the catalytic converter, it was seen that the CO emissions at the catalytic converter inlet decreased from 7.4% to 5.6% after 430 seconds.

However, when preheating the exhaust line before the catalytic converter, there was a sudden tendency for CO emissions (%) to drop with increasing inlet temperature and chemical reactions. For 1060 W preheat load, CO emission measured as 7.37% at the first second and then suddenly started to decrease within 350 seconds. After that, reached the light-off temperature at 369th seconds, and was measured at the level of 3.42%. At the end of 390th second, CO emission value was determined as 0%. When the energy applied rising to 1252 W, CO emission measured as 7.29% at the first second and then suddenly started to decrease within 270th seconds. After that, reached the light-off temperature at 277th seconds, and CO emission was measured at the level of 3.6%. And finally, at the 300th second, CO emission value was determined as 0%. When the energy applied was 1493 W, CO emission measured as 6.88% at the first second and then suddenly started to decrease within 190th seconds. After that, reached the light-off temperature at 200th seconds, and CO emission was measured at the level of 3.51%. And finally, at the 220th second, CO emission value was determined as 0%.

The carbon monoxide emission conversion efficiency of TWC over time were given in Figure 6. This figure shows that when preheating is not applied, CO emission conversion efficiency does not increase much in the first 210 seconds and is approximately 2%, and after 430 seconds this value reaches approximately 19%.

However, when the exhaust line preheating before the catalytic converter, there was a sudden trend of increase in CO conversion efficiency with increasing inlet temperature and chemical reactions. For the 1060 W preheat load, CO conversion efficiency reached 50% (light-off) at 369 seconds, and then suddenly began to increase the conversion efficiency. And finally, CO conversion efficiency was determined to be nearly 100% at the end of 390 seconds.

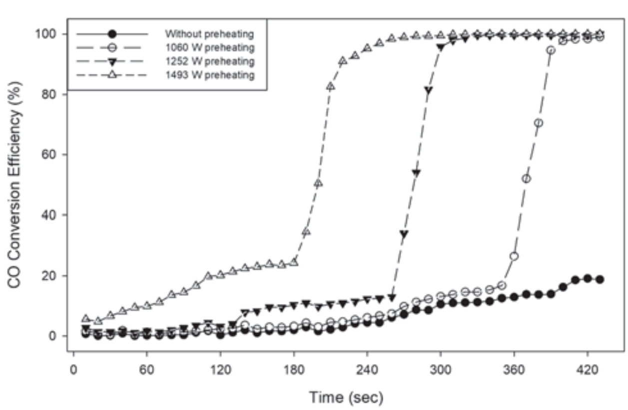


**Figure 6.** CO conversion efficiency of TWC at idle speed.

When a preheating load of 1252 W and 1493 W was applied, the times for CO emissions to reach 50% conversion efficiency (light-off) were determined as 277 and 200 seconds, respectively. The times to reach 100% conversion efficiency for these heating loads were 300 seconds and 220 seconds. In general, emission and conversion efficiency trends are similar to HC graphs.

Finally, light-off time and 100% efficiency conversion times appear to be shorter than HC emission reduction and conversion times. Therefore, the fact that carbon dioxide oxidation from carbon monoxide occurs in a single-stage reaction can be shown as quicker absorption of activation energy by absorbing heat faster. Furthermore, when the obtained data were evaluated, it was observed that the temperature for reaching the light-off for the measurements made at the catalytic converter inlet was approximately 282 °C.

### 3.4 *HC and CO emission comparison with EURO VI standards*

Along with the legal regulations, there are gradual restrictions on internal combustion engine emissions. These restrictions vary from country to country and are called TIER, EURO, LEV, BS, and so on. In this section, studies were carried out according to the EURO VI standard for CO and HC emissions. EURO emission standards are given in Table 3 and reference [28, 29] was used for HC and CO emission conversions.

