

Highly Turbocharged Gasoline Engine and Rapid Compression Machine Studies of Super-Knock

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ABSTRACT

Super-knock has been a significant obstacle for the development of highly turbocharged (downsized) gasoline engines with spark ignition, due to the catastrophic damage super-knock may cause to the engine. According to previous research by the authors, one combustion process leading to super-knock may be described as hot-spot induced pre-ignition followed by deflagration which can induce detonation from another hot spot followed by high pressure oscillation. The sources of the hot spots which lead to pre-ignition (including oil films, deposits, gas-dynamics, etc.) may occur sporadically, which leads to super-knock occurring randomly at practical engine operating conditions. In this study, a spark plasma was used to induce preignition and the correlation between super-knock combustion and the thermodynamic state of the reactant mixture was investigated in a four-cylinder production gasoline engine. The engine experiments were complemented by rapid compression machine (RCM) experiments of iso-octane and air which also used a spark plasma to investigate the fundamental physical and chemical mechanisms of super-knock. For the engine experiments, at low-speed high-load conditions, early spark timing was used to systematically induce preignition in the range of spark timing from 8 to -50 °CA ATDC in increments of 3 °CA. The intake pressure of the fresh air charge was set at 1, 1.3, 1.6 and 1.9 bar, and for each intake air pressure, the intake temperature was set at 20 and 60 °C. The results show early spark ignition could be used to trigger pre-ignition and to induce super-knock when the mixture thermodynamic state was above a critical condition. At a constant air temperature and high intake pressure, advancing the spark timing caused transitions from normal combustion to knocking conditions, to super-knocking conditions and then back to knocking conditions and to normal combustion. The transition between knocking conditions was well correlated with the thermodynamic state at the start of the in-cylinder pressure oscillations associated with knock. At a constant temperature and naturally aspirated conditions, no matter how advanced the spark timing was, only slight knock was observed, which indicates the thermodynamic state dominates the determination of knocking or non-knocking conditions. An energy density-pressure-temperature (E-P-T) diagram was developed to define super-knock, knock and normal combustion criteria. For the RCM experiments using isooctane at stoichiometric conditions with air dilution, a spark plasma was used to simulate pre-ignition. Three compression ratios were used to create different end of compression (EOC) temperatures. For each T_{EOC} , with increasing EOC pressure, the combustion process also transitioned from normal combustion with flame propagation, to sequential end-gas auto-ignition with pressure oscillations and then to detonation with severe pressure oscillations. The combustion processes observed in the RCM experiments and the thermodynamic states were similar to the state conditions at the start of the pressure oscillations of the constant temperature and high intake pressure engine experiments. The results indicate RCM studies can be used to investigate the physical and chemical mechanisms of super-knock and E-P-T diagrams can be used to predict and distinguish super-knock from other combustion modes.

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INTRODUCTION

Gasoline direct injection (GDI) engines with high boost and downsized technology are the main area of development for spark ignition (SI) engines due to the engine efficiency and power density gains that can be achieved [1][2]. However, the occurrence of a new knock mode, which has been termed as super-knock, unwanted preignition [3], mega knock [4], low-speed pre-ignition (LSPI) [5], detoknock [6], developing detonation [5],[6] or subsequent front propagation [9], has become a significant obstacle for improving the power density of SI engines, especially at low-speed, high-load operating conditions. A major concern is the damage to the engine that can occur with super-knock due to the associated high peak pressures and pressure oscillations.

Many research groups have investigated super-knock phenomena [3, 4, 5, 6, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. It is generally accepted that super-knock is induced by preignition, and the relationship between pre-ignition and super-knock has been described by the authors previously [6]. The sources of preignition can be oil films [12][14][17][26], deposits [16][27][28] and/or gas-dynamics [21]. *Dahnz et al.* [12] found one probable mechanism of pre-ignition for super-knock could be ascribed to the presence of lubricant oil droplets released from the cylinder liner. Spray impingement on the wall opposite to the injector seemed to be crucial for pre-ignition observed in the engine used in their study. *Haenel et al.* [16] investigated the effect of carbon deposits on the frequency of pre-ignition. Their results showed a clean combustion chamber without carbon deposits clearly shifted the pre-ignition frequency to lower values. *Peters et al.* [21] ascribed the stochastic occurrence of pre-ignition and the resulting super-knock events to the stochastic nature of turbulence. Simulation results showed that turbulence had a strong effect on the frequency of pre-ignition.

