Chapter 2
Low-Temperature Natural Gas Combustion Engines

Sotirios Mamalis

Abstract Advanced or low-temperature combustion engines have shown the potential to achieve high fuel conversion efficiency with minimal emissions formation and therefore can provide solutions for future powertrain systems. Numerous advanced combustion concepts have been explored, including both spark-ignited and compression-ignited concepts, and each one has been investigated using different liquid or gaseous fuels. This chapter will discuss the potential of using natural gas as a fuel for future advanced combustion engines and will present the associated benefits and challenges. The low carbon-to-hydrogen atom ratio of natural gas can enable a highly efficient combustion process with low CO_2 formation; its chemical composition mitigates soot formation during combustion, and its high octane number enables high compression ratio operation of spark-ignited engines with good knock resistance. However, the low reactivity of natural gas inhibits the compression ignition of lean fuel–air mixtures, and any combustion inefficiency may result in direct methane emissions in the exhaust. These characteristics have led researchers to investigate lean natural gas combustion using prechambers (jet ignition), high-pressure direct injection (HPDI) of diesel and natural gas mixtures, micro-pilot injection concepts with premixed natural gas and direct-injected diesel fuel, as well as kinetically controlled and low-temperature combustion concepts such as Homogeneous Charge Compression Ignition (HCCI) and Reactivity Controlled Compression Ignition (RCCI) combustion. This chapter will discuss the use of natural gas in the HCCI and RCCI combustion concepts and analyze the associated benefits and challenges.

Keywords Natural gas · Low-temperature combustion · Advanced combustion
Internal combustion engines

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2.1 Introduction

Worldwide fuel economy and emissions regulations have prompted research and development on internal combustion engines that can achieve higher fuel conversion efficiency and lower emissions formation compared to currently available spark-ignition (SI) and diesel engines. Numerous advanced combustion concepts have been proposed in the literature, primarily originating from Homogeneous Charge Compression Ignition (HCCI), which was first proposed by Najt and Foster in 1983 (Najt and Foster 1983). The HCCI concept combines the homogeneous charge of premixed SI engines with the compression ignition of diesel engines to create a lean burn concept that can achieve high thermal efficiency. The lean mixture also results in low burned gas temperature, thus preventing thermal NO_x formation during combustion. The low burned gas temperature has led many researchers to use the term "low-temperature combustion" to describe this concept, which has since been used to encompass other combustion concepts of similar nature as well. HCCI combustion is achieved by creating a homogeneous and lean fuel–air mixture and compressing it until the point of autoignition, which results in a heat release process initiated and controlled by chemical kinetics. This process is different from the heat release in SI engines, which is controlled by turbulent flame propagation, as well as from the heat release in diesel engines, which is controlled by diffusion mixing between the direct-injected fuel and the surrounding air. The absence of a spark or direct fuel injection results in having no *direct* control of the start of combustion in HCCI engines. Therefore, ignition timing can only be controlled *indirectly*, by controlling the air/fuel ratio of the mixture, the dilution level, and the initial mixture temperature.

The HCCI concept has been demonstrated through experimental testing in single-cylinder optical and metal engines (Epping et al. 2002; Sjöberg et al. 2004; Sjöberg and Dec 2004, 2005, 2007; Silke et al. 2009), as well as in light-duty and heavy-duty commercial engine platforms (Christensen et al. 1997; Olsson et al. 2001, 2002; Christensen and Johansson 2000; Hyvönen et al. 2003; Haraldsson et al. 2002, 2003, 2004; Zhao et al. 2003) using gasoline and diesel fuels. Experimental results have shown that HCCI combustion can be achieved at very lean mixtures with high compression ratio resulting in high thermal efficiency as well as low NO_x and no soot formation. However, the homogeneous nature of the mixture results in bulk autoignition, and rapid heat release rate and pressure rise rate in the cylinder, which limits the maximum attainable load. In addition, igniting a lean fuel–air mixture by compression alone requires charge heating, which can be accomplished either by intake air preheating or by residual gas trapping in the cylinder (Chang et al. 2007; Babajimopoulos et al. 2009; Olesky et al. 2012; Mamalis et al. 2012).