In the case of without preheating condition, there was only a slight decrease in HC and CO emissions due to engine heating, as shown in Figure 7 and Figure 8. The lack of EGR, cold and idling conditions were also the reasons why emission values could not reach the EURO VI standards within the measured time. The applied energy of 1060 W was not enough for HC emissions to reach the EURO VI standards, but CO emissions were close to the desired values after almost 430 seconds. When the applied energy increased to 1252 W, HC and CO emissions were observed to reach EURO VI standards at 385 and 345 seconds. When the applied energy was set to 1493 W, it was seen that the EURO VI standards in the HC and CO emissions were reached at nearly 310 and 285 seconds.

**Table 3.** EU emission standards for gasoline engines [30].

| Stage | Date | CO (g/km) | HC (g/km) |
|---|---|---|---|
| Euro I | 1992.07 | 2.72 | |
| Euro II | 1996.01 | 2.20 | |
| Euro III | 2000.01 | 2.30 | 0.20 |
| Euro IV | 2005.01 | 1.00 | 0.10 |
| Euro V | 2009.09 | 1.00 | 0.10 |
| Euro VI | 2014.09 | 1.00 | 0.10 |

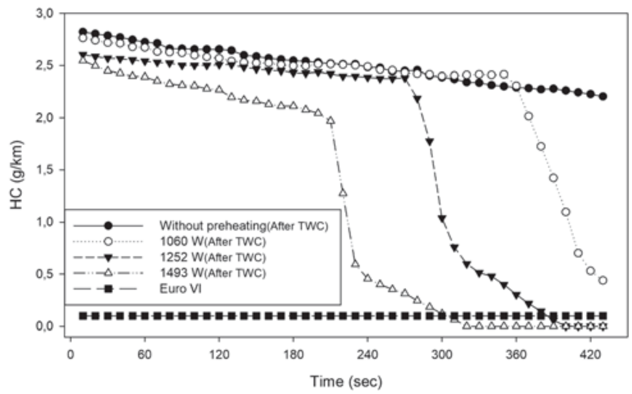


**Figure 7.** HC emissions comparison with EURO VI standards.

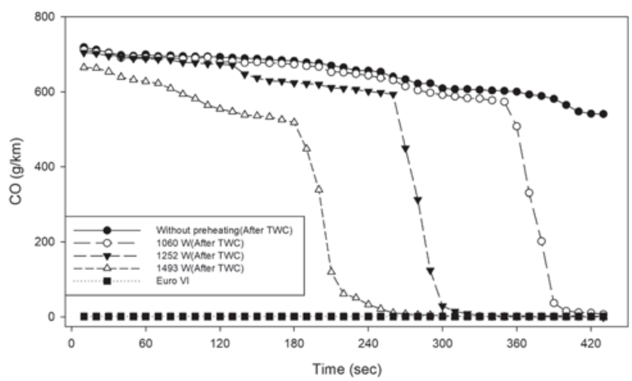


**Figure 8.** CO emissions comparison with EURO VI standards.

Figures 7 and 8 show that there was no significant reduction in HC and CO emission values at the end of 300 [4] or 800 [5] seconds when preheating load was not applied and does not meet EURO standards. However, with the preheating application, it had been observed that the time to meet the EURO standards had decreased to 285 seconds. The main purpose here was to reduce the time it took to reach the operating temperature with 50% efficiency by gradually applying different heating loads and to reach the EURO IV standards quickly. In addition, it was seen that by increasing the efficiency in heat transfer, reaching this goal can be both shorter and easier.

## 4. Conclusion

In this study, preheating effects on TWC performance were discussed. By applying varied voltage differences to the resistance which was located at 1.2 m distance from the exhaust manifold, temperature changes of exhaust line before and after the TWC were measured. Preheating was started when the engine started running. The effects of inlet temperatures on HC and CO emission behavior and converter conversion efficiency were investigated. In addition, the light-off time was determined and the measured emission values were compared with the EURO VI standard. The main conclusions can be summarized as follows:

