Analysis of Post-oxidation Phenomena in a Turbocharged DISI Engine Focused on Gas and PM Emissions and Gas Temperature

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Received on July, 19, 2021

ABSTRACT: The detailed investigation of post-oxidation phenomena based on gas emissions, PM and gas temperature were performed on a turbocharged DISI engine. In post-oxidation phenomena, rich air-fuel mixture is used inside cylinder and this rich excursation gives rise to the production of CO, THC, PM and H2 emissions. Then the scavenged O2 and emitted H2 play a key role for post-oxidation reaction (exothermic) with CO, THC and PM in exhaust manifold and in-turn can aid in increasing the temperature along with overcoming of decrease in temperature by heat absorption reaction. The actuation time delay of reaction was also investigated with emissions and temperature with fast response devices in transient mode.

KEY WORDS: Heat engine, spark ignition engine, post-oxidation, emissions, gas temperature, transient response (A1)

1. Introduction

Recently, the fuel economy and emissions have become the key research point for the automotive industries to fulfill the emissions regulation together with better performance. Considering these challenges, a wider research on these topics has been conducted and still being continued. The post-oxidation-based emissions reduction has been introduced as an alternative method to tackle emissions along with the engine performance improvement. However, the research conducted on the post-oxidation phenomenon is still limited. Hence, a detailed investigation is required to reduce the emissions out from the engine without additional modification and cost imposed on the conventional engines. Considering this research gap, scavenging-based post-oxidation phenomena was deeply investigated considering the gas emissions (CO, CO2, THC) and particulates matters (PM) and gas temperature development during the post-oxidation actuation.

The scavenging-based post-oxidation process is defined as secondary combustion in exhaust manifold between unburned hydrocarbons and scavenged air. The in-cylinder combustion used rich air-fuel mixture and this rich excursation gives rise to the production of CO, THC, PM and H2 emissions. Then the scavenged O2 and emitted H2 play a key role for post-oxidation reaction with CO, THC and PM in exhaust manifold and in-turn can aid in increasing the temperature along with overcoming of decrease in temperature by heat absorption reaction [1-5]. Apart from this, TWC life time improvement and load reduction on catalyst, reduction in residual gas fraction, and knocking tendency reduction by the in-cylinder temperature decrease etc. can be additionally grabbed from the post-oxidation phenomena. Without post-oxidation, all unburned fuel emitted is treated with a catalyst, which raises the catalyst temperature. On the other hand, when post-oxidation is actuated, the temperature of the exhaust manifold rises because an oxidation reaction occurs in the exhaust manifold, but the temperature drops as the turbocharger works. At the same time, less unburned fuel is brought into the catalyst, which prevents the catalyst from rising in temperature. In past, another methodology for the post-oxidation has been also adopted such as, secondary air injection in exhaust port that can enable secondary reaction (post-oxidation) and could increase enthalpy at turbocharger upstream and hence turbo-lag can be reduced [3-7]. However, the scavenging-based post-oxidation phenomena (adopted in this research) is different from the secondary air injection methodology. Compared to the secondary air injection method, this method does not require pump power and the amount of supplied air can be easily controlled by VVT. In this methodology, the O2 is directly short-circuited from intake to exhaust manifold through in-cylinder by the VVT tuning and it does not participate in in-cylinder combustion compared of air injected in exhaust manifold with the separate pump in the case of secondary air injection. Due to this, the in-cylinder AFR leads toward rich and exhaust port AFR becomes lean automatically. Then, this scavenged O2 mixed with rich unburned gas species in exhaust manifold and the post-oxidation actuated. In addition, this method can improve the exhaust efficiency of exhaust gas by...
scavenging overlap, and can suppress abnormal combustion such as knocking and plague.

The wider investigation on the emissions such as, CO, CO₂, THC, PM and H₂ have been also performed in the post-oxidation phenomena and found emissions reduction along with the turbo-performance improvement [1, 2, 3, 7]. It was also noted that the efficient post-oxidation can be influenced with adequate mixing, temperature level and air and exhaust gas concentration in the exhaust manifold [7, 8].