In order to mitigate the high heat release rates of HCCI combustion, researchers have proposed techniques to introduce thermal and compositional stratification to the mixture and thus stagger the autoignition process. Partial fuel stratification (PFS) is one technique proposed by Dec et al. (2011, 2015), Sjöberg and Dec

(2006), Yang et al. (2011a, b, 2012) which utilizes split fuel injections directly into the cylinder. By splitting the injection process into one early and one late injection, the mixture becomes compositionally and thermally stratified resulting in staggered autoignition throughout the combustion chamber. Direct water injection is another technique proposed by Lawler et al. (2017), Boldaji et al. (2017, 2018), which injects water in a premixed fuel–air mixture to forcefully stratify the thermal field in the cylinder through the latent heat of vaporization of water and thus stagger the autoignition process.

In addition to the methods described above, researchers have proposed the use of two fuels to control the heat release rates of low-temperature combustion engines. The Reactivity Controlled Compression Ignition (RCCI) concept that was proposed by Kokjohn et al. (2011a, b), Splitter (2011), Hanson et al. (2011) combines a low reactivity fuel injected at the port (e.g., gasoline) with a high reactivity fuel injected directly into the cylinder to create a compositional stratification in the combustion chamber. The mixing between the two different fuels in the combustion chamber creates zones of different reactivity resulting in staggered autoignition and lower heat release rates compared to HCCI. The RCCI combustion concept has been demonstrated in light- and heavy-duty engines and has shown good controllability and fuel conversion efficiency comparable to diesel engines (Hanson et al. 2012; Splitter et al. 2011; Klos et al. 2015; Kokjohn and Reitz 2013; Kavuri et al. 2016; Lim et al. 2014). The lean, low-temperature combustion process prevents thermal NO_x formation; however, the direct fuel injection of the high reactivity liquid fuel results in some particulate emissions albeit at considerably lower levels than conventional diesel combustion.

Research on low-temperature combustion concepts such as HCCI and RCCI has been primarily focused on using gasoline and diesel fuels due to their widespread commercial use. However, a number of studies have focused on exploring advanced combustion with natural gas, as an alternative to liquid fuels that can provide solutions for sustainable future transportation and power generation.

Natural Gas HCCI Combustion

HCCI combustion with natural gas has been explored for use in heavy-duty vehicles, locomotives, and stationary power generation. However, the high Research Octane Number (RON) of natural gas requires higher compression ratio and/or higher heat addition to the fuel–air mixture to achieve autoignition compared to gasoline. Aceves et al. performed CFD simulations with detailed chemistry of a supercharged HCCI engine using methane and investigated the effect of compression ratio on combustion (Aceves et al. 1999). It was found that combustion could be well controlled through equivalence ratio and the trapped Residual Gas Fraction (RGF), but high-speed cylinder pressure sensing was necessary for control. The high load limit of the engine was posed by peak cylinder pressure and NO formation. Flowers et al. continued this modeling study using actual natural gas composition and investigated the effect of varying fuel composition on HCCI combustion (Flowers et al. 2001). HCCI combustion was found to be sensitive to natural gas composition, and active control is required in order to compensate for changes in composition typical throughout the world. Changes in natural gas composition may shift the peak heat release timing by as much as 10 Crank Angle Degrees (CADs), with significant effects on efficiency and emissions formation. The concentration of propane and butane present in natural gas can significantly affect HCCI combustion. Three control strategies were proposed: (i) adding Dimethyl Ether (DME) to the fuel–air mixture, (ii) intake gas preheating, and (iii) using hot Exhaust Gas Recirculation (EGR), which were found to be effective in controlling the heat release rate over a wide range of operating conditions.

Fiveland et al. performed experimental testing and modeling on a heavy-duty natural gas HCCI engine operating at 1000 rev/min and φ of 0.3 in order to examine the sensitivity of HCCI combustion to fuel composition (Fiveland et al. 2001). The presence of higher order hydrocarbons increased the reactivity of the mixture and reduced the temperature of autoignition. Butane had a sensitivity of 2.5 °C/%, propane had 1.5 °C/%, and ethane had 1.0 °C/%. Based on the experimental results, it was concluded that fluctuations in natural gas composition may result in high-speed or low-speed effects on engine performance.