1. When the obtained data are evaluated, the light-off temperatures for the catalytic converter inlet are 282°C and 290°C for CO and HC. Since carbon dioxide oxidation from carbon monoxide occurs in a single stage reaction and requires less activation energy, the light-off temperature of the CO is lower. For hydrocarbon oxidation, reactions occur in more than one stage, which means that higher temperatures and more heat and activation energy are needed,
2. The light-off time was reached at 395, 295, 220 seconds for HC conversion with preheating of 1060, 1253 and 1493 Watt. The light-off time was not reached for the specified period without preheating,
3. For CO conversion, light-off times were reached at 369, 277,200 seconds,
4. Both HC (ppm) and CO (%) emissions were reduced to zero at the end of 430 seconds with increasing temperature and reaction rates, for all energy values,
5. Finally, the EURO VI standard could not be achieved for the specified period without preheating. With the preheating of 1493 W, the EURO VI standards were achieved at 310 seconds for HC and 285 seconds for CO.

## Appendix A

### *Uncertainty analysis*

All experiments contain some errors due to the tools used, the people or machines performing the experiment. In order to analyze these errors and to show the reliability of the data obtained as a result of the experiments, the uncertainty analysis method, which is a more sensitive method compared to other methods, first introduced by Kline and McClintock [31], has been used in recent years. Errors made by personnel taking measurements in experimental measurements are not considered as uncertainty. Uncertainty analysis is an evolving field and there are unnoticed changes over the years [32].

Let R be the magnitude to be calculated by any experimental setup. Let $x_1, x_2, x_3, \ldots\ldots, x_n$ be the n independent variables affecting this size. In this case, R can be written as follows:

$$R = f(x_1,\ x_2,\ x_3, \ldots\ldots, x_n)$$

In addition, the fixed error amount of each independent variable effective in experiments is $w_{x_1}, w_{x_2} w_{x_3}, \ldots\ldots, w_{x_n}$. If we write this case instead of in magnitude R, according to the Pythogorean theorem, the worst possible case and the smallest possible case are expressed as follows.

**Table A1.** Measurements and errors obtained in the experiments.

| Measurement method | Measurement parameter | Measuring range | Precision | Uncertainty |
|---|---|---|---|---|
| Catalytic converter conversion efficiency | Carbon monoxide | – | – | % 5.4 |
| | Hydrocarbons | – | – | % 6.4 |
| Capelec CAP 3200 Exhaust gas analyzer | Carbon monoxide | 0–15% | 0.01% | % 4 |
| | Hydrocarbons | 0–20000 ppm | 1 ppm | % 4.6 |
| Temperature measurement thermocouples | Temperature | (−200 °C)–(1300 °C) | 1 °C | % 2.5 |

$$W_R = \left\{ \left( \frac{\partial R}{\partial_{X_1}} w_1 \right)^2 + \left( \frac{\partial R}{\partial_{X_2}} w_2 \right)^2 + \cdots + \left( \frac{\partial R}{\partial_{X_n}} w_n \right)^2 \right\}$$

The combined standard uncertainty of the measurement result is the calculated standard deviation of the result. In other words, it is the positive square root of the calculated variance. This uncertainty analysis was made for the CO and HC emissions that we have measured in experiments and the conversion efficiencies calculated in theory. In the content of this study, a sample uncertainty analysis was presented for measurement and calculation in working time, which was thought to have the highest engine and measurement instabilities. In this analysis, HC measurement uncertainty was calculated with a commonsense basis, and conversion efficiency errors were calculated using the uncertainty approach.

For example, if the HC emission values measured for the 30th second engine operating condition of the 6 kW heater of the electrical resistances in the experimental setup shown in Figure 1 were taken into consideration:

$$\left.\begin{array}{l} 1.\ \text{Measurement} : 498\ \text{ppm} \\ 2.\ \text{Measurement} : 462\ \text{ppm} \\ 3.\ \text{Measurement} : 468\ \text{ppm} \end{array}\right\} \text{Average}$$
$$= \frac{498 + 462 + 468}{3} = 476\ \text{ppm} \ = HC_N$$

The highest uncertainty in measurement:

$$W_{HC} = \frac{HC_{Meas.max} - HC_N}{HC_N} x100 = \frac{498 - 476}{476} x100 = \%4.6$$
$$= 22ppm$$

According to this calculation, the uncertainty in the measurement was determined as 22 ppm. After the error in the measurement was determined as above, the error in the calculations was continued to be determined by the uncertainty analysis.