Also, it is well known that the temperature variation directly reflects the heat generated during the post-oxidation phenomena. Hence, it is necessary to use a fast response device that can show the concurrent chemical reactions between gas species behavior and heat generated due to that. Several thermocouples such as J, K, R and E type were used to implement for the temperature measurement in internal combustion engines which actually does not reflect the real time trend of heat generation during combustion behavior [9]. Also, until now there are not enough research that have been conducted to perform fast response of temperature measurement and its characterization during combustion process due to complexity in combustion and gas dynamics phenomena. Hence, it is necessary to adopt a fast response temperature measuring device named as “two-wire thermocouple”, so that measurement of the fast response heat generated during the post-oxidation phenomena in exhaust manifold could be measured and this can further help in the oxidation delay time estimation that would reflect the speed of the chemical reactions [10].

Considering the above challenges and research objectives, it was decided to conduct a detailed investigation of gas and PM emissions and gas temperature development and its characteristic in the scavenging-based post-oxidation phenomena.

2. Experimental Setup

2.1. Engine Test Bench

A 4-cylinder turbocharged DISI engine was adopted in this study to conduct and investigate the scavenging-based post-oxidation phenomena. The engine was coupled with a low inertial HORIBA dynamometer to simulate the actual driving condition. A dummy TWC system was used to maintain exhaust pressure without using its catalyst function. The essential and respective instruments and sensors were installed on the test bench to fulfill the required objectives. The engine technical specifications are given in Table 1. The engine setup is shown in Fig. 1. The dynamometer controller was used to regulate the engine speed and load. The intake, in-cylinder and exhaust pressure were measured by the Kistler sensors.

In addition, a two-wire thermocouple was installed at the TWC downstream to measure the fast response temperature development in post-oxidation condition. Since, the sensor is very delicate and costly, a safety system was also designed to ensure protection of the sensor by exhaust gas dynamics and vibration, and to obtain precise measurement data with allying the flow direction to the probe perpendicular. The K-type thermocouple was used to observed the mean value of temperature. The measurement positions were selected based on the required objectives as given in Table 2.

![Fig. 1 Experimental Test Bench.](image)

### Table 1. Engine technical specifications.

| Variables                        | Measurement Positions                      |
|----------------------------------|-------------------------------------------|
| No. of Cylinders                 | Inline 4                                   |
| Volume Capacity (L)              | 1.6                                        |
| Bore X Stroke (mm)               | 79.7 X 81.1                                |
| Compression Ratio                | 10.5                                       |
| Max. Power (kW/rpm)              | 140 /5600                                  |
| Max. Torque (Nm/rpm)             | 240 /1600-5200                             |
| Max. Speed (rpm)                 | 6400                                       |
| Valve Train                      | DOHC 16 Valves                             |
| Fuel Injection                   | Direct Injection                           |
| Aspiration                       | Turbocharger                               |

### Table 2. Measurement positions.

| Variables                               | Measurement Positions                      |
|-----------------------------------------|-------------------------------------------|
| Emissions                               | Exhaust port 1, TC upstream and TWC downstream |
| CO and CO₂ (NDIR), THC (FID)            | Exhaust port 1, TC upstream and TWC downstream |
| PM (EEPS and TEM)                       | Exhaust port 1, TC upstream TC downstream and TWC downstream |
| Temperature                             | TWC downstream                             |

2.2. Experimental Methodology

In the experiment, the following methodology was adopted to achieve the desired research objectives.

- Firstly, the engine cooling water was warmed up till 85 deg. C temperature. The intake temperature was controlled around 30 deg.C.
After the engine had reached the desired temperature, post-oxidation reaction was actuated by tuning the engine speed, torque, VVT and spark timing.

After a sustainable post-oxidation reaction was achieved, the emissions, PM and temperature were measured and analyzed.

The fast response devices (NDIR500 and HFR500 Fast FID) were used for the CO, CO$_2$ and THC emissions steady and transient response behavior observation during post-oxidation phenomena. The data sample for the PM concentration with EEPS 3090 and PM size/morphology with thermophoretic sampling and Transmission Electron Microscopy (TEM) analysis [11] were also collected at the respective positions.

The two-wire thermocouple was used for the fast response temperature measurement. The voltage signal was measured with the two-wire thermocouple and data was captured. After getting the raw data of voltage, post-processing was performed to convert the voltage into temperature with the calibration data of R-type thermocouple and then further analysis were performed. Then, the gas temperature were estimated with the time constant compensation [10].

