Rapid Communication

Qiang Zhang, Yubo Yang, Demin Jia, and Menghan Li*

Knocking characteristics of a high pressure direct injection natural gas engine operating in stratified combustion mode

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Abstract: Knocking becomes an increasingly important issue in direct injection natural gas engines with the application of new combustion modes. In this article, the knocking characteristics of natural gas engine operating in stratified combustion mode were studied with the aid of cylinder pressure oscillations and combustion parameters. The results indicated that knocking tendency will be stronger when operating in stratified combustion mode. The first to the fourth circumferential modes and the first radial mode are the featured modes for knocking behavior, while knocking is more serious when the duration of 10–50% of total energy released is shorter.

Keywords: knocking, natural gas engine, stratified combustion mode, pressure oscillation

1 Introduction

Knocking is an important issue in internal combustion engines. When serious knocking occurs, high-pressure oscillations will be induced, leading to possible damages to the engine structures as well as high noises and vibrations. Thus, it is important to understand the theory and changing regularity of knocking behavior in internal combustion engines.

With the implementation of the increasingly stringent emission standard and the increasingly urgent demand for energy saving, natural gas engines have become more and more concerned [1]. In conventional spark ignition natural gas engines, knocking is mainly induced by end-gas auto-ignition, while in high pressure direct injection natural gas engines, knocking is mainly attributed to the rapid pressure rise caused by the rapid propagation of flame front, which could result in the subsequent reflections of shock waves and great pressure gradient [2,3]. When diffusion-dominated combustion mode is adopted in high pressure direct injection natural gas engines, diesel is injected near the top dead center and natural gas is injected shortly after; thus, mixing and combustion of most gaseous fuel happen at the same time.

Nevertheless, when stratified combustion mode is adopted, natural gas is injected before the injection of diesel; thereby, the proportion of premixed natural gas will be enlarged and premixed combustion of natural gas becomes more important.

The knocking phenomena have been extensively studied in spark ignition natural gas engines. However, in high pressure direct injection natural gas engines, studies regarding knocking are scarce; most studies are focused on the combustion process and emission characteristics [4]. This article aims to investigate the knocking behavior of a high pressure direct injection natural gas engine operating in stratified combustion mode. The main pressure resonance modes were analyzed with the aid of the filtered cylinder pressure and the effects of injection parameters were evaluated.

2 Experimental procedures

The test engine is a six-cylinder turbocharged high pressure direct injection natural gas engine. The layout of the test bed is the same as that given in ref. [5]. During the experiments, the in-cylinder pressure was collected by

* Corresponding author: Menghan Li, School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, China, e-mail: sdulmh@163.com

Qiang Zhang: School of Energy and Power Engineering, Shandong University, Jinan, China, e-mail: sdzqtg@163.com

Yubo Yang: School of Energy and Power Engineering, Shandong University, Jinan, China, e-mail: 1557582188@qq.com

Demin Jia: Future Technology Research Institute, Weichai Power Co., Ltd., 197A Fushou East Street, Weifang, Shandong, China, e-mail: j19863692585@163.com

AVL Indicom combustion analyzer. In order to obtain the detailed information of the pressure oscillations, cylinder pressure curves of 100 consecutive cycles were recorded with a resolution of 0.2°CA , which means that the sampling frequency is 39 kHz. To avoid the channeling effect, the pressure sensor was flush mounted to the bottom of the cylinder head. During the experiments, the engine speed and engine torque were maintained at 1,300 rpm and 1,200 N·m, respectively. This operating condition was selected since it is a common operating condition for heavy duty trucks. The main specifications of the engine are provided in Table 1. The test scheme is shown in Table 2. When the start of natural gas injection is later than the end of diesel injection, the combustion mode is defined as diffusion-dominated; otherwise, the combustion mode is defined as stratified. Among all the cases, only case 1 is diffusion-dominated mode, all the other cases are stratified combustion mode. When operating at the stratified combustion mode, GSOI (injection timing of natural gas), DSOI (injection timing of diesel) as well as NDI (injection interval between natural gas and diesel) were varied to assess the effects of these parameters.