Although pre-ignition is required for the occurrence of super-knock, pre-ignition by itself does not always lead to engine knock. Preignition may lead to super-knock, heavy-knock, slight-knock, and non-knock [6]. The root cause as to why super-knock can severely damage engines is the magnitude of the intensity of the combustion mode. One scenario is that super-knock occurs due to hot spot induced gaseous detonation. *Zeldovich* [29] classified combustion modes into different categories, including thermal explosion, detonation and deflagration, based on the relationships between the spontaneous propagation speed, the C-J detonation speed, the sound speed and the laminar flame propagation speed. *Gu and Bradley* [30] extended the auto-ignition theory of a hot spot. The authors proposed two dimensionless parameters: $r_0/a/\tau_c$ (the ratio of the residence time of the acoustic wave with speed “a” in the hot spot with radius r_0 to the short excitation time in which most of the chemical energy is released, τ_c) and ξ (the acoustic speed to the localized auto-ignition velocity) to classify the different combustion modes. The hot spot induced combustion mode is defined by a peninsula on a plot of $r_0/a/\tau_c$ against ξ . *Kalghatgi and Bradley* [31] used this method for super-knock analysis and found that super-knock case was located at the ‘developing detonation’ zone. *Dai et al.* [32] investigated the effect of a cold spot with a fuel with a strong negative temperature coefficient (NTC) behavior on combustion mode and found different cold spots could also induce

different combustion modes. Furthermore, super-knock was also recognized as ‘developing detonation’. Previous work by the authors [11][33] showed the combustion process of super-knock could be described as hot-spot induced pre-ignition followed by deflagration transitioning to detonation induced by another hot spot, and the thermodynamic state played an important role in determining the occurrence of super-knock.

These studies show pre-ignition is generally accepted as the source of super-knock and pre-ignition can lead to super-knock, heavy knock, slight knock and non-knock. The severe damage associated with super-knock is attributed to detonation aspects of the combustion process. While much has been learned on the possible sources of preignition, criteria do not exist to classify when different knock modes will occur in the presence of a pre-ignition source. The objective of this study was to systematically investigate the effects of state conditions on the types of knocking modes observed in order to propose knocking criteria in terms of fundamental combustion parameters, like end-of-compression pressure and intake air temperature. Two experimental platforms were used in the study; a highly turbocharged gasoline engine and a rapid compression machine (RCM). A spark plug was used as a pre-ignition source in each set of experiments and the state conditions were systematically varied.

EXPERIMENTAL SETUP AND METHODOLOGY

Multi-Cylinder Gasoline Direct Injection Engine Experiments

The specifications of the multi-cylinder gasoline direct injection (GDI) engine are listed in Table 1, and a schematic of the experimental setup is shown in Figure 1. The cylinder pressure was measured using a Kistler model 6052C pressure transducer with 30 MPa overload pressure and 160 kHz natural frequency. The charge output from the transducer was converted to an amplified voltage using a Kistler model 5011 charge amplifier. The 1440 pulses per engine cycle signal produced from a crank-shaft encoder AVL 365 was used for engine crank angle detection. An AVL IndiMODUL system was used for combustion analysis and crank angle-based high-speed data acquisition (DAQ). Air-to-fuel ratio (AFR) was measured using an NTK instrument. Adjustments of injection timing, injection duration, and ignition timing were controlled using an ETAS INCA system.