Olsson et al. performed a similar experimental study using a Volvo TD100 heavy-duty engine modified for natural gas HCCI combustion and also performed modeling of the same engine to study the effect of compression ratio on combustion (Olsson et al. 2002). Hydrogen enrichment was used to control combustion phasing on a cycle basis. Compression ratio was varied from 15:1 to 21:1, but was found to have a small effect on the heat release rate. High compression ratio resulted in higher peak cylinder pressures but also enabled the engine to operate leaner and reduce NO_x formation. Overall, the compression ratio should be high enough to enable lean operation with low NO_x at high load, but also offer good control authority at maximum load.

Yap et al. studied the effects of hydrogen addition on natural gas HCCI combustion using a light-duty research engine with residual gas trapping (Yap et al. 2004). The hydrogen was produced using an exhaust-assisted reformer, and it was introduced into the cylinder as hydrogen-rich EGR. The addition of hydrogen in the fuel–air mixture resulted in lower intake air preheating requirement for autoignition. However, even with the addition of hydrogen, some intake air preheating was required in combination with residual gas trapping. The benefit of hydrogen in reducing the autoignition temperature was more effective at low loads; however, the addition of hydrogen resulted in higher cylinder temperatures at high load and higher NO_x compared to pure natural gas HCCI. In subsequent experiments, Yap et al. utilized low-temperature exhaust gas fuel reforming to produce reformate gas with up to 16% hydrogen by volume (Yap et al. 2006). This reformate gas was recirculated to the intake and mixed with the fresh natural gas–air mixture to control autoignition. It was confirmed that the addition of hydrogen reduced the intake air preheating requirement for autoignition.

The engine-reformer closed-loop operation showed that the hydrogen addition also promoted stable HCCI operation and extended the low load limit without reducing combustion efficiency. NO_x emissions decreased with the addition of hydrogen-rich reformate gas; however, CO and unburned hydrocarbon emissions

(UHC) increased. The addition of hydrogen also had minor benefits on the indicated specific fuel consumption (Fig. 2.1). The water content in the exhaust gas contributes to the increase of hydrogen production in the reformer and thus offsets the energy loss due to the oxidation reactions.

Soylu modeled a natural gas HCCI engine using a zero-dimensional model to investigate the combustion characteristics and phasing strategies (Soylu 2005). Controlling the equivalence ratio, and temperature and pressure conditions at Intake Valve Closing (IVC), is critical for controlling combustion phasing and can be achieved through Variable Valve Actuation (VVA), Variable Compression Ratio (VCR), and EGR. However, increasing the EGR fraction was found to reduce the maximum attainable thermal efficiency and load. The addition of propane to natural gas–air mixtures was also found to be effective in controlling combustion phasing, albeit being a low-speed control alternative. Provided that good combustion phasing control is achieved, fuel conversion efficiency of 45% can be achieved at IMEPn of 4–5 bar.

Natural gas HCCI engines have also been considered for stationary power generation, including distributed generation and Combined Heat and Power (CHP) systems. Kobayashi et al. investigated the potential of using a 50 kW natural gas HCCI engine in a CHP system and performed experimental testing, first on a single-cylinder research engine and then on a four-cylinder turbocharged engine (Kobayashi et al. 2011). Experimental results indicated that the load range of turbocharged HCCI can exceed that of naturally aspirated SI engines (Fig. 2.2). When the peak cylinder pressure is limited, high thermal efficiency with extremely low NO_x can be achieved by raising the engine compression ratio and limiting the boost pressure. The four-cylinder turbocharged HCCI engine achieved 43.3% brake thermal efficiency at 0.98 MPa bar Brake Mean Effective Pressure (BMEP) with 13.8 ppm of engine-out NO_x emissions (Fig. 2.3), which confirmed the potential of