3. Results and Discussion

In the post-oxidation phenomena, the main source of heat generation is CO oxidation. The oxidation process of CO is represented as below [2],

\[
CO + OH = CO_2 + H
\]  

(I)

while the reaction equations

\[
CO + O_2 = CO_2 + O
\]  

(II)

and

\[
CO + O (+M) = CO_2(+M)
\]  

(III)

are less effective due to the low reaction rate constant. It was also noted that hydrogen (H$_2$) concentration plays a key role in the actuation of the post-oxidation reaction as it assists in the formation of OH radicals that is as shown in the chemical reaction below,

\[
H + O_2 = O + OH
\]  

(IV)

\[
H_2 + O = H + OH
\]  

(V)

\[
H + O_2 (+M) = H_2O_2 (+M)
\]  

(VI)

and the production of H$_2$O is mainly driven by

\[
H_2 + OH = H_2O
\]  

(VII)

For the oxidation of CO (equation (I)), OH needs to be produced mainly by equation (IV) and (V). The OH production is also influenced by equation (VI).

3.1. Steady State Analysis

In the steady state analysis, the gas emissions, PM and gas temperature with and without post-oxidation phenomena were conducted.

3.1.1. Emissions (CO, CO$_2$, THC and PM)

CO, CO$_2$ and THC emissions were analyzed at various positions (refer Table 2) in post-oxidation condition at 1600 rpm, 160 Nm and 90 deg. overlap. The FID response delay 0.9 ms (9 deg. at 1600 rpm) and the NDIR response delay 8 ms (77 deg. at 1600 rpm) were deducted from the measured data to synchronize the actual variation of THC and CO/CO$_2$ with the engine stroke and valve dynamics.

In Fig. 2, the comparison of (a) THC (b) CO and (c) CO$_2$ contents at exhaust port of cylinder 1, TC upstream and TWC downstream positions are plotted. Moreover, the simulated gas velocity with the VVT dynamics are also shown in the same graph (2 (d)). It can be observed that the THC and CO level decreased and CO$_2$ level increased as moving from port towards TWC downstream. This is due to the post-oxidation reaction that is taking place and also inhomogeneity exists between exhaust port 1 and TC upstream. This engine-out THC and CO contents are participating in a chemical reaction with scavenged O$_2$ and OH radicals (eqs. I & II) hence forming CO$_2$ and H$_2$O. From the graph, we can draw two conclusions. First, the THC content is decreasing in each respective stroke at exhaust port. This indicates that post-oxidation reaction is taking place. Moreover, it must be kept in mind that mutual cylinder gas dynamic effects are also contributing hence the peaks are observed in every stroke at TC upstream and TWC downstream. Secondly, in the case of THC at exhaust port position, it can also be observed that one peak is rapidly declining around EVO. This is due to when the exhaust valve of cylinder 1 opens, the fresh unburned/burned gases (CO and CO$_2$) from current cycle appeared when effective valve opened. The THC rapidly decline due to higher pressure difference between exhaust valve to port that caused higher velocity hence residing time for the THC in port drastically decreases and FID did not detect enough THC concentration that can be observed in (Fig. 2 (a)). Further, as intake valve opens and overlap started, fresh air pushed the remaining THC towards exhaust port which was remaining inside the cylinder and near exhaust valve and hence THC increased.

The PM measurement by the EEPS 3090 system is done near atmospheric pressure to avoid volatile and nonvolatile particle’s condensation. Also, the ribbon heating system were used in the sample line to avoid the water condensation in the sample line. Moreover, the catalytic stripper (CTS) device was also used to
increase the sample intake temperature to further evaporate SOF, volatile and semi-volatile particles. The gas sample was taken from various positions in the exhaust manifold i.e. exhaust port 1, TC upstream, TC downstream and TWC downstream (shown in Table 2) and passed through the EEPS with the help of in-built pump and dilutor. The gas sample and air ratio was set to 1.5:9.

The temperature of the sample line was set to 350 deg. C with the help of CTS. The experiments were performed as in post-oxidation condition (engine speed- 1600 rpm, load- 160 Nm, valve overlap- 90 deg. and ignition timing- 0 deg. bTDCf) and without post-oxidation condition (engine speed- 1600 rpm, load- 160 Nm, valve overlap- 60 deg. and ignition timing- 0 deg. bTDCf).

