Research Report

Achieving Lower Exhaust Emissions and Better Performance in an HSDI Diesel Engine with Multiple Injection

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Abstract

The effects of multiple injection on exhaust emissions and performance in a small HSDI (High Speed Direct Injection) Diesel engine are investigated. It is possible to increase the maximum torque, which is limited by the exhaust smoke number, while decreasing the combustion noise under low speed, full load conditions by advancing the timing of the pilot injection. Dividing this early-timed pilot injection into a series of smaller injections serves to further decrease the noise while suppressing the increase of HC emission and fuel consumption. These effects result from the enhanced heat release rate of the pilot injection fuel, which is due to the reduced amount of adhered fuel on the cylinder wall. At light loads, the amount of pilot injection fuel must be reduced, and the injection must be timed just prior to the main injection in order to suppress a possible increase in smoke and HC. After-injection, a small amount of fuel injected immediately after the end of the main injection, reduces smoke, HC and fuel consumption.

Keywords Diesel engine, Multiple injection, Pilot injection, After-injection

1. Introduction

Recently, common rail fuel injection systems are mainly used in small HSDI diesel engines. The system enables flexible control over the timing and frequency of injections since the fuel can always be kept at the required pressure in an accumulator rail, unlike in other conventional jerk-type injection systems. Multiple injection[1, 2] is the key to exploiting this unique feature of the common rail system towards further reduction in exhaust emissions and improvement in performance.

In this study, the effects of multiple injection on a small HSDI diesel engine and its mechanisms are examined by both exhaust emission tests and in-cylinder observations.

2. Apparatus and experimental conditions

A single-cylinder research engine equipped with a common rail fuel injection system was used. The bore, stroke and displacement volume were 83 mm, 92 mm and 498 cm^3, respectively. Four valves and a center injection layout was applied. An external supercharging apparatus was used to adjust the charging efficiency to that of today's typical turbo-charged engine. A shallow dish-type combustion chamber was used. The aspect ratio of the combustion chamber and the compression ratio were 3.9 and 17.0, respectively. The port swirl ratio was set to 2.3. An AVL 450 type noise meter was used for combustion noise evaluation. The experiments were conducted under light, medium and full loads; the operating conditions are detailed in **Table 1**.

Table 1 Experimental conditions.

Load Condition	Full	Medium	Light
Engine Speed (rpm)	1200	2000	1380
Indicated Mean Effective Pressure (MPa)	Adjusted (Smoke < 2.5FSN)	0.53	0.30
Injection Quantity (mm^3/stroke)		(25.3)	(15.0)
Common Rail Pressure (MPa)	90	80	55
Charging Efficiency (%)	105	108	91
EGR Ratio (%)	0	16	31

3. Effects of multiple injection and its optimum pattern

3. 1 Early-pilot injection

3. 1. 1 Performance at full load

Figure 1 shows the effect of pilot injection timing on engine torque at 1200 rpm under the limited smoke number of 2.5 FSN. The main injection timing and the pilot injection quantity were kept constant as 4 deg. ATDC and 4.5 mm^3, respectively. The symbol '■' in the figure denotes the base condition without pilot injection.

When the pilot injection was timed after -40 deg. ATDC, the indicated mean effective (IMEP) decreased below the base condition. This is because the main injection quantity had to be decreased to limit the exhaust smoke number. Also, the combustion noise was higher than that of the base condition due to the steep heat release of the pilot injection fuel.

However, when the pilot injection was timed before -40 deg. ATDC, the pilot injection increased IMEP because the main injection quantity could be increased within the allowed smoke number. Under this condition, the enhancement of IMEP and the

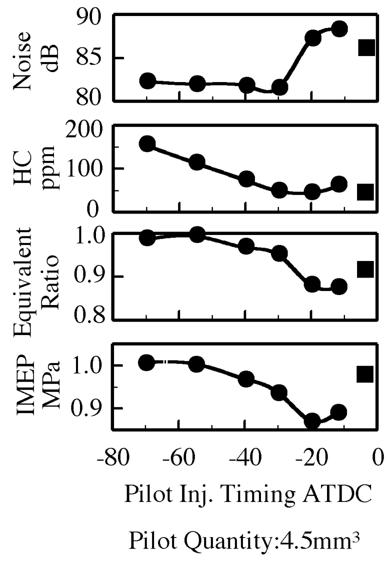

Fig. 1 Effects of pilot injection timing on engine performance at full load.

decrease in combustion noise with respect to the base condition (Symbol ■) were 6% and 4 dB, respectively. This kind of pilot injection is hereinafter designated as “early-pilot injection” in this paper. It should be noted that the equivalent ratio was almost 1.0 when the pilot timing was -55 deg. ATDC. This means that the early-pilot injection enabled almost complete use of all the air in the cylinder.

