Black Smoke Removal System for Diesel Forklift

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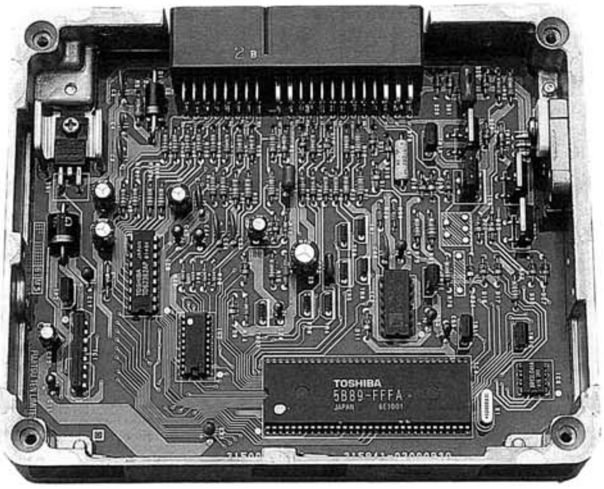

Diesel engine is prevalently used for transportation, industry and generation of electric power, because of low fuel consumption and high generating power characteristics.
Diesel engine which has overcome the point of a great deal of nitrogen oxides in its exhaust gas caused by high combustion temperature with using EGR (Exhaust Gas Recirculation) system, recently attracts attention as an environmental engine not to promote earth warming for the reason of less carbon dioxide due to low fuel consumption.
Meanwhile, diesel engine has an issue of black smoke (diesel particulate) in the exhaust gas, and demand of black smoke reduction is getting increase especially for indoor operation. We would like to introduce the black smoke removal system for forklift so that we developed and made it for mass-production.

1. Introduction

With the prevalence of automobiles, automotive emission regulations are becoming stricter every year. To meet these regulations, Fujitsu TEN has developed and produced emission control, electronic fuel injection (EFI), and diesel exhaust gas recirculation (EGR) computers in cooperation with automotive manufacturers. To protect the global environment, these days, the automotive industry is determining voluntary regulations which are even severer than the governmental ones, and are expecting an ultimate system beyond the existing regulations.

The automotive manufacturers have been carrying out intensive research since the 1980s into diesel vehicles to remove their black smoke, but have not no general-purpose system has been completed yet because of technical difficulties. For limited uses (such as forklifts), the diesel particulate filter (DPF) with maintenance is available in some overseas markets although its trapping mass is not prescribed and manual intervention is required for regeneration.

We have developed a control system for a forklift as a DPF system with maintenance, and have successfully commercialized a system that can completely remove black smoke emitted from a diesel vehicle.

2. System outline

The system traps black smoke emitted from a diesel engine with a DPF and displays the trapped mass on an LED panel mounted in front of the driver's seat. By monitoring the mass, the driver burns the particulate to regenerate the DPF. For regenerating, the driver should turn the engine off, connect an external AC power supply to the vehicle, and press the Regeneration switch on the operator panel. Regenerating will be completed in about one hour.

This system burns particulate using heat from the heater and air from the blower. By detecting the filter temperature with the temperature sensor and the flow rate with the flow rate sensor, the system controls combustion to achieve the preset value.

During regeneration, the starter relay is controlled to prevent the engine start. If a system error occurs, the warning buzzer is sounded, the fail-safe mechanism activated, and a diagnostic code (error code) is displayed on the LED panel (Figures 1 and 2).