![Fig. 2 Fast response emissions (a) THC, (b) CO and (c) CO2 at various exhaust manifold positions and (d) simulated gas velocity at exhaust port and TC upstream in post-oxidation condition.](image)

After measuring of PM concentration, the dilution and particle size channel width correction factors were multiplied as 140 and 0.0625 which gives the total PM (#/cm3) in terms of particulates number (PN) concentration. The total PN concentration with and without post-oxidation condition is presented in Fig. 3. It is shown that PN appeared higher in post-oxidation (90 deg. OL) compared to without post-oxidation (60 deg.) condition. PN increased at port in post-oxidation condition due to injection timing delayed and inhomogeneity in the cylinder increased. The injection timing was selected based on ECU map (70 deg. aTDC suction for w/o post-oxidation conditiona and 110 aTDC suction for with post-oxidation condition). In the case of effective post-oxidation, as we move from port towards TC upstream, firstly, the PN concentration increases and then its decreases as we progress towards TWC downstream. The increments in PN concentration appeared between exhaust port to TC upstream due to the inhomogeneity effects that had occurred and dominated on the post-oxidation phenomena at higher overlap. This happened as mostly O2 resides near port and unburned and burned gases such as, CO, CO2, H2 and PN were pushed forward towards TC upstream [7]. Also, since most of the PN diameters are 100 nm or less, it follows the flow path. Thereafter, PN decreased due to post-oxidation reaction in exhaust manifold as moving from TC upstream towards tail pipe. In the case of 160 Nm, 60 deg. OL, PN appeared lower as the combustion inside the cylinder was near to stoichiometric condition. The geometric distribution of PN with various positions at post-oxidation condition (90 deg. overlap) is presented in Fig 4. It can be noted that the PN concentration is higher with large diameter (approximate diameter 39 nm) because the lower diameter particles were consumed faster in the post-oxidation condition. However, at the lower overlap (60 deg.), both lower diameter (approximate diameter 12 nm) and higher diameter (approximate diameter 39 nm) PN were observed because of not consumption in the post-oxidation phenomena.

Furthermore, the PN analysis was also performed with the ignition timing (SA) tuning. It was noted that the PN appeared higher in the exhaust manifold when ignition timing was set to 0 deg. bTDCf (post-oxidation condition) as shown in Fig. 5. This is due to the combustion phase which was shifted to late and hence the combustion timing decreased that lead to higher unburned gases.
in the exhaust manifold. However, in the case of 5 deg. bTDCf (non-post-oxidation condition), enough time was available for the combustion inside the cylinder and hence less PN came out to the exhaust.

![Graph showing PN geometric distribution with post-oxidation at various exhaust manifold positions.]

Fig. 4 PN geometric distribution with post-oxidation at various exhaust manifold positions.

![Graph showing PN trend with ignition timing (SA) tuning at 1600 rpm, 160 Nm and 90 deg. overlap at various exhaust manifold positions.]

Fig. 5 PN trend with ignition timing (SA) tuning at 1600 rpm, 160 Nm and 90 deg. overlap at various exhaust manifold positions.

![Graph showing comparison of PN geometric distribution with EEPS and TEM at 1600 rpm, 160 Nm and 90 OL.]

Fig. 6 Comparison of PN geometric distribution with EEPS and TEM at 1600 rpm, 160 Nm and 90 OL.

A comparison between two different strategies i.e. TEM (Transmission Electron Microscope) and EEPS was also made for measuring the PN particles in order to determine the accuracy of the results. From Fig. 6, we can see that approximately the results from both strategies came out to be similar at different exhaust manifold positions. This had shown that the measurements conducted by the EEPS device were in a reasonable range.

3.1.2. Gas Temperature

The temperature was measured at the TWC downstream position with the using of fast response two-wire thermocouple. The same operating conditions were selected to analyze the temperature development trend with and without post-oxidation condition. A two-wire thermocouple with probe thicknesses of 25 and 50 micrometers (µm) were used to observe the fast response characteristic of temperature. The probe of the thermocouple was made with the cromel/alumel material that functions on similar principles to that of R-type thermocouple [10]. Since two-wire thermocouple is considered to be an extremely sensitive and fragile device hence proper measures to ensure the device’s safety was also taken into consideration. For this purpose, a protector was designed for the two-wire thermocouple which not only ensured that proper temperature measurement but also sensor’s safety. A schematic diagram of the whole protection system is as shown in Fig 7 (a).

