

Study on the Generation Mechanism of Backfires

Shinji SAITO*

Masaya ADACHI*

ABSTRACT

In motorcycle engines, backfires can become an issue with increased cylinder bore size. It has been thought that backfires are caused by an extra ignition at an overlapping top dead center or by backflows into combustion chamber of high temperature exhaust gas during exhaust stroke. As a result of taking pressure measurements inside the combustion chamber, at the inlet and exhaust ports, and of observing the inside of the combustion chamber with a high speed CCD camera, it was found that an extremely slow-burning cycle exists which continuously burns during the exhaust stroke. Further, it was confirmed that the extremely slow-burning cycle caused the fresh air-fuel mixture introduced in the subsequent intake stroke to ignite thus generating backfires. This paper provides an overview of the investigation and describes some of the factors that influence the extremely slow burning cycle.

1. Introduction

Backfires occur as an explosive ignition sound from an engine intake port when the throttle is opened suddenly. This poses concerns in terms of product appeal. However, the present fact is that there has not been any theoretical analysis of the backfire generation mechanism to date.

Up to now, the source of the ignition for backfires had been identified as the ignition occurring during an overlap at top dead center (ignition spark during overlap), or as the high-temperature burned gas flowing back into the combustion chamber due to an exhaust pressure wave from another cylinder. However, there were cases when a backfire occurred even when these factors had been eliminated. This project took pressure measurements in each relevant part during backfires and observed the inside of a cylinder using a high-speed camera. Here we report the results, which show that there are sources of ignitions for backfires other than ignition sparks during overlap, or the backflow of burned gas.

2. Test equipment

2.1 Engine control device

Table 1 presents the main specifications for the engine being tested. This research utilized a 996-cm³ V-type twin-cylinder (longitudinal cylinder arrangement) engine. The tests were conducted primarily on the back cylinder.

Backfires occurred most frequently when the throttle was

Table 1 Major specifications of test engine A

Engine type	4-stroke V-90° twin cylinder
Cooling type	Liquid-cooled
Bore × stroke	98 × 66
Compression ratio	9.4
Valve train	DOHC 4-valve
Maximum power (kW/r/min)	77.3 / 9000
Maximum torque (Nm/r/min)	93.1 / 7000
Ignition timing	15° (BTDC)

opened up suddenly while reducing speed under a no-load condition. Backfire tests of all kinds used to be conducted by manually operating the throttle, but this caused variations in the frequency of occurrence and was also not very precise. For this research, therefore, the device indicated in the diagram at the top of Fig. 1 was fabricated and used for testing.

This device monitors the engine speed, and when revolutions fall below a set value, it triggers a magnetic valve that operates an air cylinder. As shown at the bottom of Fig. 1, this device is made to open the throttle a specified amount (θth) for a specified time (T1). The device repeatedly snaps the throttle with the engine under no load conditions, a specified number of times. The relationship between the engine speed and throttle opening during actual operation is shown at the bottom of Fig. 1.

* Asaka R&D Center

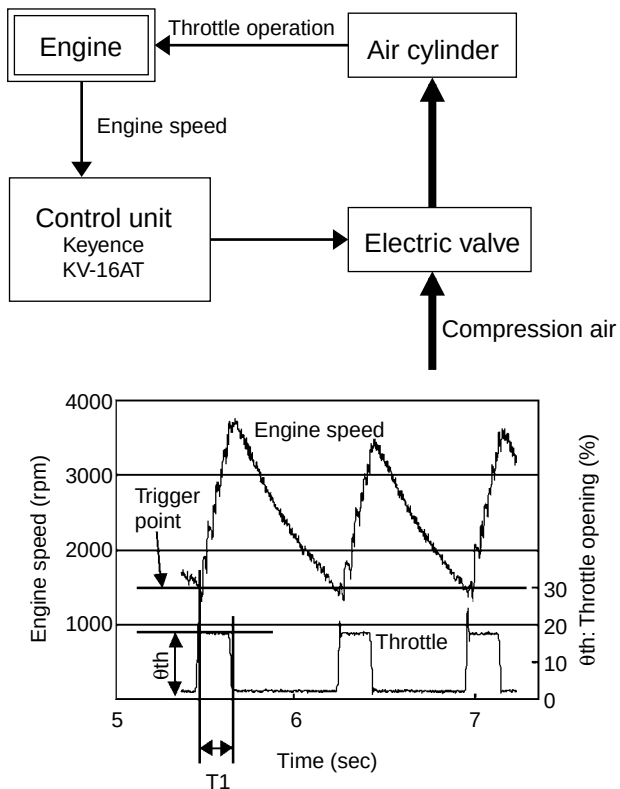


Fig. 1 Backfire test device

2.2 Pressure sensor installation position

Various pressure measurements were conducted in order to clarify the backfire generation mechanism. Fig. 2 shows the names and installation positions of each pressure sensor used. A Kistler 5053C pressure sensor was used to measure combustion pressure, and Toyoda PMS-5 pressure sensors were used to measure intake and exhaust port pressure. In order to measure cylinder pressure accurately in the vicinity of bottom dead center, a Toyoda PMS-5 pressure sensor was also attached to the cylinder wall at a location 35 mm below the deck surface, which corresponds to a 95° crank angle from the top dead center position.