Figure 2 shows the cylinder pressure and rate of heat release in the typical early-pilot injection case, whose timing was -55 deg. ATDC. In-cylinder images of the combustion process are also shown. Combustion of the early-pilot injection generated a mild heat release in two stages. In-cylinder observations revealed that this two-stage heat release occurred via non-luminous flame combustion. Based on these results, the two-stage combustion is believed to be a premixed compression ignition consisting of cool flame and hot flame combustion. This premixed combustion caused a mild increase in pressure and shortening of the main ignition delay, leading to a combustion noise decrease. The premixed combustion also reduced smoke due to the enhanced use of air in the cylinder. This meant that the quantity of injected fuel could be increased under the limited smoke number condition, which in turn increased the IMEP. These effects are exactly the same as those observed in the well-known “fumigation fuel supply method” [3], in which part of the fuel is injected during the suction stroke.

Early-pilot injection is thus regarded as a good example of how the common rail system can enable a well-known phenomenon to be put to good practical use.

3. 1. 2 Emissions under partial load conditions

Figure 3 shows the relationship between pilot injection timing and emissions under light load conditions (Table 1). The emissions were also evaluated under medium load conditions, which showed the same trends as those observed under light load conditions. The symbol '■' in Fig. 3 shows the base condition, i.e., the case without pilot injection. NOx decreased with advancing pilot timing until -50 deg. ATDC. Pilot injection increased smoke when the pilot timing was close to the main injection. However, the smoke could be decreased to the baseline level by advancing pilot injection timing. In other words, reduction of NOx could be achieved without any concomitant increase

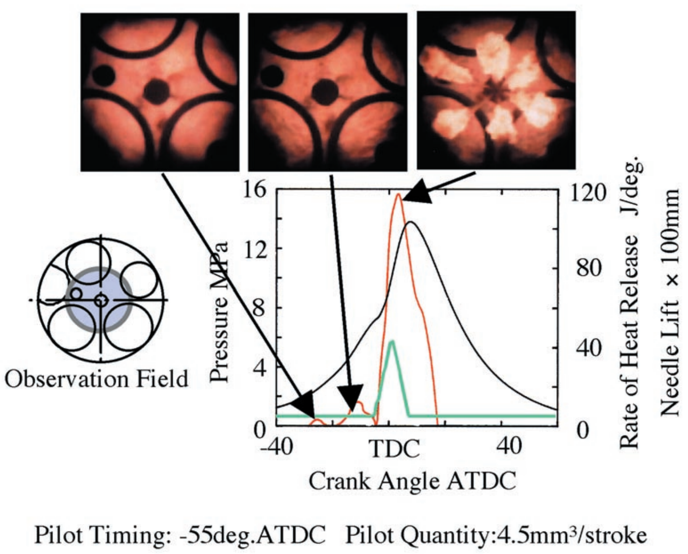

Fig. 2 Combustion process of early-pilot injection at full load.

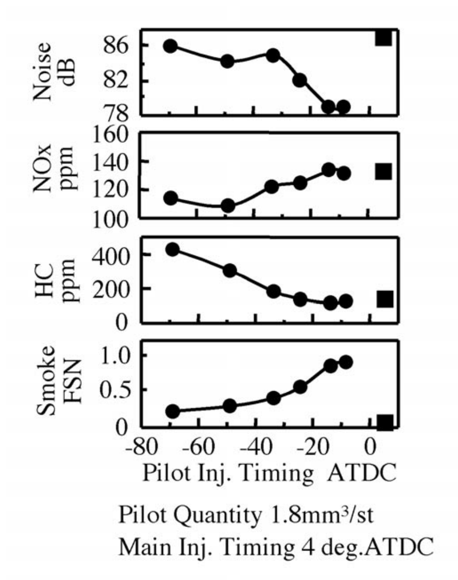

Fig. 3 Effects of pilot injection timing on emissions and noise at light load.

in smoke through the use of early-pilot injection. Applying early-pilot injection under these partial load conditions had the disadvantage of increasing the HC and noise levels, however, one method to suppress these disadvantages is illustrated in **Fig. 4**.