In the measurement, firstly, probe hot junction temperatures at various exhaust manifold positions were recorded and then an analysis to detect the actual gas temperature from probe hot junction temperatures was carried out. By adopting the use of a mathematical model [10], we were able to calculate and predict the actual gas temperature from probe hot junction temperatures that were detected by the two-wire thermocouple.
\[ T_g = T + \tau \left( \frac{dT}{dt} \right) \]  
(VIII)

Where, \( T_g \) is the gas temperature, \( T \) is the probe hot junction temperature and \( \tau \) is the time constant. Based on the above Eq. (VIII), the gas temperature from both probes can be calculated as in Eqs. (IX) and (X).

\[ T_{g1} = T_1 + \tau_1 \left( \frac{dT}{dt} \right) \]  
(IX)

\[ T_{g2} = T_2 + \tau_2 \left( \frac{dT}{dt} \right) \]  
(X)

Theoretically, the gas temperature \( T_{g1} \) and \( T_{g2} \) should be equal. But some difference exists due to the wires of different thermal inertia, diameter and thickness were used hence the use of time constants \( \tau_1 \) and \( \tau_2 \) were introduced in Eqs. (IX) and (X). Hence, the time constant \( \tau_1 \) and \( \tau_2 \) were calculated to overcome this limitation with the use of several measured data using the “least square method” that can minimize the error. The detailed theoretical model and its explanation can be referred in [10]. The purpose of this analysis was to determine and compensate the time constant errors that had encountered during our measurement which will help us to understand better about the actual temperature development and dynamics in the exhaust manifold during post-oxidation condition.

Fig. 8 (a) Two-wire thermocouple probes and gas temperature (b) time constant calculated at 1600 rpm, 160 Nm and 60 deg. overlap (w/o post-oxidation condition).

As we can see from the experimental results (Fig. 8 (a)), we were able to detect four peaks of temperature due to the mutual effects of all the cylinders. We can observe from these results as well that when the exhaust valves of the respective cylinders were opening, their influence was observed at the TWC downstream position. When the exhaust valve of cylinder 1 opened, exhaust gases started to flow out towards the exhaust side due to which the peak rises. This gas was detected from the two-wire thermocouple situated at the TWC downstream position. It was also observed that \( T_1 \) was showing significant peaks whereas \( T_2 \)’s peaks are much smaller. This was due to the thickness of the wire as the 25 µm wire was quick to detect the exhaust gas sample’s temperature (due to the time constant (\( \tau \)) being smaller as shown in Fig. 8 (b)). Furthermore, the gas temperature \( T_{g1} \) and \( T_{g2} \) were also calculated based on the Eqs. (IX) and (X) which is shown in the same Fig. 8 (a). The mathematical model took \( \tau_1 \) and \( \tau_2 \) into consideration and reduced the error and time response limitations that were observed on our actual experimental test data. The trend shows that the gas temperature response is faster than the probes temperature. This appeared due to the time constant effect that was included in the calculation. Hence, it can be stated that by the use of the two-wire thermocouple, it is possible to acquire the fast response temperature dynamics that can possibly help in the resolving of the combustion based temperature development complexity.

In Fig. 9, the probes temperature and calculated gas temperature are presented in both (a) without post-oxidation and (b) with post-oxidation condition for two cycles. From the graphs, it can be observed that the temperature range is smaller in without post-oxidation condition compared to with post-oxidation condition. This is due to the exothermic reaction between \( O_2 \) and \( H_2 \) with CO and THC in post-oxidation condition and hence temperature increased. For the supporting of this statement, the heat of combustion for the CO and THC (CH\(_4\)) consumption with and without post-oxidation were calculated. Then, the increment in
temperature ($\Delta T_{cal}$) that could be enhanced by the post-oxidation reaction of CO and THC was also calculated by the difference in enthalpy of with and w/o post-oxidation condition and temperature relation ($\Delta H = M.Cp\Delta T_{cal}$) assuming adiabatic process. The calculated temperature difference ($\Delta T_{cal}$) seems to be slightly higher than the measured temperature difference ($\Delta T_{meas}$) with and without post-oxidation. The deviation between calculated temperature ($\Delta T_{cal}$) and measured temperature ($\Delta T_{meas}$) appeared due to heat losses was not considered in the calculation. $\Delta H$ indicates the enthalpy increment in post-oxidation, $M$ is the total mass of CO, H$_2$ and CH$_4$, and $Cp$ is the mass averaged specific heat constant at constant pressure.