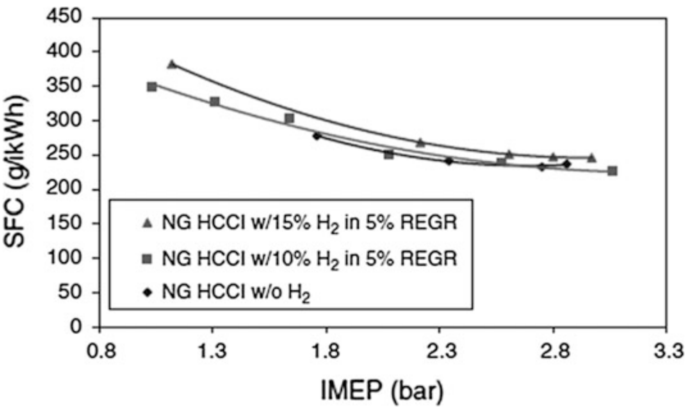


Fig. 2.1 Specific fuel consumption for natural gas HCCI combustion supplemented with 10 and 15% hydrogen, as presented by Yap et al. (2006)

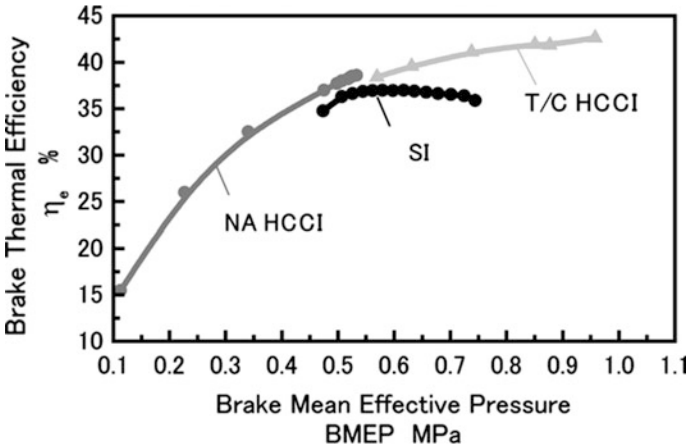
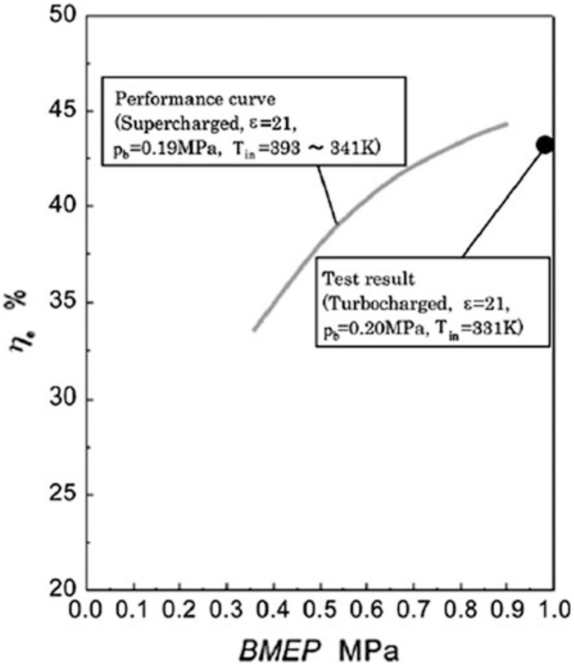


Fig. 2.2 Brake thermal efficiency and load range for naturally aspirated SI, HCCI, and boosted HCCI operation, as presented by Kobayashi et al. (2011)

Fig. 2.3 Performance of a four-cylinder, natural gas, turbocharged HCCI engine, at 1800 rev/min, compression ratio 21:1, and intake pressure of 2 bar, as presented by Kobayashi et al. (2011)



natural gas HCCI to provide high efficiency and low emissions for CHP applications.

Djermouni et al. investigated turbocharged natural gas engines by performing thermodynamic analysis including energy and exergy calculations (Djermouni and

Ouadha 2014). Increasing the compressor pressure ratio resulted in increased thermal and exergetic efficiencies; however, increasing the intake temperature to facilitate autoignition resulted in reducing both efficiencies. The lean, low-temperature HCCI combustion resulted in high exergy loss during combustion, thus increasing the equivalence ratio increased the exergetic efficiency. Overall, exergy analysis was useful in understanding the losses associated with the gas exchange and combustion processes and designing natural gas HCCI engines for maximum efficiency.