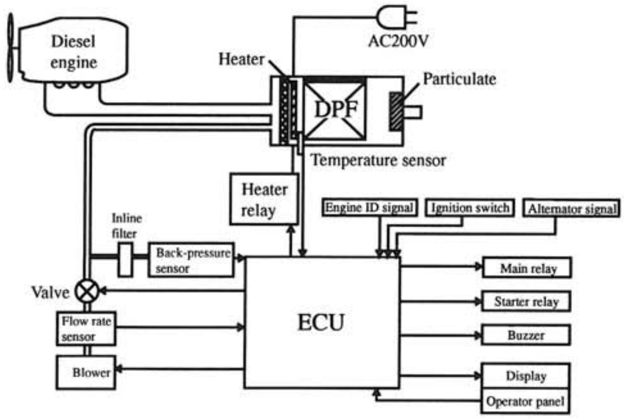

Figure 1. System diagram of DPF

2.1 Principle of removing black smoke

We adopted a porous honeycomb DPF made of a ceramic material called cordierite. This automotive DPF has a high trapping efficiency, a low pressure loss, and a high heat resistance. The porous cell wall of the DPF built into the exhaust muffler traps particulate in black smoke emitted from a diesel engine. The DPF is protected from engine vibrations by a heat-resistant exhaust-sealing cushion material. (Figure 3)

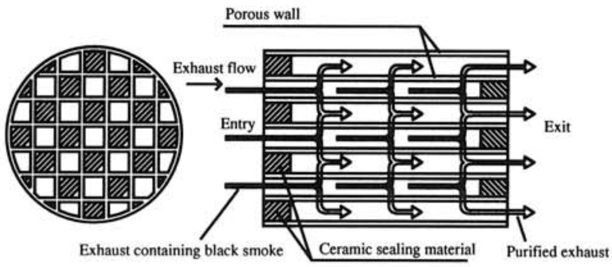

Figure 3. Structure of diesel particulate filter

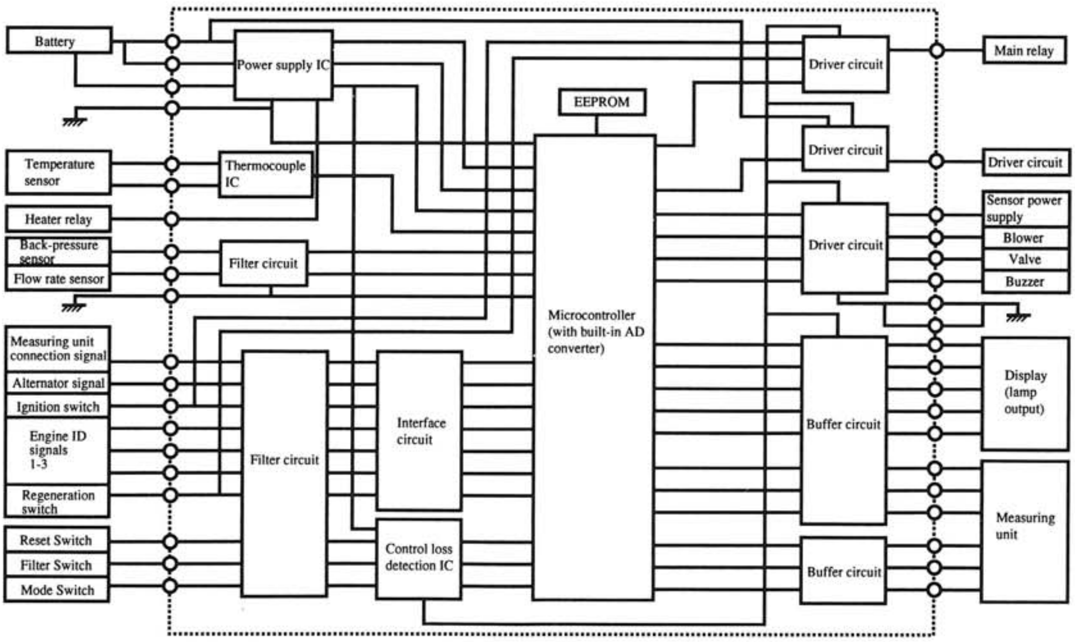

Figure 2. Block diagram of electronic control unit

2.2 Detection of trapped mass

2.2.1 Trapped mass estimation technology

To ensure the long life of the DPF, the maximum filter temperature at regeneration should be limited. The accurate estimation of the particulate mass trapped by the DPF is important for this purpose. So far, a method using exhaust back-pressure corrected by the air intake into the engine and an electromagnetic method have been discussed. A forklift keeps the maximum number of engine revolutions constant and usually operates in this engine operation mode. To simplify the system, we only adopted the back pressure at the maximum speed for trapped mass estimation control using the forklift operation mode.