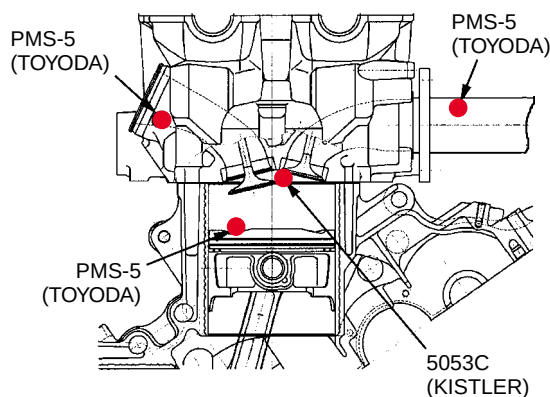


Fig. 2 Installation positions of pressure sensors

3. Backfire generation circumstances

3.1 Conditions for backfire generation

Empirically, it is known that backfires occurred more frequently when the throttle was opened suddenly on an engine running at low speeds. This is thought to be because combustion is unstable when the engine is under a low load. The conditions for backfire can be summarized as follows:

- The engine is a large-bore engine.
- Backfires occur after operation under low load conditions, at low speeds.
- The throttle is operated with a small opening.
- The throttle valve is opened suddenly.

3.2 Conditions most conducive to backfire generation

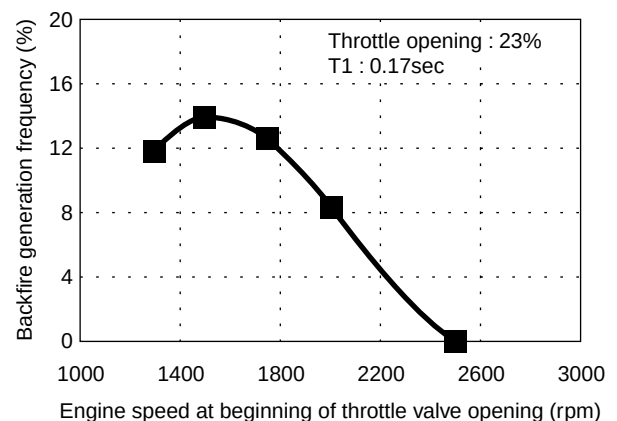
The test engine described in section 2.1 was set to the conditions shown in Table 2, and the conditions under which backfire occurred most frequently were confirmed.

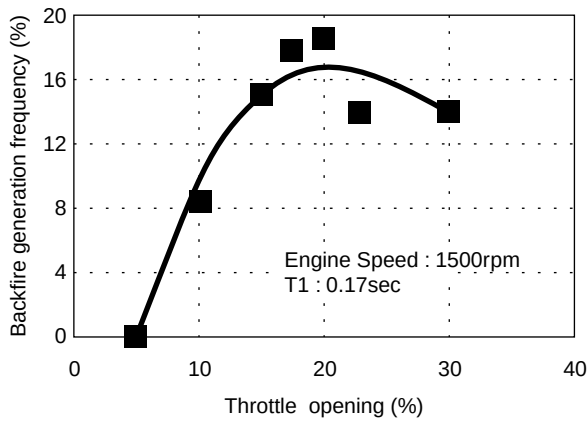
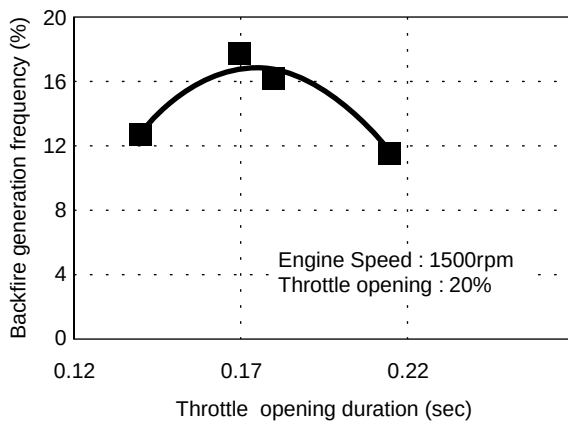
Table 2 Operating conditions

Item	Operating conditions
Engine speed at start of operation (rpm)	1300, 1500, 1700, 2000, 2400
Throttle opening (%)	5, 10, 15, 18, 20, 22, 30
Operating time (sec)	0.14, 0.17, 0.18, 0.20

The conditions were set as follows:

- (1) Backfire generation frequency was measured while changing the engine speed at which the throttle was opened (Fig. 3).
- (2) Selecting the engine speed at which backfires occurred most frequently, backfire generation frequency was measured while changing the throttle opening (Fig. 4).
- (3) Selecting the engine speed and throttle opening at which backfires occurred most frequently, backfire generation frequency was measured while changing the throttle operation time (Fig. 5).

