ABSTRACT: GPF system is expected as a solution for PN/PM regulation which is becoming stricter in gasoline engines. The management system of GPF temperature and residual soot amount in GPF is necessary for the GPF system to execute GPF regeneration control safely and effectively. Therefore, in this study, logics were investigated for GPF temperature and amount of residual soot, and the logics were verified by a test vehicle. This paper describes the development process and verification results.

KEY WORDS: Heat engine, Particulate filter, Design/control, GPF regeneration control (A1)

1. Background

In recent years, various regulations on exhaust emissions and fuel economy are becoming stricter worldwide. In the case of gasoline engines, regulations concerning soot emissions from engines (PM/PN regulations) have been added [1], and GPF (Gasoline Particulate Filter) is attracting attention as a solution.

GPF is a filter that traps soot contained in exhaust gas and has the effect of depositing soot in the porous body of the filter and reducing soot emissions in the exhaust gas. GPF regeneration control is required for vehicles equipped with GPF to burn soot at an appropriate time depending on the amount of soot remaining in GPF. This is because excessive accumulation of soot in GPF can cause filter burnout or clogging.

In particular, the estimation of GPF temperature and the residual soot in GPF are essential for implementing safely and effectively GPF regeneration control. In this study, estimation logics of residual soot and GPF temperature were constructed and tested in-vehicle. Furthermore, this study reports the development process and verification results.

2. Overview of GPF control

2.1 GPF control

Figure 1 shows the entire units of GPF control.

(1) Units for accumulated soot estimation

These units estimate amount values of accumulated soot and amount of ash load remaining in the GPF. The internal control units are shown below.

① Ash load estimation unit
② Calculation of filter efficiency unit
③ Soot emissions estimation unit
④ Accumulated soot estimation unit

(2) Units for burned soot estimation

These units estimate amount of burned soot in GPF based on information such as oxygen concentration in GPF and GPF temperature. The internal control units are shown below.

⑤ Oxygen concentration estimation unit
⑥ Burned soot estimation unit
⑦ GPF temperature estimation unit

(3) Unit for residual soot estimation

This unit calculates amount of residual soot in GPF based on the difference between amount of accumulated soot and amount of burned soot which are described above⑤.

(4) Unit for GPF regeneration control

The regeneration control unit ① calculates each command value of GPF regeneration control based on the calculated amount of residual soot in the GPF. The GPF regeneration control is described in detail in the next chapter.

2.2 GPF regeneration control

GPF regeneration control has two control methods: passive control and active control based on GPF conditions and engine operating
conditions. Table 1 shows the features of the two control methods

1) Passive regeneration method
Fuel cut supplies oxygen required for GPF regeneration. This method does not intervene in the engine control strategy. It uses natural heating of the GPF due to the exhaust gas to obtain the necessary GPF temperature regeneration conditions. The possibility to regenerate depends on the availability of fuel cut off.

2) Active generation method
Slightly lean operation supplies oxygen for GPF regeneration. When the GPF temperature is lower than the regeneration temperature, the exhaust temperature is raised by ignition retard to target GPF temperature.

Figure 2 shows a time chart of GPF regeneration control. The passive regeneration control will be described using the first half of the time chart as an example. When the GPF temperature reaches the regenerable temperature at high engine load conditions such as suburban driving, the fuel cut (F/C) during deceleration supplies oxygen to GPF and accumulated soot is burned in GPF.

On the other hand, when the engine load is low and the frequency of fuel cut is low during such as traffic congestion, the active regeneration control can be implemented. The latter half of the time chart shows this scene. When the GPF temperature is below the regenerable temperature in a situation that GPF has large amount of accumulated soot, active regeneration control raises the GPF temperature to the regenerable temperature by ignition retard and supplies oxygen to the GPF by slightly lean operation. However, this comes with the disadvantage of NOx breakthrough.