Figure 4 shows the relationship between pilot injection quantity and emissions for early-pilot injection at -67 deg. ATDC. The symbol '●' corresponds to ordinary single pilot injection, while the symbol '★' corresponds to double-pilot injection, in which the total pilot injection quantity of 4.3 mm^3 was divided up into two injections, one at -64 and the other at -44 deg. ATDC. Medium load conditions (Table 1) were used.

An increase in the quantity of single pilot injection ('●' in Fig. 4) caused HC emission and fuel consumption to increase, and the NOx and noise levels to decrease. However, the increases in HC emission and fuel consumption could be markedly suppressed by the double pilot injection ('★' in Fig. 4). The double pilot injection also further reduced combustion noise, which can be explained by comparing the heat release rate patterns shown in **Fig. 5**. The figure shows that the double pilot injection exhibited a higher heat release around -10 deg. ATDC compared with the single pilot, although the total amount of pilot fuel was virtually the same in the two cases. The ratio of fuel burned before the start of the main injection to the total fuel amount of pilot injection was 32% in the single pilot case, and 61% in the double pilot case. Clearly, the double pilot injection increased the total heat release. This led to a decreased ignition delay of the main injection fuel due to the increased temperature in the cylinder at the start of the main injection. Thus, combustion noise was reduced. The increase in the combustion ratio with the double pilot injection is thought to be mainly caused by the decrease in the adhered fuel on the cylinder wall. This is discussed in detail in **Section 4**.

3. 2 Close-pilot injection

Figure 6 shows the HC emission of the early-pilot injection with the single or double pattern under light load conditions. Under these conditions, the double pilot injection could not suppress the increase in HC. The reasons for this lie in the peculiar process conditions with the low-speed and light-load operation, such as deteriorated atomization and evaporation of the pilot fuel spray due to the low injection pressure and weak airflow. Under these circumstances, the close-pilot injection, which was timed close to the main injection, reduced HC with a minimum smoke increase as shown in **Fig. 7**. Besides, the combustion noise and indicated fuel consumption were remarkably improved. These are

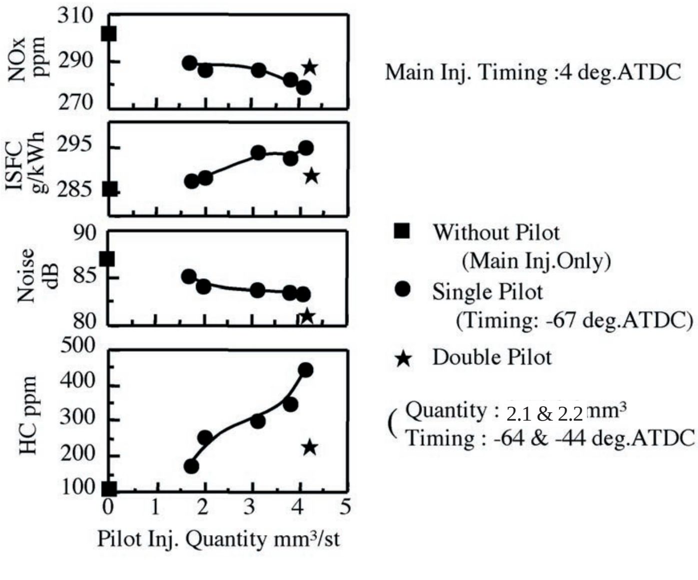

Fig. 4 Effect of pilot injection quantity and frequency at medium load.

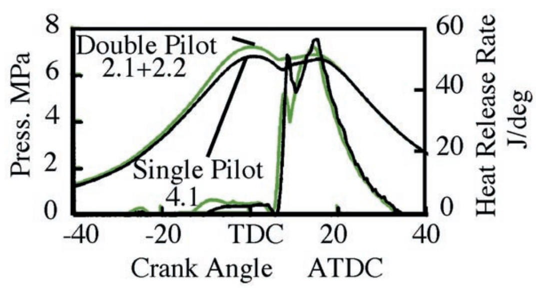

Fig. 5 Heat release rate of single and double pilot injection.