3 Results and discussions

3.1 Analysis of the typical knocking behavior

Figure 1 illustrates the cylinder pressure curves with and without obvious knocking phenomena. When the test engine is operated at engine speed of 1,300 rpm and engine torque of 1,200 N·m, knocking will not occur when DSOI is set to 21°BTDC and GSOI is set to 14°BTDC (operating at conventional diffusion-dominated combustion mode). Nevertheless, obvious knocking will happen when GSOI remains at 14°BTDC and DSOI is retarded to 9°BTDC (operating at stratified combustion mode). This could be explained by the increased flame propagation speed caused by the increased gaseous fuel consumed in

Table 2: Test scheme

Case	1	2	3	4	5	6	7	8	9	10	11	12	13
DSOI/ $^\circ\text{BTDC}$	21	9	11	13	15	9	11	13	15	9	11	13	15
GSOI/ $^\circ\text{BTDC}$	14	14	14	14	14	17	17	17	17	20	20	20	20
NDI/ $^\circ\text{CA}$	-7	5	3	1	-1	8	6	4	2	11	9	7	5

the premixed combustion, which could lead to higher pressure rise rate and increased peak cylinder pressure.

In order to extract the information of pressure oscillations, the cylinder pressure signals were processed by a band-pass filter (1.7–20 kHz). The cut-off frequencies were selected because at frequencies lower than 1.7 kHz, the in-cylinder pressure signals are dominated by the motion of the piston and the combustion process, while at frequencies higher than 20 kHz, the pressure signals are weak and unreliable. The pressure oscillation curves are

Figure 1: Cylinder pressure curves and time-domain pressure oscillation curves (a) as well as the corresponding frequency-domain power density spectra (b).

Table 1: Engine specifications

Item	Parameter
Engine model	In line, 6 cylinders, 4-stroke
Intake system	Turbo charged and intercooled
Bore $\times$ Stroke (mm $\times$ mm)	126 $\times$ 155
Total displacement (L)	11.57
Compression ratio	18:1

Table 3: Frequencies for acoustic modes

m, n	f_{10}	f_{20}	f_{01}	f_{30}	f_{40}	f_{11}
$\lambda_{m,n}$	1.84	3.05	3.83	4.2	5.33	6.71
$f_{m,n}$ (kHz)	4.42	7.32	9.20	10.08	12.80	16.11

Note: m and n denote the mode numbers of circumferential and radial modes, respectively; $\lambda_{m,n}$ denotes the acoustic mode factor determined by Bessel's equations; $f_{m,n}$ denotes the frequencies for acoustic modes.

demonstrated in Figure 1a. As illustrated, when diffusion-dominated combustion mode is applied, the amplitudes for pressure oscillations are remarkably lower. When stratified combustion mode is adopted, the pressure oscillations are at high levels owing to the intensified combustion process (Figure 1a). Figure 1b shows the frequency-domain pressure oscillation signals after fast Fourier transformation, i.e., the power density spectra. It could be seen from the processed signals that the dominant frequency bands are in the range of 4.3–5.4, 6.4–7.7, 8.9–9.6, 10.3–11.4 and

12.2–13.1 kHz. The first four strong frequency bands have power densities higher than 0.10, while the fifth strong frequency band has power densities higher than 0.05. According to the calculated frequencies for acoustic modes (Table 3) [6], the most important acoustic modes in the research engine are the first to the fourth circumferential mode (f_{10} – f_{40}) and the first radial mode (f_{01}). When obvious knocking happens, the signals of these acoustic modes are stronger than those in the conditions without knocking, indicating that these five modes are the most important acoustic modes for distinguishing knocking in the high pressure direct injection natural gas engines.

3.2 Effect of injection timing on knocking characteristics

As generally agreed, the maximum amplitude of pressure oscillation (MAPO) is a meaningful index for the evaluation of knocking phenomena. Thus, in this section, the

Figure 2: MAPO during the 100 cycles of different GSOI and DSOI (a) GSOI14°BTDC, (b) GSOI17°BTDC and (c) GSOI20°BTDC.