Table 1. GPF regeneration control
(Passive method/Active method)

| Regeneration Method | Passive Regeneration | Active Regeneration |
|--------------------|----------------------|---------------------|
| O2 Supplying Method | Fuel Cut             | Slightly Lean (λ=1.05) (Option) |
| Warming GPF Method  | Exhaust gas temperature depends on operation points | Raising exhaust gas temperature by ignition retard |

3 Study of soot emission estimation logic

3.1 Examination of soot emission estimation logic
The soot emission estimation logic estimates the amount of raw soot emissions from engine exhaust ports. This study evaluated the performance of two soot emission estimating methods that are the MAP method based on estimation maps and the physical model method. Figure 3 shows features of each method.

![Estimation methods of soot emission](image)

| Method               | MAP method | Physical model method |
|----------------------|------------|-----------------------|
| Feature              |            |                       |
| Simple logic         |            | Complicated logic     |
| Short calc. time     |            | Long calc. time       |
| Many man-hours for    |            | A few man-hours       |
| calibration process  |            | High versatility      |

3.2 Establishment of soot emission estimation logic

Figure 4 shows the MAP method. In the MAP method, various engine tests of engine-out soot emissions were conducted, and MAP values were calibrated by the results. This logic has MAPs which compensate transient change of engine operations. Therefore, the logic is able to deal with estimation error due to transient operation and various environments by adding various corrective MAPs such as water temperature correction and air-fuel ratio correction based on the MAP of soot emissions at steady conditions.

![MAP method of PM emission estimation](image)

In addition, the physical model was examined. Figure 5 shows the overview of the physical model. The physical model considers a rich mixture and adhering fuel on the cylinder wall as main factors for the generation of soot. Furthermore, this model calculates soot emissions by using equations of probability distribution of the mixture $P_{mix}$ and the probability distribution of adhering fuel on the cylinder wall $P_{ad}$. [2]
This model integrates the probability distribution of the gas mixture and the probability distribution of adhering fuel on the cylinder wall to calculate the total probability density function $P(Z)$ in the cylinder by introducing the fuel deposition rate $\alpha$ shown in Eq (2.1).

$$\alpha [-] = \frac{M_{ad}}{M_{total}}$$ (2.1)

$$P(Z) = (1 - \alpha)P_{mg}(Z) + P_{ad}(Z)$$ (2.2)

$M_{ad}$ means the amount of fuel adhered to the engine wall [kg], $M_{total}$ means the total amount of fuel injected [kg], and $Z$ means the mass fraction [-]. In addition, PN emissions are calculated by using the following formula for time variation of soot.

$$\frac{d[PN]}{dt} = \bar{w}_{PN}$$ (2.3)

$[PN]$ means the PN number concentration [#m$^{-3}$], and $\bar{w}_{PN}$ means the PN average reaction rate [#m$^{-3}$/s]. $P_{mg}$ means the total probability density function $P(Z)$. Additionally, PN reaction rate $w_{PN}$[#m$^{-3}$/s] are substituted, and Eq. (2.4) is derived.

$$\bar{w}_{PN} = \int_{0}^{1} P(Z)w_{PN}dZ$$ (2.4)

Eq. (2.4) calculates PN emissions taking into account the distribution of fuel in the cylinder.

The reason was considered that the physical model equation did not accurately reproduce the increase of soot emissions during a transitional period at engine high loads, which was likely to occur in acceleration. In order to improve the accuracy, it is necessary to review the physical model. Therefore, for the next step, this study decided to use MAP method for the estimation logic of soot emissions.

### 4. Examination of residual soot estimation method

#### 4.1 GPF Operation Estimation Model

This study examined two GPF internal calculation models to construct the residual soot estimation logic (Fig. 7). One model is a simple GPF model that facilitates the application process and treats the distribution of soot deposition and temperature in the filter as uniform.