2.2.2 Trapped mass estimation method

The DPF trapping status is estimated by the electronic control unit (ECU). The ECU estimates the trapped amount by interpolative calculations using a signal from the back-pressure sensor and the one-dimensional constant maps stored in the ECU. For this calculation, the maximum back-pressure sensor output (peak hold value) stored in memory is used.

The back-pressure sensor is an absolute pressure sensor used for automotive EGR. The pressure-sensitive part of the sensor consists of a semiconductor diaphragm. An inline filter (also used in automobiles) is installed in the sensor pipe to protect the sensor from contamination by diesel particulate and other substances. This sensor is not destroyed even when the water condensed from exhaust is frozen. This epoch-making sensor has its own filter for high resistance against contamination (Figure 4).

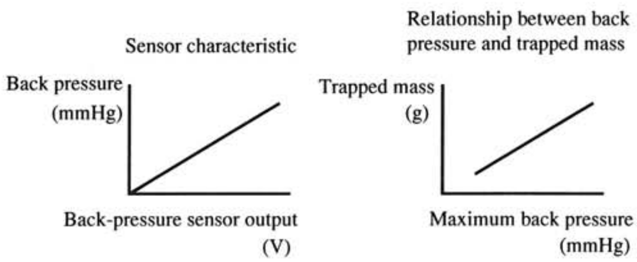

Figure 4. Trapped mass inference by back-pressure sensor

2.2.3 Trapped mass display method

The trapped mass estimated by the ECU is displayed. When the ignition switch is turned, the ECU is activated and the LED display enters check mode. The green, yellow, and red LED lamps indicating the trapped mass and the red LED warning lamp light for one second. Then the three trapped mass indicator lamps light according to the trapped mass stored in the ECU memory. As the trapped mass increases, more lamps are lit in the order green, yellow, and red. The DPF cannot be used unless regenerated by burning the particulate. Regeneration is required when the yellow lamp is lit.

If the red lamp is lit, burning the particulate may crack or melt the DPF because of abnormally high temperatures. Before the red lamp lights, a warning not to make the DPF too dirty to regenerate is given in two stages. Even after the yellow lamp lights, the DPF can be used for four to eight more hours (depending on the engine model, aging, vehicle weight, and acceleration). Therefore, the DPF can be regenerated after a job, during a break, or at the end of the day.

This trapped mass estimation has enabled the DPF to be used for a long time until the regeneration limit. The trapping status display on the LED panel and the buzzer remind the driver to regenerate the DPF.

2.2.4 Vehicle model identification method

From the combination of harness EG signals 1 to 3 (high or low level), the system identified the vehicle model. If the number of signal lines is n, the system can handle up to 2^n vehicle models. The identification result is stored in the EEPROM of the ECU. Each time it is activated, the system collates the identification result with the harness information. If they do not match, the system warns of a failure. If it is difficult to tell which information is correct (e.g., when the harness is half-disconnected), the system uses a map of a model which makes mass detection early to prevent overtrapping. The priority is model 1 > model 2 > model 3. (Figure 5)

3. Regeneration

3.1 Procedure

If particulate is trapped from black smoke beyond a certain level, the trapped particulate must be removed and the DPF pressure loss must be returned to the original level. This regeneration procedure is as follows:

① Stop the vehicle where an external power supply is available and turn the ignition switch off.
② Plug the external power supply (200 VAC) into the power connector at the right end of the interface panel.
③ Press the Regeneration switch on the display panel.