HC conversion efficiency of catalytic converter:

$$\eta_{HC} = \frac{HC_i - HC_o}{HC_i} \times 100$$

It is calculated by the formula. Here the $HC_i$ is HC emission measured before the catalytic converter. The $HC_O$ is HC emission value measured after the catalytic converter. And $\eta_{HC}$ is the conversion efficiency of the catalytic converter.

The formulas for the uncertainty analysis were given above [33]. Accordingly, the uncertainty in the HC emission conversion efficiency of the catalytic converter can be calculated as follows:

$$W_{\eta_{HC}} = \left\{ \left( \frac{\partial \eta_{HC}}{\partial_{HC_i}} \ w_{HC} \right)^2 + \left( \frac{\partial \eta_{HC}}{\partial_{HC_O}} \ w_{HC} \right)^2 \right\}^{1/2}$$

Differential expressions in this equation are calculated as follows:

$$\frac{\partial \eta_{HC}}{\partial_{HC_i}} = \frac{\partial}{\partial_{HC_i}} \left[ \frac{HC_i - HC_O}{HC_i} \times 100 \right] = \frac{(-HC_O) \times 100}{(HC_i)^2}$$

$$\frac{\partial \eta_{HC}}{\partial_{HC_O}} = \frac{\partial}{\partial_{HC_O}} \left[ \frac{HC_i - HC_O}{HC_i} \times 100 \right] = \frac{(-1) \times 100}{HC_i}$$

If differential expressions are substituted in the uncertainty formula:

$$W_{\eta_{HC}} = \left\{ \left( \frac{(-HC_O) \times 100}{(HC_i)^2} \ w_{HC} \right)^2 + \left( \frac{(-1) \times 100}{HC_i} w_{HC} \right)^2 \right\}^{1/2}$$

$$W_{\eta_{HC}} = \left\{ \left( \frac{(-458) \times 100}{(476)^2} (22) \right)^2 + \left( \frac{(-1) \times 100}{476} (22) \right)^2 \right\}^{1/2}$$

$$\left\{ (-4.447)^2 + (-4.621)^2 \right\}^{1/2} = \{41.129\}^{1/2} = \%\ 6.4$$

It was calculated. With the uncertainty analysis in the same situation, the conversion efficiency of the catalytic converter was calculated as 5.4% for CO.

The uncertainty values of the HC and CO conversion efficiencies calculated with the measurement precision and error values of the CO and HC components measured with the exhaust gas measuring device in the experiments were presented in Table A1.

## Abbreviations

| | |
|---|---|
| cc | Centimeter cube |
| cm | Centimeter |
| EGR | Exhaust gas recirculation |
| g | Gram |
| hp | Horsepower |
| km | Kilometer |

| | |
|---|---|
| m | Meter |
| min | Minute |
| mm | Millimeter |
| MPFI | Multi port fuel injection |
| ppm | Particle per million |
| rpm | Revolution per minute |
| s, sec | Second |
| SI | Spark ignition |
| TWC | Three-way catalytic converter |
| vol. | Volume |

**List of symbols**

| | |
|---|---|
| $CH_4$ | Methane |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| HC | Hydrocarbons |
| K | Kelvin |
| kW | Kilowatt |
| L | Liter |
| $N_2O$ | Nitrous oxide |
| $NH_3$ | Ammonia |
| NO | Nitrogen monoxide |
| $NO_x$ | Oxides of nitrogen |
| $O_2$ | Oxygen |
| V | Voltage |
| $\eta_{cat}$ | Catalytic converter efficiency |
| $\dot{m}_{in}$ | The amount of emissions entering the catalytic converter |
| $\dot{m}_{out}$ | The amount of out flow emissions from the catalytic converter |
| I | Emission of HC and CO |

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