It was also noted that the four peaks appeared in both cases in a cycle due to the four cylinder combustion and gas dynamics effects. Also, the magnitude variation appeared higher in the case of with post-oxidation condition. This had appeared due to the higher in-homogeneity in secondary combustion that leads to unstable post-oxidation in the exhaust manifold. This can be improved if the mixing of unburned gas species with scavenged O$_2$ will be able to enhanced in the exhaust manifold [7]. The influence of the post-oxidation in the temperature development was also observed. This shows that the enthalpy generated by the post-oxidation not only increased the temperature but also the rising rate of temperature. From Figs. 8 and 9, it can be also stated that the response time of the thermocouple is enough to analyze the cylinder-to-cylinder influence on gas temperature. The four peaks shows the mutual cylinder effects on the gas temperature. The authentication of the temperature measurement by the two-wire thermocouple was also done with the comparing of data with K-type thermocouple. In this case, the mean value of the calculated gas temperature from two-wire thermocouple was compared with the K-type measured data. Slight deviation was observed in the lower overlap (w/o post-oxidation condition) and overall results of two-wire thermocouple matches with the K-type data and deviation is below 5%. The deviation might have appeared due to the extrapolation of calibration range and different material properties of two-wire (R-type) and K-type thermocouple.

### 3.2. Transient State Analysis

Fast response devices such as HFR500 Fast FID (for THC), NDIR500 (for CO and CO$_2$) and two-wire thermocouple (for gas temperature) were used for the gas emissions and temperature at TWC downstream position for transient characteristics during zone shifting from post-oxidation to non-post-oxidation and vice versa. The experiments were performed in such a way that the mode was switched from post-oxidation to non-post-oxidation zone and vice versa by the intake valve changing, assuming the time delay by the VVT and transportation is insignificant as shown in Fig. 10. The overlap changed with intake valve (IV) tuning is shown in Fig. 11.

It can be seen that initially, the engine is running in the post-oxidation condition (at 90 deg. overlap) and it shifted to non-post-oxidation zone at 10$^{th}$ second and then further it shifted from non-post-oxidation to post-oxidation zone at 41$^{st}$ second. The engine speed and ignition timing were kept to constant at 1600 rpm and 0 deg. bTDCf, respectively. As intake valve changed from 90 deg. to 60 deg. overlap, the load was changed based on the overlap by the ECU command.

![Fig. 10 Transient mode intake valve tuning.](image1)

![Fig. 11 Valve overlap with intake valve tuning.](image2)

The experimental results of emissions and temperature changes in the transient response with intake valve tuning are presented in Fig. 12. It can be noted that the CO concentration decreases as zone shift from post-oxidation (90 OL) to non-post-oxidation (60 OL) due to the in-cylinder AFR approaches from rich towards stoichiometric condition. The CO$_2$ and THC concentration shows reverse trend as of CO. Again, when zone shifted from non-post-oxidation to post-oxidation, CO increased. It was also noted that the high fluctuation in CO, CO$_2$ and THC were observed in the post-oxidation condition due to the unstable secondary combustion that perhaps occurred due to the improper mixing between scavenged O$_2$ and unburned gases in the exhaust manifold. However, when zone shifted from non-post-oxidation to post-oxidation, initially, CO gives sharp increment and then its level gradually lowers as time passes. Similarly, CO$_2$ first decreased sharply and then it gradually increases as time passed. This phenomenon appeared due to the time delay in the actuation of the post-oxidation. Initially, the sharp increment of CO and
decrement of CO\textsubscript{2} appeared due to the exit of in-cylinder unburned/burned gas species level as there was no post-oxidation reaction actuated yet. However, as time passes, the CO and THC decreased and CO\textsubscript{2} increased due to the favorable environment for post-oxidation. In this reaction, the CO and THC gradually reacts with O\textsubscript{2} and OH radicals and forms CO\textsubscript{2} and H\textsubscript{2}O. As a result, enthalpy was generated that lead to higher temperature in the exhaust manifold. The transient response of the two-wire probe temperature are plotted in Fig.12 (c). It can be seen that the thinner wire (25 μm) shows higher fluctuation compared to thicker wire (50 μm) wire. This appeared due to the thinner wire (25 μm) as it possess better response. When, IV changed from 90 deg. to 60 deg., the engine operation shifted from post-oxidation zone to non-post-oxidation zone and hence temperature decreases. In this case, we can also observe that the fluctuation is very low compared to post-oxidation condition. This appeared because in the post-oxidation phenomena still unstable combustion is happening due to the improper mixing of O\textsubscript{2} and unburned gas in the exhaust manifold that leads to higher temperature variation. Again, when IV changed from 60 deg. to 90 deg., the zone shifted from the non-post-oxidation to post-oxidation. However, it takes some time due the delay in the chemical reaction between O\textsubscript{2} and unburned gas species (CO, THC and PM) that can be observed in the Fig.12. It was also noted that the visible effects of the post-oxidation on emissions and temperature was observed at the TWC downstream due to the actuation of chemical reaction that happened due to better mixing and longer reaction time. However, at the exhaust port and TC upstream, the emissions appeared mostly comes from the in-cylinder combustion. There is a minor influence of the post-oxidation at these positions due to the inhomogeneity effects that appeared and dominated on the post-oxidation between exhaust port and TC upstream. The actuation time delay of the reaction was also calculated at TWC downstream based on gas species (CO, CO\textsubscript{2} and THC) and temperature variation with non-post-oxidation to post-oxidation zone shift as shown in Fig. 12. It can be noted that when zone shifted from non-post-oxidation to post-oxidation by the intake valve tuning, the actuation time of the chemical reaction appeared approximately 80 cycles (6s). This time delay represents the time taken by the gas species to react with each other and contribute towards temperature development.