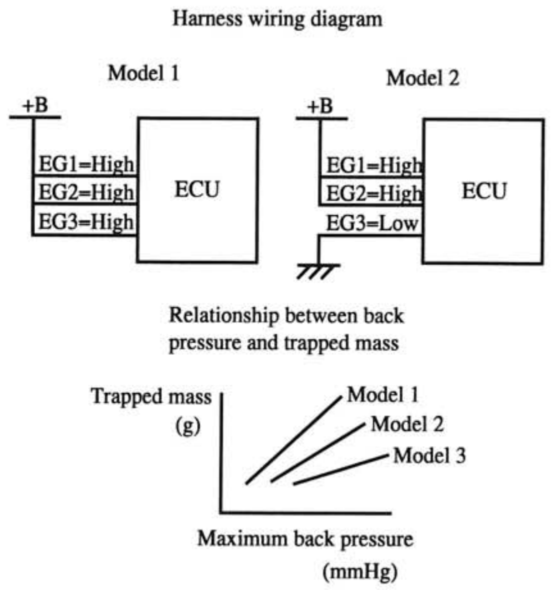

Figure 5. Trapped mass inference by wiring harness EG signal

④ The buzzer sounds for 0.5 seconds and the LED lamps on the display panel all light, excluding the alarm lamp, to indicate regeneration has started.
⑤ The trapped mass indicator lamps go out one by one.
⑥ Once the DPF has been regenerated, the ECU power automatically goes off. This regeneration requires about one hour. If the power cable is unplugged or the power supply fails during regeneration, the warning lamp lights and the buzzer sounds for five seconds.

3.1.2 Operation mechanisms

This section explains the operation mechanisms of the ECU and functional parts during regeneration.

① The heater relay is turned on to apply power to the heater.
② The valve is opened and the blower is turned on to supply air necessary for combustion.
③ By detecting the actual air flow rate with the flow rate sensor, the blower is controlled.
④ By detecting the filter temperature with the temperature sensor, the heater relay is controlled to keep the optimum temperature for burning particulate.

The above feedback control based on the temperature and flow rate sensors regulates particulate burning. The stable supply of combustion energy not dependent on the supply voltage enables combustion heat control and fine adjustment of the air flow rate. This prevents the DPF being damaged from overheating.

Under this control, the blower first supplies air at a high flow rate to preheat the DPF. Once the DPF has reached the particulate ignition temperature, the flow rate is reduced to control the heater temperature. After combustion, the flow rate is increased again to cool the DPF and prevent a thermal shock by engine startup. (Figures 6 to 8)

3.1.3 Valve drive method

To enhance the endurance of the valve and ensure its operational accuracy, feedback duty control by the battery voltage keeps the average applied voltage constant. Thus a low-cost valve whose rated voltage is lower than the battery voltage can be used. During regeneration, stable operation can be maintained by increasing the duty ratio, even when the battery voltage goes down (Figure 9).