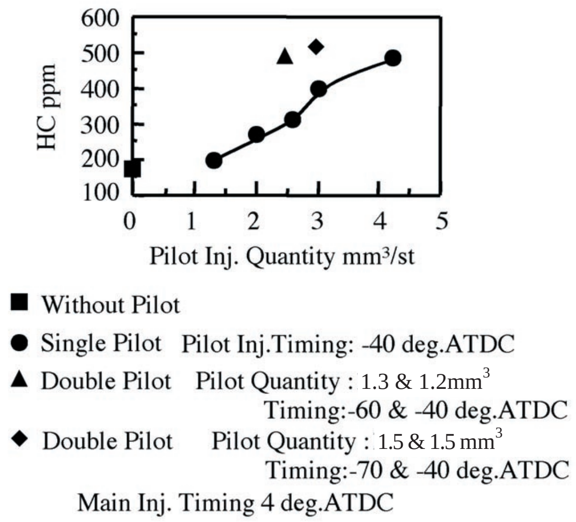

Fig. 6 Effect of double pilot injection on HC emission at light load.

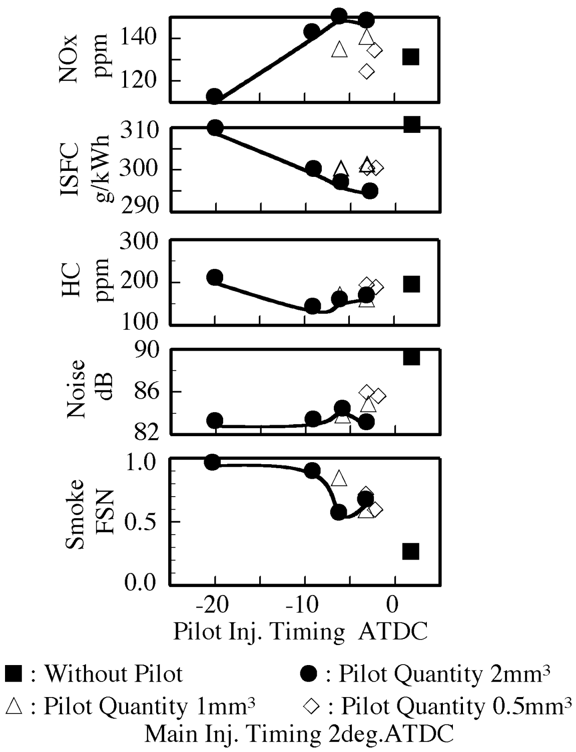

Fig. 7 Effects of close pilot injection at light load.

caused by the shift in the heat release timing of the pilot injection towards TDC, which served to increase thermal efficiency and in-cylinder temperature. It should be noted that the quantity of the close-pilot injection must be less than 1 mm^3 in order to suppress NOx increase as much as possible.

3. 3 After-injection

The effect of after-injection, where a small amount of fuel was injected just after the main injection, is shown in **Fig. 8**. Reductions in smoke, HC and fuel consumption were achieved for short injection intervals. However, NOx was increased in the process. It became clear that after-injection should be used in combination with an increase in EGR to compensate for the NOx increase, as shown in **Fig. 9**. The combination ensured the simultaneous reduction of smoke and fuel consumption, while maintaining the same level of NOx.