Table 1. Specifications of the test engine used in this study

Engine	4-cylinder in-line, turbo-charged, direct injection
Bore × stroke	77 mm × 85.8 mm
Displacement	1.6 L
Compression ratio	9.9:1
Injector	Bosch 6-hole, high pressure injector, side mounted
Fuel	Gasoline (RON=93 and MON=83)
Number of intake valves	2
Number of exhaust valves	2
Position of Spark plug	Centrally mounted

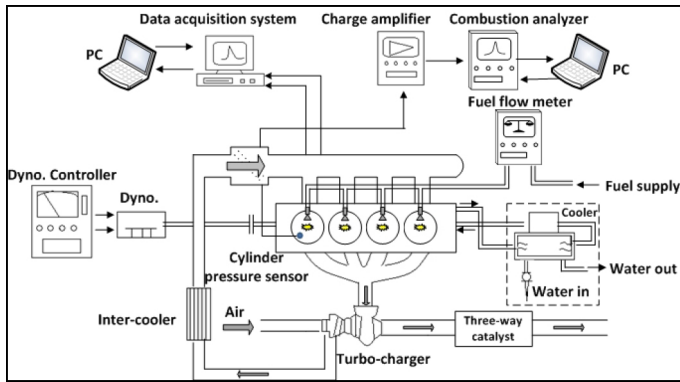


Figure 1. Diagram of the experimental setup of the test engine facility

Super-knock often occurs at low-speed and high-load engine operating conditions, so the minimum-speed operating point of maximum engine torque was selected as the super-knock test point for this study. The operating parameters are listed in Table 2.

The test procedure consisted of two steps for each operation point. First, the normal combustion mode was achieved at a wide open throttle (WOT) condition based on the original engine calibration parameters to achieve the 'baseline' case for each intake pressure and temperature condition. The intake absolute pressure of the fresh charge was set to 1, 1.3, 1.6, and 1.9 bar and for each intake air pressure two intake temperatures of 20 and 60 °C were tested.

According to previous research by the authors, super-knock can be caused by hot-spot induced pre-ignition. Therefore, in the second step of the test procedure, pre-ignition was induced by advancing the spark timing. Specifically, for each intake pressure and intake temperature, the spark timing was varied from the baseline timing to -50 °CA ATDC in increments of 3 °CA.

The detection criteria for super-knock are listed in Table 3. For this engine, the amplitude of knock limit permitted pressure oscillation is 2 bar. The specific threshold values for super-knock detection at different condition are shown in Table 4.

Table 2. Super-knock test point of the engine

Speed	1500 rpm
Throttle	WOT (Wide Open Throttle)
Intake manifold absolute pressure	1.0 bar, 1.3 bar, 1.6 bar, 1.9 bar
Intake temperature (after inter-cooler)	20 °C, 60 °C
Spark timing ^a	from 8 to -50 °CA ATDC in increments of 3 °CA
Fuel injection pressure	15 MPa
Fuel injection timing	296 °CA BTDC
Air-fuel ratio	14.5
Oil temperature	90 °C
Coolant temperature	90 °C

^a Top dead center (TDC), referenced to the top of the combustion stroke.

Table 3. Super-knock detection criteria

Indication Parameters	Threshold value
Peak pressure	50% above the average peak pressure of normal combustion
Pressure oscillation	Above 1 order of permitted knock intensity

Table 4. Threshold values for super-knock detection at different condition

T_{intake} (°C)	P_{intake} (bar)	Average peak pressure of normal combustion (bar)	Permitted pressure oscillation (ΔP) (bar)	Peak pressure of super-knock criteria (bar)	ΔP of super-knock criteria (bar)
20	1.9	67	2	100	20
20	1.6	65	2	98	20
20	1.3	54	2	81	20
20	1.0	48	2	72	20
60	1.6	55	2	83	20
60	1.3	57	2	86	20
60	1.0	54	2	81	20