Fig. 3 Backfire generation map
(Changing engine speed)

Fig. 4 Backfire generation map (Changing θ_{th})Fig. 5 Backfire generation map (Changing T_1)

The results of tests conducted under the above conditions showed that backfires occurred most frequently when the test engine was running at 1500 rpm at the time the throttle started to be opened, the throttle was opened 20%, and remained open for 0.17 sec. This test engine was adjusted to idle at a speed of 1200 rpm, so it is apparent that 1500 rpm was slightly higher than its idle speed. We also found that backfire generation frequency changed relatively little when the throttle was opened 15% or more.

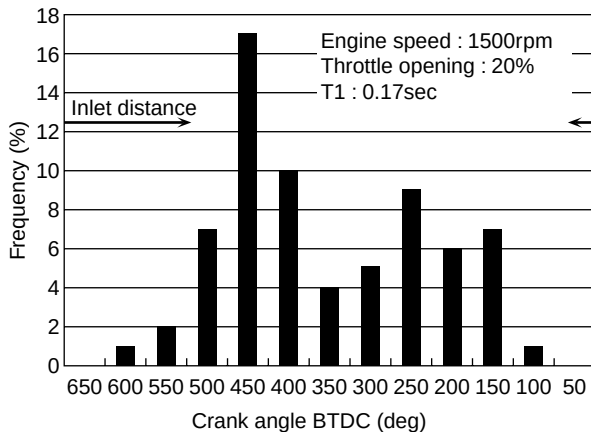


Fig. 6 Throttle opening timing

3.3 Influence of throttle open timing

The relationship between backfire generation frequency and throttle open timing is shown in Fig. 6. It is apparent that backfire frequency is lower when the throttle is opened while the inlet valve is open. This was because the lag in fuel that is generally said to follow the inflow of air became more marked and the air-fuel ratio shifted toward the lean side when the throttle valve was opened while the inlet valve was open, thus making it less likely that backfires would occur.

4. Results of pressure measurements of each part during backfire

4.1 Pressure at the time of backfire generation

The pressure waveforms for each part during backfire occurrence are shown in Fig. 7.

With the throttle fully closed (the blue line in the lower graph), the engine speed decreases (the red line in the lower graph), then the throttle opens in the vicinity of 1500 rpm. Immediately after that, the pressure in the intake port (the green line in the upper graph) and the pressure inside the cylinder (the red line in the upper graph) both rise, and backfiring takes place. The rise in pressure can also be seen with the Kistler pressure sensor, though the waveform peaks are lower because the measurement range is different.

The exhaust port pressure wave (the orange line in the upper graph) shows no change in the vicinity of the overlap at the top dead center immediately before the backfire occurs. This shows that the backfire is not generated by the influence of an exhaust pressure wave from another cylinder, as had previously been thought.

Ordinarily, operation under a no-load condition at a decreasing speed causes a misfiring cycle. In the case of a misfiring cycle, the condition approaches adiabatic compression and adiabatic expansion. Therefore, the pressure in the cylinder at the instant when the exhaust valve

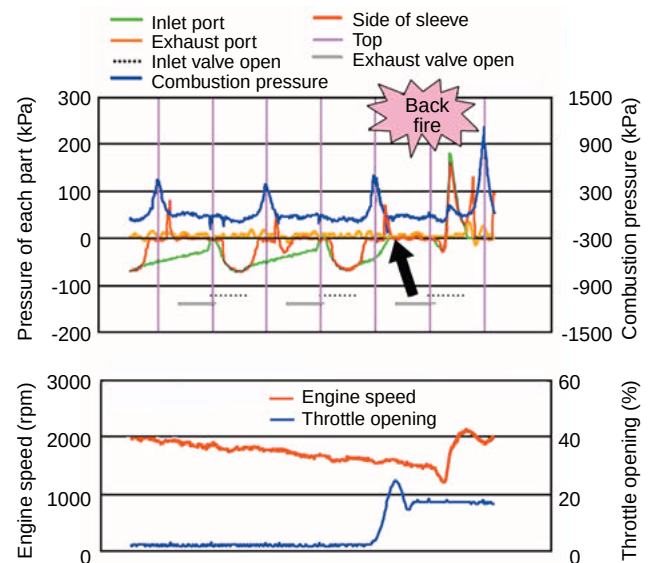


Fig. 7 Pressure of each part when a backfire is generated

opens becomes generally equal to the pressure at the start of the compression stroke before that, as shown in the upper graph in Fig. 8. In the case of an ordinary slow-burning cycle, there will be pressure of 100 kPa or more at the instant when the exhaust valve opens, as shown in the lower graph in Fig. 8.