4. Spray characteristics of early-pilot injection

4. 1 Shadowgraph observation

The development of the fuel spray in early-pilot

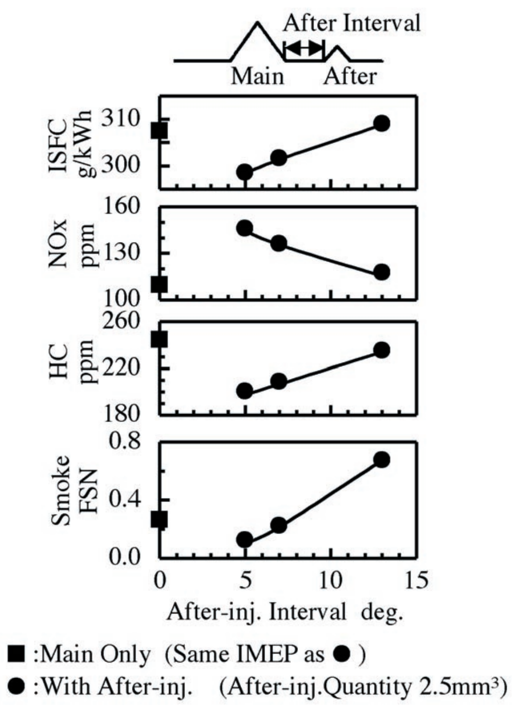

Fig. 8 Effect of after-injection interval on emissions (End of main to start of after).

injection was observed with an optically accessible engine. The pilot injection timing was -50 deg. ATDC, the common rail pressure was 80 MPa, and the engine speed was 1200 rpm. Photographs were taken at 0.05 ms intervals. **Figure 10** shows the penetration length of the spray tip from the start of injection. Examples of the photographs are also shown. As shown in Fig. 10(a), the penetration length for an injection amount of 6 mm^3 agreed with calculations based on Hiroyasu's equation, which is well applicable to a continuous fuel spray at a constant injection pressure. In this case, the spray tips went out of the observation field 0.17 ms after the start of injection. Furthermore, the in-cylinder observation in Fig. 10(b) shows that the injection rate remained strong at 0.3 ms. This can be inferred from the fact that the fuel spray appears black due to the attenuated shadowgraph light as a result of the high droplet density. For an injection amount of 2 mm^3, the penetration of the spray tip was suppressed, as shown in Fig. 10(a). At 0.3 ms in Fig. 10(b), the injection had already terminated and the droplet density was low, as revealed by the fact that the fuel spray images are pale.

These results suggest that decreasing the amount of the pilot injection in one shot suppresses the penetration length of the spray tip. This is supposed to result in the reduction of adhered fuel on the cylinder wall, which is not used in combustion.

4. 2 Fuel adhesion to cylinder wall

A glass window was attached to the spray impinging area on the cylinder wall to observe the phenomenon of fuel adhesion. The weight of the adhered fuel was examined by using blotting paper placed on the spray impinging area. The air density was adjusted to the value observed at the actual pilot timing (-40 deg. ATDC). Approximately one hundred injections were carried out at an engine

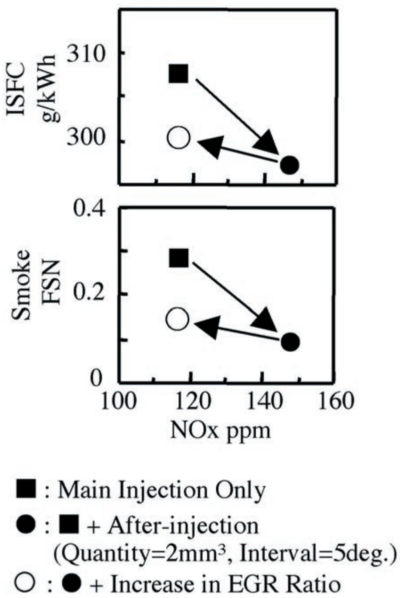

Fig. 9 Improvement of emissions and fuel consumption with after-injection plus increase in EGR ratio.

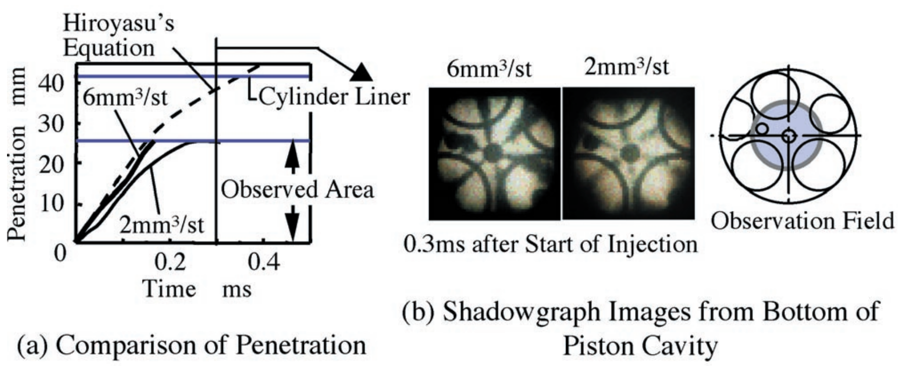

Fig. 10 Spray characteristics of early pilot injection.

speed of 1200 rpm. Only the pilot injection was carried out in order to avoid a large heat release from the main injection.