Rapid Compression Machine (RCM) Experiments

To investigate the combustion regime of super-knock, a Rapid Compression Machine (RCM) was also used. The detailed information about the RCM can be found in Ref [33]. Briefly, the RCM has a stroke of 495 mm and a combustion chamber bore of 50.8 mm. A quartz end-window was used to allow optical access to the entire combustion chamber in axial direction. The combustion images were recorded using a high speed camera (Photron SA-Z) with a 50 mm lens (Nikon Micro Nikkor 1:2.8G) with spatial resolution of 128×128 pixels, which allows the maximum frame rate of 360,000 frames per second (fps). The pressure was measured using a flush mounted piezoelectric sensor (Kistler 6125C) and a charge amplifier (Kistler 5018A). The spark plug (Denso K20R) was mounted on the opposite side of the pressure sensor with electrodes located on the center of the combustion chamber. The data acquisition and synchronization between the spark plug, high speed camera, and pressure sensor were controlled by a National Instrument chassis (cDAQ-9178) and an analog input module (cDAQ-9223). The spark plug and high speed camera were triggered based on the combustion chamber pressure, and the timing was controlled within 1 ms after the end of compression for different knock cases.

In order to study super-knock phenomena, the RCM experiments considered conditions relevant to downsized boosted engines. Pure iso-octane (>99%) was used as the fuel. The rest of the test mixture consisted of ultra-high purity nitrogen (>99.999%) and oxygen (>99.995%). The equivalence ratio of the mixture was $\phi = 1$ with an inert nitrogen to oxygen molar ratio of 3.76, i.e. the molar ratio of iso-octane:oxygen:nitrogen was 1:12.5:47. The mixture was prepared using a dedicated stainless steel mixing tank at room temperature (302 K). Three compression ratios, CR = 9.8, 12.2 and 15.5 were used for the RCM experiment, which includes the majority of the range of compression ratios found in modern gasoline spark ignition engines. For the safety reasons, the targeted maximum pressure at the end of compression was limited to 30 bar in the RCM experiments. All the RCM tests were conducted at an initial temperature of 302 K. Table 5 lists the test conditions.

Table 5. Test conditions of RCM

CR	Target conditions at the end of compression		Initial conditions	
	p [bar]	T [K]	p ₀ [bar]	T ₀ [K]
9.8	10	641	0.45	302 K
	11	641	0.53	
	12	641	0.57	
	13	641	0.62	
	14	641	0.66	
	15	641	0.71	
	17	641	0.81	
	20	641	0.95	
12.2	25	641	1.19	
	12	681	0.42	
	13	681	0.46	
	14	681	0.5	
	15	681	0.54	
	16	681	0.57	
	17	681	0.62	
	19	681	0.68	
15.5	20	681	0.73	
	22.5	681	0.85	
	25	681	0.91	
	13	729	0.34	
	14	729	0.37	
	15	729	0.4	
	16	729	0.42	
	17	729	0.45	
	20	729	0.53	
	25	729	0.66	
	30	729	0.79	

RESULTS AND DISCUSSION

Results of Engine Experiments with Fixed Intake Temperature and Varying Intake Pressure

Figure 2 shows the effect of spark timing changes on the in-cylinder pressure traces at different intake pressures, while intake temperature was kept constant for all cases at 20 °C. For each intake pressure, spark timing was varied from the baseline timing to -50 °CA ATDC in increments of 3 °CA. For clarity, only the traces which are indicative of mode transition are plotted in the figure. As shown in Figure 2a and 2b, for the two lowest intake pressures, advancing the spark timing caused the transition from normal combustion to knocking conditions and then back to normal combustion. No matter how advanced the spark ignition timing was, only a slight pressure oscillation was detected at knocking condition, and the pressure oscillations were much lower than the ΔP of super-knock criteria presented in Table 4. In other words, super-knock was not identified at these low intake pressures, which means that super-knock is not expected for naturally aspirated operation of this engine. The effect of higher boosting levels is seen in Figure 2c and 2d. Advancing the spark timing at higher intake pressures resulted in a transition from normal combustion to knocking, followed by super-knocking and then back to knocking conditions and eventually to normal combustion again. The peak pressure and pressure oscillation of the cases which were classified as super-knock cases in Figure 2d (spark ignition timings of -18 and -21 °CA ATDC) reached approximately 250 bar and 190 bar respectively, which were much higher values than observed at the same spark timing for $P_{\text{intake}} = 1.6$ bar presented in Figure 2c. An important observation is that super-knock was detected only within a specific spark timing range; not at the earliest or latest spark timings studied.