Consider the cycle before backfire occurs in Fig. 7. This may at first appear to be a misfiring cycle, but the cylinder pressure (section of graph indicated by the arrow) at the instant when the exhaust valve opens is clearly higher than the cylinder pressure at the start of the previous compression stroke, showing that this is not a misfiring cycle. However, the pressure is not as high as it is in a usual slow-burning cycle. In other words, this can be understood as an extremely slow-burning cycle that is close to being a misfiring cycle. For the purposes of this research, we decided to term this kind of cycle where combustion occurs so slowly an extremely slow-burning cycle.

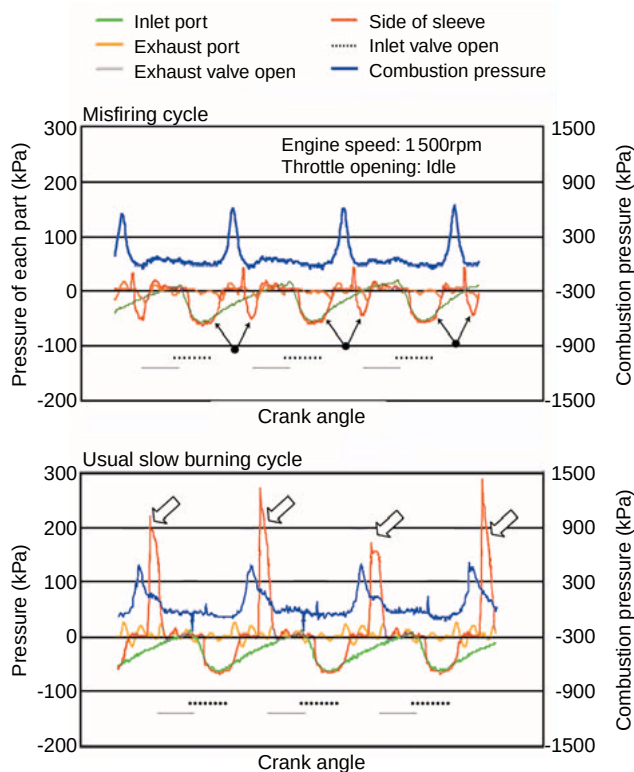


Fig. 8 Pressure of each part during a usual slow-burning cycle and during a cycle when a misfire is generated

4.2 P-V diagram

The P-V diagram for an extremely slow-burning cycle measured using a DS-0928 Ver. 3.58 combustion analyzer made by Ono Sokki Co., Ltd. is shown in Fig. 9. The cylinder pressure rises during the latter part of the intake stroke, and backfiring occurs. Consider the transitional portion of this cycle from the combustion to the exhaust stroke (the circled section of the graph). Immediately before the exhaust stroke, the cylinder pressure does not change even though the exhaust valve is open.

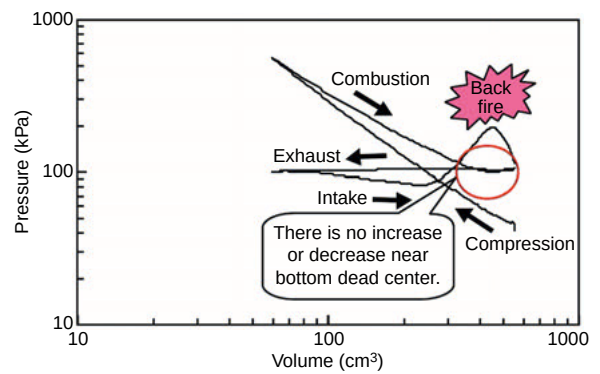


Fig. 9 P-V Diagram (Extremely slow-burning cycle)

Let us compare this again with a usual slow-burning cycle and a misfiring cycle. As shown in the bottom graph in Fig. 10, during a usual slow-burning cycle, the cylinder pressure drops toward atmospheric pressure when the exhaust valve opens because combustion is taking place. Also, as shown in the upper graph in Fig. 10, pressure is negative at the start of compression during the misfiring cycle, so the cylinder pressure is also negative immediately before the exhaust valve opens. When the exhaust valve opens up, the cylinder pressure rises toward atmospheric pressure. The extremely slow-burning cycle does neither of the above.