Drive duty ratio = target applied voltage/battery voltage

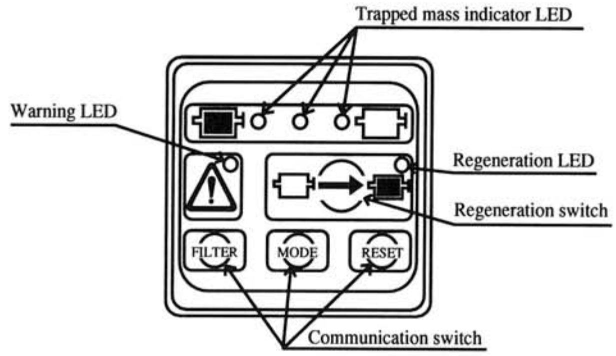

Figure 6. Display

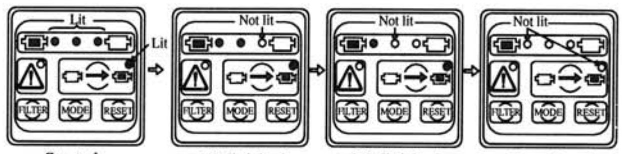

Figure 7. Indication while regeneration

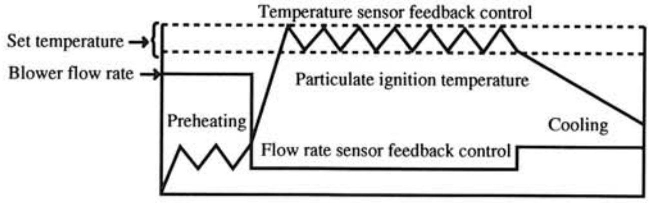

Figure 8. Pattern of particulate combustion

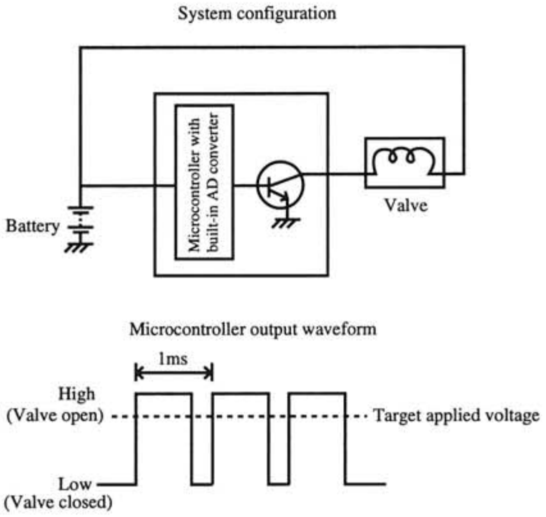

Figure 9. Valve driving method

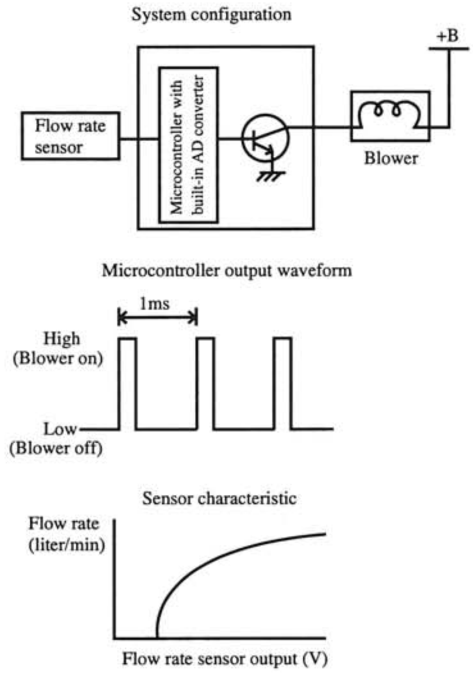

Figure 10. Blower driving method

3.1.4 Blower driving method

Even when the same voltage is applied to the blower, the discharge air flow rate varies with the vehicle because the ventilation resistance differs. The air flow rate also differs depending on transitional changes (aging). To keep the air flow rate stable, we adopted feedback duty control using a hot-wire flow rate sensor. Under this control, the secondary air can be supplied with high precision during regeneration for smooth combustion. (Figure 10)

Driving duty ratio = basic duty + corrected duty

(The following processing is done every 500 ms.)

[Target air flow rate > flow rate measured] → Corrected duty 0.5% up

[Target air flow rate < flow rate measured] → Corrected duty 0.5% down

3.2 Self-diagnosis method

We adopted microcontroller-controlled diagnosis (self-diagnostic function). The microcontroller diagnoses the system and parts and gives the results via the display and buzzer. This function prevents a system error from inducing an engine problem or part failure. If the microcontroller detects a fault by self-diagnosis, the warning LED lights and the buzzer sounds for five seconds. The fault position can be displayed by pushing the Mode switch on the display panel.