A divided GPF model was also examined. The calculation portions of this model were divided to take the distribution of soot deposition and temperature into consideration for improving calculation accuracy. The GPF model was divided into three sections, and the section 1 was set to an unequal length shorter than sections 2 and 3. Figure 7 shows the features of each model.
4.2 GPF temperature estimation logic

Figure 8 shows an overview of the GPF temperature estimation logic of the simple GPF model. The GPF temperature estimation logic estimates the GPF temperature based on the exhaust temperature measured by a thermocouple on the upstream of the GPF. Specifically, this logic estimates the GPF temperature by performing the offset process and the primary delay process. The offset values was the steady-state difference between the exhaust temperature and the GPF temperature. Primary delays were calculated by using the difference between transient phases of exhaust temperature and the GPF temperature. Furthermore, the amount of temperature increase due to regeneration was added to this logic.

Figure 8 shows the estimation logic of the divided GPF model for GPF temperature. This logic divides the model into sections 1-3. It calculates estimated GPF temperatures from section 1 through sections 2 and 3 in sequence based on the temperature estimation logic of the simple GPF model for soot section individually. Furthermore, the logic calculates the average value of three GPF estimated temperatures. Finally, the average value means estimated temperature of overall GPF.

5. Performance Verification of the estimation logic using the actual engine test

5.1 GPF Specifications and Installation on Experimental Vehicles

Table 2 shows the specifications of GPF filter used in this study, and Figure 12 shows the overall view of GPF and its case. The case was divided into four parts with bolts so that the filter is able to be easily replaced when GPF gets damaged by burnout. Additionally, a thermocouple connector mount, measurement devices for exhaust compositions and mounting brackets for pressure sensors were welded on the surface of the case.

Figure 13 shows the layout of the GPF mounted on the vehicle. In general, there are three layouts for mounting GPF on vehicles. One is
under floor, which is mainly mounted downstream of catalyst, and the others are closed couple which is mounted near to be catalyst and four-way catalyst which a catalyst is combined with GPF. This study adopted the under floor, which was easy to control GPF temperature for preventing GPF burnout.

| Material          | DHC-680 (uncoated) |
|-------------------|--------------------|
| Diameter          | 118.4 mm           |
| Length            | 100 mm             |
| Wall Thickness    | 0.157 mm           |
| Cell Density      | 220 cpsi           |

Table 2. Specification of filter made by NGK

5.2 Temperature estimation and verification (at engine bench)

This study verified the estimation accuracy of the GPF temperature estimation logic of the simple model and the divided model by using the engine bench. The verification condition of this test was steady-state operation during a certain period of time, and F/C was performed after the GPF temperature was raised up to predetermined value. Afterwards the temperature change was measured when the GPF was cooled down, and GPF temperature decreased from the predetermined value by cool down behavior. Figure 14 shows positions of thermocouples on GPF. Each thermocouple was mounted on each section. Actual temperature of overall GPF was calculated by the average value of three actual temperature values.

Figure 15 shows the temperature estimation results of the simple model at the initial temperatures of 650°C and 700°C. Additionally, figure 16 shows the temperature estimation results of the divided model at the initial temperatures of 650°C and 700°C. The estimated temperature error of the simple model was 20°C or more. However, the estimated temperature error of the divided model was within 10°C. Although the number of calibration man-hours increased, the accuracy of the divided model was improved by division of computing parts and partial calibration.
5.3 Residual soot estimation and verification results (at engine bench)

Figures 17 and 18 show the verification results of the residual soot estimation of simple model and the divided model. Table 3 shows the regeneration conditions of this verification test. The verification method accumulated a certain amount of soot in GPF and regenerated GPF at 650°C and 700°C. Afterwards the estimated residual soot was verified by calculating maximum error values of results of regeneration temperature at 650°C and 700°C. The estimation error (full scale ratio) of the simple model was 23% F.S. at 650°C and 43% F.S. at 700°C. That indicated that the estimation accuracy of the simple model was insufficient.