The extremely slow-burning cycle, therefore, can be described as a cycle in which the cylinder pressure neither increases nor decreases during the time before and after the exhaust valve opens. The reason for this is that it is a cycle

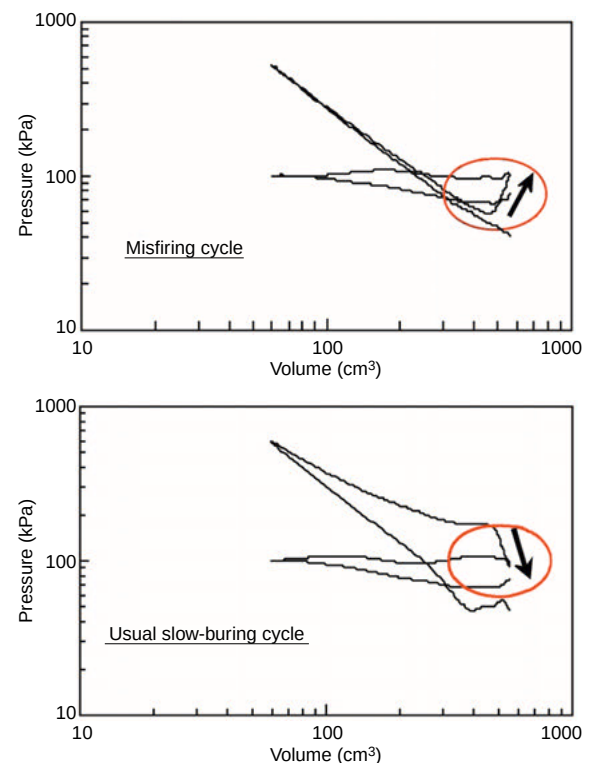


Fig. 10 P-V Diagram (Misfiring and usual slow-burning cycle)

in which the slow burning is made even slower, and combustion continues to take place even when the exhaust valve opens.

The extremely slow-burning cycle can be understood as a phenomenon that occurs during the state of transition from the misfiring cycle to the slow-burning cycle. As shown in Fig. 11, reducing volumetric efficiency generally causes the burning velocity in the usual combustion cycle to gradually grow slower, until ultimately it becomes a misfiring cycle. When there is a transition from a no-load condition at decreasing engine speed to idle, the situation is reversed. In other words, a transition takes place from a misfiring cycle to a slow-burning cycle. At this time, the misfiring cycle does not suddenly become a slow-burning cycle. Rather, the extremely slow-burning cycle can be understood to occur as an intermediate condition between a misfiring cycle and a slow-burning cycle. The rate of heat release in this extremely slow-burning cycle amounted to 140–160 J.