The three trapped mass indicator lamps indicate the system fault position with a diagnostic code at 10-second cycles (Display 1 for seven seconds and Display 2 for three seconds). If no system fault is detected, the three trapped mass indicator lamps are off for 10 seconds. (Figures 11 and 12 and Table 1)

4. Conclusion

We mounted the newly developed system on a 2Z engine for Toyota forklifts. The new system reduces the black smoke density from 20% to 0% (measured with a Bosch smoke meter at free acceleration). One type of ECU could be applied to three types of engines: 2Z, 1DZ (domestic specifications), and 1DZ (European specifications). From now on, we will develop a general-purpose system applicable to other types of engines.

This development project was carried out jointly with Toyoda Automatic Loom Works, Ltd. We thank to Toyota Motor Corp. and affiliates for their cooperation.

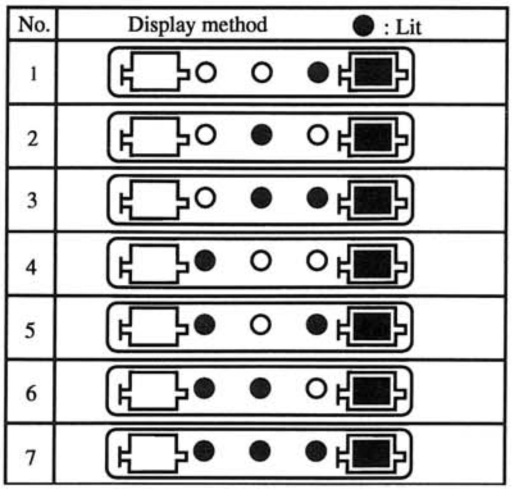

Figure 11. Comparative table of code number

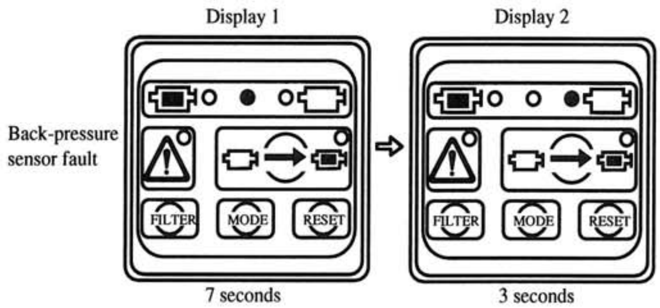

Figure 12. Indication of diagnostic code

Table 1 Diagnostic codes

The microcontroller displays the following diagnostic codes not only to warn of faults but to ensure fail-safe operations.

Diagnostic code		Faulty item	Purpose	Fail-safe measures
Display 1	Display 2			
1	1 to 5	Heater or temperature sensor	Preventing a vehicle fire by overheating	Regeneration prohibited (during regeneration) Heater relay off
2	1, 2	Back-pressure sensor	Preventing engine stalling by DPF overtrapping	Standard value (atmospheric pressure)
3	1	Alternator harness signal	Preventing overtrapping or engine stalling by DPF regeneration failure	
4	1 to 3	Blower or flow rate sensor	Preventing an abnormal flow rate from causing sparks	Regeneration prohibited (during regeneration) Flow rate feedback control of blower output prohibited
5	1, 2	DPF	Preventing engine stalling by DPF overtrapping	
	3, 4	Harness	Preventing engine stalling by DPF overtrapping	Control for the model of the earliest trapping detection adopted
6	1	ECU internal memory	Preventing engine stalling by DPF overtrapping	
7	1	Battery	Preventing abnormal control by dead battery	Regeneration prohibited (during regeneration or generation

<References>

1) Y Kumagai,A Particulate Trap System Using Electric Heating Regeneration for Small Trucks, SAE Paper 920141.
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