Table 4: Averaged MAPO of different cases

	DSOI21 (bar)	DSOI9 (bar)	DSOI11 (bar)	DSOI13 (bar)	DSOI15 (bar)
GSOI14	2.87	4.05	4.41	4.86	4.53
GSOI17	—	3.81	4.53	5.41	5.84
GSOI20	—	2.28	3.59	5.98	7.52

knocking characteristics are evaluated by this index. It is shown in Figure 2a and Table 4 that when diffusion-dominated mode is applied, the values of MAPO are generally lower and the averaged MAPO is 2.87 bar, implying that the knocking tendency is weak. When stratified combustion is adopted, the averaged MAPOs of most conditions are higher than that of diffusion-dominated combustion mode. This could be explained by the combustion parameters shown in Table 5. The calculation method of the combustion parameters could be found in ref. [7]. It can be observed that when stratified combustion mode is adopted, the ignition of natural gas (CA10%, 10% of total energy released) will be delayed attributed to the delayed injection of diesel. When the injection of natural gas is prior to the injection of diesel, premixed natural gas/air mixture will be formed before ignition, resulting in increased proportion of premixed combustion and subsequently shortened CA10–50% (10–50% of total energy released). Thereby, it could be inferred that CA10–50% is closely related to knocking tendency, i.e., higher knocking intensities are more likely to be observed at combustion processes with shorter CA10–50%. As illustrated, the pressure oscillation amplitude is the lowest at DSOI of 21°BTDC at GSOI of 14°BTDC. This is because when

Table 5: Combustion parameters of different cases

Case	CA10%/°ATDC	CA50%/°ATDC	CA10–50%/°CA	CA10–90%/°CA
1	–1.75	5.95	7.7	17.85
2	6.65	11.6	4.95	9.5
3	5.7	10.55	4.85	9.8
4	4.15	8.75	4.6	10.4
5	2.15	6.8	4.65	13.85
6	5.6	10.1	4.5	9.2
7	4.5	8.8	4.3	8.8
8	3.35	7.45	4.1	8.95
9	2.1	6.1	4	9.8
10	5.7	11.5	5.8	12.6
11	4.2	8.75	4.55	9.35
12	2.45	6.3	3.85	7.85
13	1.45	5.15	3.7	8.2

DSOI is much advanced than GSOI, diffusion-dominated combustion mode is formed. In this case, the non-monotonic trend of pressure oscillation amplitude is caused by the change in combustion mode. At stratified combustion mode with more advanced DSOI, the concentration gradient is beneficial for flame propagation, leading to increased possibility of cavity resonances. Therefore, knocking behavior is more significant at relatively advanced DSOI when natural gas is injected after the injection duration of diesel (Figure 2a–c).

In addition, it can be seen from Figure 2 and Table 4 that the effects of GSOI on MAPO vary with DSOI. This is because at different DSOIs, NDI, i.e., duration between the start of natural gas and diesel injection, is the parameter that really matters. When the injection interval is excessively small, the amount of premixed natural gas is relatively small, resulting in less intense combustion and weakened pressure oscillations. Nevertheless, when the injection interval is excessively large, the mixture near the ignition location is over-mixing leading to slowing down of flame propagation and reduced pressure resonances. Thereby, when the injection interval is in the range of 1–5°CA, MAPO could reach its highest value, implying that knocking is more serious at these operating points.

4 Conclusion

In this article, the typical knocking behavior of a high pressure direct injection natural gas engine is investigated and the effects of injection parameters on the knocking characteristics are assessed. The main findings could be summarized as follows:

- (1) Knocking intensity will be increased when stratified combustion mode is adopted; the first to the fourth circumferential modes and the first radial mode are the primary acoustic modes for the evaluation of knocking in high pressure direct injection natural gas engines.
- (2) CA10–50% is closely related to the proportion of premixed combustion and knocking tendency. Generally, knocking tendency is stronger at shorter CA10–50%.
- (3) Knocking behavior is more serious when injection of natural gas is slightly prior to diesel.

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