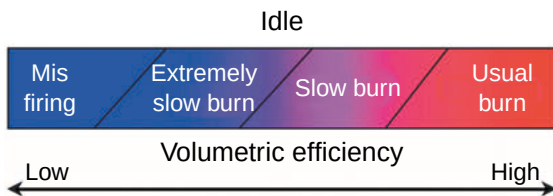


Fig. 11 Location of extremely slow burning cycle

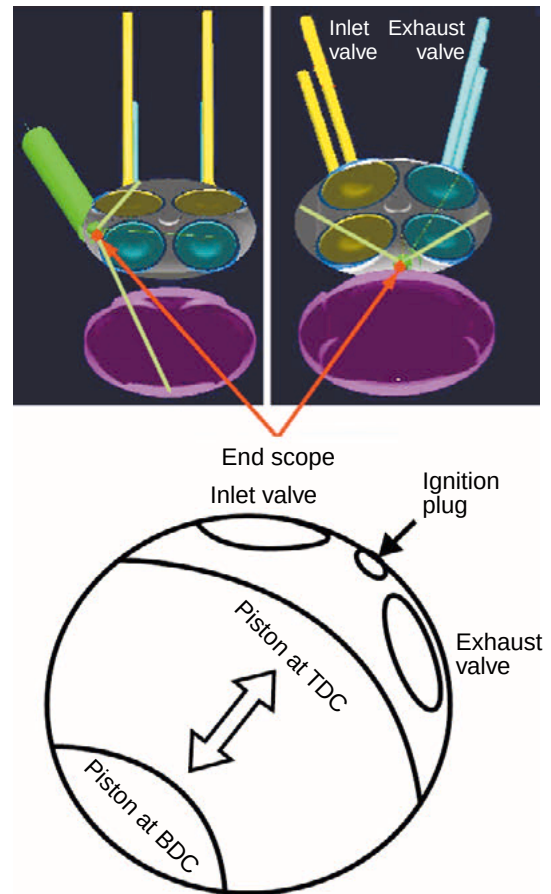


Fig. 12 Observation area in cylinder

5. Observations of the inside of the cylinder

Examination of the cycles immediately preceding the cycle in which backfire occurred showed that these were all extremely slow-burning cycles. This suggested that the extremely slow-burning cycle was the source of ignition for backfires. We hypothesized that an extremely slow-burning cycle has such a slow burning velocity that it does not finish combustion during the combustion stroke, and so its combustion continues into the exhaust stroke. Backfires can be considered to take place when the inlet valve opens during the latter part of the exhaust stroke, and the new air-fuel mixture enters the hot cylinder where it undergoes combustion, so that the backfire occurs during the intake stroke.

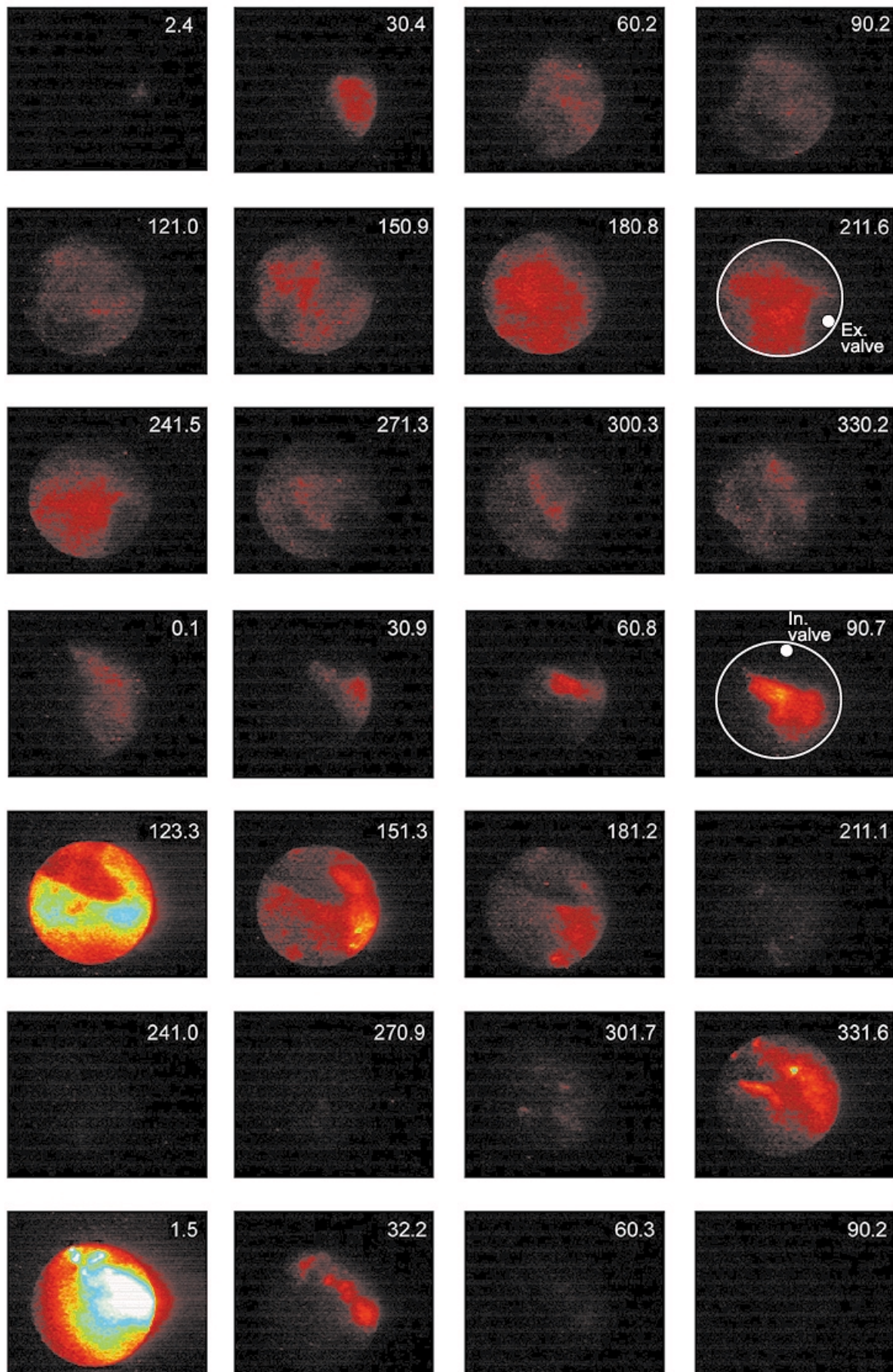
The continuation of combustion during the exhaust stroke can be confirmed by measuring the cylinder temperature difference between cases when extremely slow-burning cycles occur and when they do not. However, it has been difficult to measure such temperatures accurately under the high-temperature, high-pressure conditions inside the cylinder, and moreover within a period of just several milliseconds. Consequently, visual observation inside the cylinder was implemented.