On the other hand, the estimated error of the divided model was 12% F.S. at 650°C and 4% F.S. at 700°C. The estimation accuracy improvement effect was confirmed by the divided model similar to the GPF temperature estimation logic.

Table 3. Regeneration conditions

| Regeneration Temp[℃] | Engine Speed[rpm] | Air Flow[g/s] | Operation Time[sec] |
|----------------------|-------------------|--------------|---------------------|
| 650                  | 3000              | 35           | 200                 |
| 700                  | 2400              | 45           | 200                 |

Fig17. Verification of the estimated residual soot amount with the simple model

Fig18. Verification of the estimated residual soot amount with the divided model

5.4 Transient verification results (actual vehicle driving)

Based on the above stated results, the soot raw emission estimation logic adapted the MAP method, and GPF internal calculation logic adapted the divided model to construct the GPF temperature estimation logic and the residual soot estimation logic. In addition, these estimation logics were implemented in the actual vehicle control system and was verified by WLTC driving cycle.

Figure 19 shows the estimated GPF temperature and residual soot in the WLTC hot mode. In this verification test, there was no regeneration due to low GPF temperature. Furthermore, it was not possible to measure residual soot with a balance, because very low soot is only accumulated in GPF during this driving cycle. Therefore, the actual amount of residual soot was calculated by integrated PM values of PM sensor after this tests. The maximum estimated error of GPF temperature estimation was 22.3°C, and the estimated mean error was 4.9°C. The estimated error (full scale ratio) of the residual soot estimation was 19.4%.

Figure 20 shows the estimation results of GPF temperature and residual soot in the WLTC cold mode. The maximum estimated error of GPF temperature was 23.1°C and, the mean estimated error was 5.7°C. The estimated error of residual soot (full scale ratio) was 21.4%.
5.5 Transient verification results and discussion

The average estimation error of the temperature estimation in WLTC hot mode and cold mode was less than 10°C, and the results indicated generally good estimation accuracy. However, the maximum error was about 23°C because there were sudden changes of temperature, and estimation logic did not follow actual value in some places. The solution of improving the accuracy is readjusting the time constants of the first-order delay (see LPF fig.8). It was found that when soot emissions increased due to rapid changes of load conditions such as acceleration, there was a gap between actual values and estimated values of residual soot compared to steady states. On the other hand, the verification process turned out difficult due to very low residual soot amounts. Improvement measures include investigation of the cause for the increase of soot emissions in the actual engine and the addition of the soot emission transient correction logic corresponding to the cause. Based on these results, we plan to implement the further calibration for the MAP method and the divided model to improve the accuracy estimation. As the other way to improve the accuracy, we can increase the number of divisions of the divided model. Furthermore, we can improve the formula for the physical model of soot raw emissions logic.

6. Conclusion

The vehicle verification for the soot residual estimation logic and the GPF temperature estimation logic, which were essential for implementing safely and effectively GPF regeneration control, was conducted. Summarizing, the following conclusion was reached.

1. Accuracy verification of the physical model and MAP method for soot emission estimation logic was carried out by using the actual engine. The accuracy of the physical model for soot emission at transients needs to be improved. On the other hand, the accuracy of the MAP method was better than the physical model in this evaluation.

2. The results of the accuracy verification for the simple model and the divided model showed the effect of improving the estimated accuracy by applying the divided model which was confirmed in the residual soot estimation logic and the GPF temperature estimation logic.

3. The results of accuracy verification in WLTC mode of residual soot estimation logic and GPF temperature estimation logic, which combined soot emission estimation logic (MAP method) and GPF internal calculation model (divided model) showed the following results.

   WLTC hot: The error of residual soot estimation was 19.4%.
   The average error of GPF temperature was 4.9°C.

   WLTC cold: The error of residual soot estimation was 21.4%.
   The average error of GPF temperature was 5.7°C

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