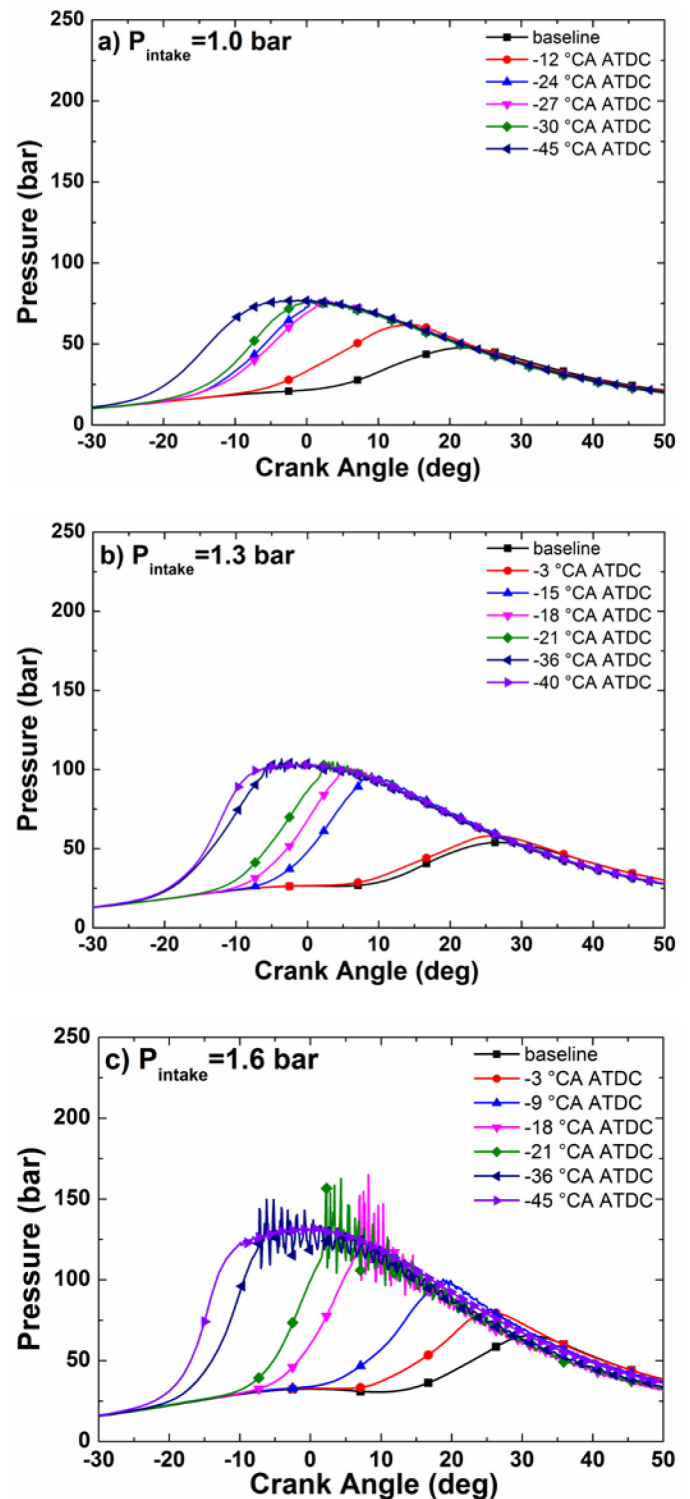


Figure 2. Experimental results for in-cylinder pressure showing the transition between combustion modes as a result of spark timing changes at different intake pressures. The intake temperature was set to 20 °C for all cases.