A hole 10 mm in diameter was opened in the side wall of the test engine combustion chamber to mount an endoscope made by AVL List GmbH. The top illustration of Fig. 12 shows the area of observation in the combustion chamber. The sectorial portion of the green lines in this

figure is the observation area. The bottom illustration of Fig. 12 presents a schematic view of the combustion chamber interior as observed through the endoscope.

A C5836-60 image intensifier made by Hamamatsu Photonics K.K. was attached to the rear end of the endoscope, and the images were recorded using a Kodak EKTAPRO HS motion analyzer model 4540, which is a high-speed CCD camera. This was used to photograph the continuous sequence of phenomena occurring from when the extremely slow-burning cycle began to after the backfire took place. The recording rate was 4500 frames per second. Fig. 13 presents images recorded at approximately every 30° of crank angle. The figures inside these images show the crank angle. Although the original images are monochrome, the images in Fig. 13 have been put through a process of coloration based on differences in luminance.

Here, it can be seen how ignition begins from the spark plug at 15° before top dead center, and how the flame then spreads after top dead center. Approximately 130° after top dead center, the exhaust valve starts to open, but this can only be verified on the images at points past 180° after top dead center. After this, combustion continues during the exhaust stroke, or in other words, combustion continues even though the exhaust valve is open. The images show that combustion then continues up to the intake stroke. The inlet valve opens in the vicinity of 30° after top dead center and combustion begins in the area of the inlet valve, and backfiring takes place.



Note: Values in photos indicate the crank angle (deg).

Fig. 13 Photographs of burning in cylinder

It can be seen that intense combustion is occurring especially in the vicinity of 120° after top dead center. Then, the backfiring ends and the transition from the intake to the compression stroke takes place. Next, combustion again takes place during the compression stroke after a point around 300° after top dead center has been passed. A bright burning condition similar to diffusive combustion occurs in the area around top dead center, then combustion stops after top dead center. The ignition timing is 15° before the top dead center, which means that this is not ignited by the spark plug. The image also suggests that ignition is not from the ignition plug.

We reason that this phenomenon occurs as described below. Since backfiring occurs during the intake stroke, the temperature inside the cylinder rises at the end of the intake stroke, when the compression stroke begins. As a result, self-ignition takes place during the compression stroke and combustion begins.

Therefore, observation of conditions inside the cylinder when backfiring occurs led to the determination that the source of ignition for backfires is an extremely slow-burning cycle in which combustion continues even during the exhaust stroke.

6. Relationship between the extremely slow-burning cycle and backfires

The results of the investigation into the relationship between backfire generation frequency and extremely slow-burning cycle occurrence frequency are shown in Fig. 14. The backfire test device described earlier was used to snap the throttle approximately 250 times with the engine under no load. The frequency of backfire generation and the frequency of extremely slow-burning cycles occurring immediately before the throttle was opened were both measured. This test was carried out a total of six times, with the air-fuel ratio being changed across the range of 9.5 - 13.0.

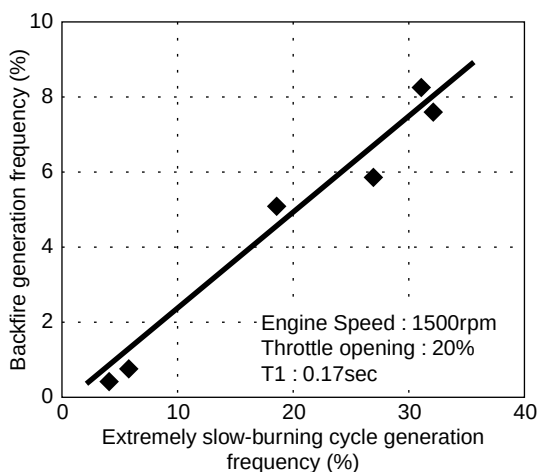


Fig. 14 Relationship between the extremely slow-burning cycle and backfiring

This revealed that a proportional relationship generally exists between the frequency of occurrence of backfires and of extremely slow-burning cycles. The slopes of these straight lines are about 0.25 and 1 or less, which indicates that there are cycles in which backfire generation will not occur even when cycles of extremely slow burning do occur. This is thought to be because the extremely slow-burning cycles, of course, have variations of the combustion itself, and also because the frequency of occurrence varies with the timing of inlet and throttle valve opening.