Lighter components of the adhered fuel are expected to evaporate from the blotting paper during the weighing experiments due to exposure to heat in the cylinder. The decrease in weight was carefully corrected for by comparing the composition profile of the adhered fuel with that of the original fuel using gas chromatography. The images and measured weights of adhered fuel are shown in **Fig. 11**. A large amount of adhered fuel was observed to trickle from the impinging point for pilot fuel amounts above 4 mm^3. For pilot amounts below 4 mm^3, hard spray impingement was not observed. However, for injection amounts below 1 mm^3, fine droplets were observed, possibly caused by the deteriorated fuel atomization due to the severe pressure drop at the needle seat, which is peculiar to the case of small injections with the common rail fuel injector. The weight of the adhered fuel with a single pilot injection (Symbol ▲) was undetectable for injection amounts below 2 mm^3. Above 2 mm^3, the adhered fuel increased with the injected fuel amount. Under these conditions, the fuel adhesion could be reduced by the double pilot injection (Symbol ★).

Based on these results, it is believed that the increase in the rate of heat release induced by the double pilot injection (**Section 3.1**) was mainly caused by the decrease in the adhered and lost fuel on the cylinder wall.

5. Conclusion

The effects of multiple injection on the exhaust emissions and performance of a small HSDI diesel engine and the mechanisms that brought about these effects were investigated using emission tests, pressure indicator analyses and in-cylinder observations. The following were clarified:

(1) It is possible to increase the maximum torque, which is limited by the exhaust smoke number, while reducing the combustion noise under low speed, full load conditions by advancing the timing of the pilot injection. Under medium load conditions, dividing the early-timed pilot injection into a series of smaller injections serves to further decrease the noise while maintaining the deterioration of HC emission and fuel consumption within an acceptable level. This is because splitting up the pilot injection reduces the adhered and lost fuel on the cylinder wall.

(2) Close-pilot injection, which is timed to occur immediately preceding the main injection, significantly reduces combustion noise and fuel consumption while maintaining an acceptable smoke increase under light load conditions.

(3) After-injection, which involves injecting a small amount of fuel immediately after the end of the main injection, can reduce smoke, HC and fuel

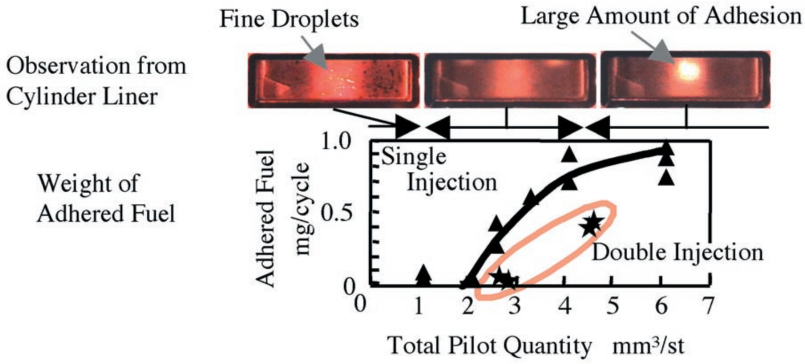

Fig. 11 Characteristics of fuel adhesion to cylinder liner.

consumption. The combination of using after-injection and a higher EGR improves the trade-off among smoke, fuel consumption and NOx.

Acknowledgements

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References

1) Imarisio, R., et al. : "Multiple Injection, a Cost Effective Solution for Emission Reduction of Common-Rail DI Diesel Engines", Aachener Kolloquium Fahrzeug-und Motorentechnik, **9**(2000), 1047-1062
2) Badami, M., et al. : "Influence of Multiple Injection Strategies on Emissions, Combustion Noise and BSFC of a DI Common Rail Diesel Engine", SAE Tech. Ser., No.2002-01-0503, (2002)
3) Alperstein, M., et al. : "Fumigation Kills Smoke", SAE Trans., **66**(1958), 574

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