4. Conclusions

A detailed investigation of scavenging-based post-oxidation phenomena focused on gas and PM emissions and gas temperature were performed. The following conclusions can be drawn form this research,

- It was noted that the temperature (two-wire thermocouple) and gas measurement (NDIR500 and HFR500 fast FID) instruments has enough response to investigate the post-oxidation phenomena on the exhaust emissions and temperature as it can reflect the actual gas dynamics in the exhaust manifold that can possibly help in the resolving of the combustion based temperature development complexity in post-oxidation phenomena.

- It was noted that the gas and PN emissions appeared higher at the exhaust port due to the in-cylinder rich combustion in the post-oxidation condition. Then, the gas and PN emissions decreased from TC upstream onwards as effective post-oxidation occurred at this stage and as a consequence temperature increased.

- It was noted that the post-oxidation does not appear effectively at the exhaust port and TC upstream as inhomogeneity effects had dominated on it. However, it appeared visibly at TWC downstream.

- When zone shifted from non-post-oxidation to post-oxidation, initially, CO gives sharp increment and then its level gradually lowers as time passes. Similarly, CO\textsubscript{2} first decreased sharply and
then it gradually increases. This phenomenon appeared due to the time delay in the actuation of the post-oxidation.
• Initially, the sharp increment of CO and decrement of CO2 appeared due to the exit of in-cylinder unburned/burned gas species level as there was no post-oxidation reaction actuated yet. However, as time passes, CO and THC decreased and CO increased due to the favorable environment for post-oxidation.
• The actuation time delay of the post-oxidation was calculated based on the emissions concentration changes and temperature development as approximately 80 cycles (6s).

This paper is written based on a proceeding presented at JSAE 2021 Annual Congress.

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Acknowledgments
This research work is the result of research project sponsored by the Research Association of Automotive Internal Combustion Engines (AICE) including the subsidy from the Ministry of Economy, Trade and Industry (METI). Also it was carried out as a collaborative research program with the Research Association for Combustion Engines (FVV: Forschungsvereinigung Verbrennungskraftmaschinen e.V.), Frankfurt, Germany. The project post-oxidation (No: 234 EN) is co-funded by the German Ministry of Economics and Energy (BMWi) in the frame of the CORNET program via AiF e.V. and performed in cooperation with Institut für Verbrennungsmotoren und Kraftfahrwesen (IVK), Stuttgart University. The authors gratefully acknowledge the concerned personnel and contributions of Mr. Kazuki Endo (Meiji Univ.) for PM measurement and discussion and Mr. Rodolfo Tromellini and Mr. Jan Przewlocki (Stuttgart Univ.) for simulation calculation and data analysis. Moreover, we would like to thanks to Tokyo Dylec Corp. for providing the catalytic stripper instrument during research.