6.1 Cases of other test engines

The relationship between backfire generation frequency and extremely slow-burning cycle occurrence frequency was confirmed using a different test engine. Table 3 shows the main specifications for that engine, which is designated engine B, while the test engine described up to this time is designated engine A. Fig. 15 presents the relationship between backfires and extremely slow-burning cycles using the same axes as in Fig. 14.

A proportional relationship also exists between backfires and extremely slow-burning cycles in test engine B, and it lies generally along the same straight line as for engine A. The fact that two engines with these widely varying specifications show generally the same tendency can be taken to suggest that similar tendencies are also to be found in other engines.

Table 3 Major specifications of test engine B

Engine type	4-stroke single cylinder
Cooling type	Air-cooled
Bore $\times$ stroke	100 $\times$ 82
Compression ratio	8.3
Valve train	SOHC 4-valve
Maximum power (kW/rpm)	28.1 / 5750
Maximum torque (Nm/rpm)	52.3 / 4500
Ignition timing	8° (BTDC)

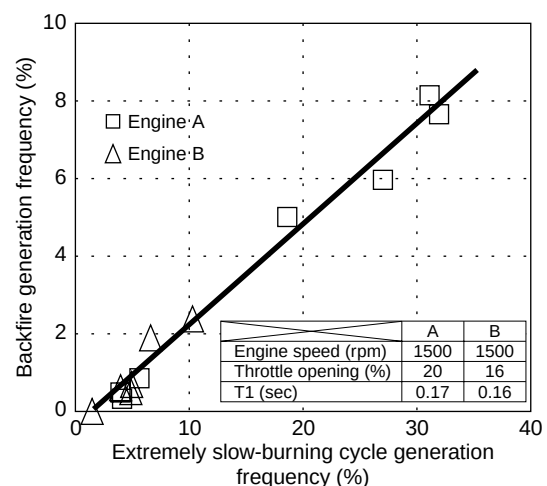


Fig. 15 Relationship between the extremely slow-burning cycle and backfiring with a different test engine

6.2 Factors affecting extremely slow-burning cycles

Factors that affect burning velocity include the air-fuel ratio, compression ratio, squish area, and swirl ratio. Tests were conducted of the relationship between extremely slow-burning cycles and backfires with different values for these four items. The results are shown in Fig. 16. It is apparent that, in general, changes to specifications that increase burning velocity cause a reduction in the frequency of extremely slow-burning cycle occurrence, which results in a corresponding reduction in the frequency of backfire generation. Even in such cases, a proportional relation continued to exist between the frequency of occurrence of backfires and of extremely slow-burning cycles.

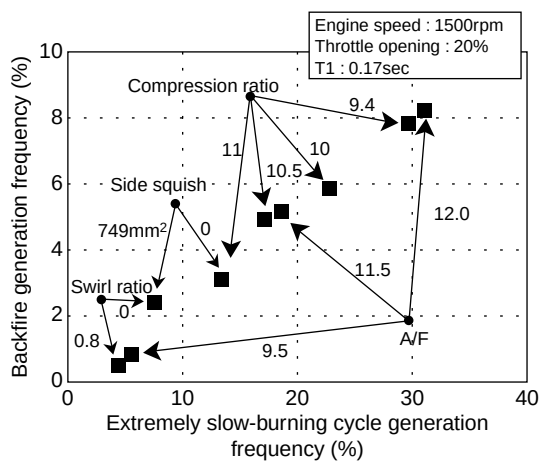


Fig. 16 Factors affecting extremely slow-burning cycles

7. Conclusion

We have analyzed the mechanism of backfire generation, for which no systematic analysis had been previously conducted. As a result, we have determined that other causes for backfire generation exist in addition to those considered in the past. The conclusions reached through this research are summarized below:

- (1) Extremely slow-burning cycles occur while reducing engine speed under a no-load condition, and combustion continues in these cycles even during the exhaust stroke.
- (2) Backfires occur with extremely slow-burning cycles acting as a source of ignition.
- (3) Combustion by self-ignition take place during the compression stroke immediately following backfire generation.
- (4) The occurrence of extremely slow-burning cycles can be reduced by increasing burning velocity.

References

- (1) Kondo, T., Iio, S., Hiruma, M.: A Study On the Mechanism of Backfire in External Mixture Formation Hydrogen Engines-About Backfire Occurred by Cause of the Spark Plug, SAE Paper 971704
- (2) Koyanagi, K., Hiruma, M., Furuhashi, S.: Study on Mechanism of Backfire in Hydrogen Engines, SAE Paper 942035

■ authors ■



Shinji SAITO



Masaya ADACHI