Judith et al. also performed numerical simulations of a light-duty, natural gas HCCI engine for cogeneration applications and focused on identifying the interactions between engine speed, compression ratio, air/fuel ratio, residual gas trapping, and intake air preheating on enabling HCCI combustion over a wide operating range (Judith et al. 2017). Model predictions showed that natural gas HCCI combustion could be achieved at compression ratio of 25:1 to 31:1, but ignition timing at the highest compression ratios was more difficult to control. By varying the air/fuel ratio and the Residual Gas Fraction, the autoignition timing was greatly influenced by the heat capacity of the mixture, its reactivity, and the oxygen concentration. In a similar fashion to HCCI combustion with liquid fuels, operation with natural gas depended heavily on compression ratio and intake temperature.

Sofianopoulos et al. also investigated natural gas HCCI combustion for distributed power using a small free-piston linear alternator concept (Sofianopoulos et al. 2017). The free-piston engine was modeled using three-dimensional Computational Fluid Dynamics (CFD) with detailed chemistry in order to identify the gas exchange, mixture preparation, and combustion processes required for HCCI combustion with natural gas. The free-piston engine was modeled to operate at a constant frequency of 20 Hz, which resulted from the mass of the reciprocating components as well as from the requirements posed by the linear alternator. The ports of the free-piston engine were designed to eliminate short-circuiting of fresh mixture from the intake to the exhaust and to trap more than 50% of residual gas in order to enable autoignition of the lean natural gas–air mixture. Natural gas HCCI operation was simulated for ten consecutive cycles, and the heat release rate and cylinder pressure are shown in Fig. 2.4. The free-piston engine was operated at effective equivalence ratio of 0.32 with residual gas trapping, which resulted in modeled combustion efficiency of 97.3% and gross indicated efficiency of 38.1% at 1 kW power output.

Dual-Fuel Advanced Natural Gas Combustion

Although HCCI combustion with natural gas has been demonstrated experimentally and its efficiency and emissions benefits have been documented, the high heat release rates during combustion limit the achievable upper and lower engine load. In order to reduce the heat release rates, researchers have utilized dual-fuel combustion that introduces compositional stratification to the air–fuel mixture and results in a staggered autoignition process. Stanglmaier et al. performed experimental testing on a heavy-duty, John Deere 8.1 L PowerTech natural gas engine, which was modified to operate on dual-fuel HCCI combustion at low to moderate

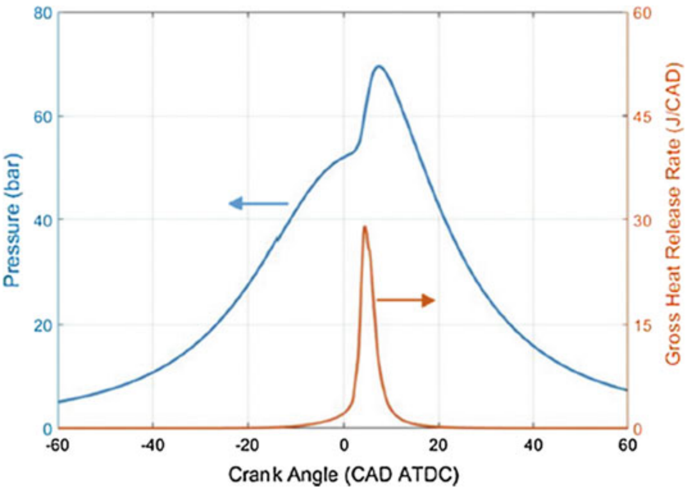


Fig. 2.4 Simulated cylinder pressure and heat release rate of a single-cylinder, natural gas, free-piston HCCI engine operating with residual gas trapping at effective equivalence ratio of 0.32, as presented by Sofianopoulos et al. (2017)

loads (Stanglmaier et al. 2001). The engine was equipped with port fuel injectors, which were used to inject Fischer–Tropsch (FT) naphtha fuel enhanced with 1000 ppm of Ethyl Hexyl Nitrate (EHN) to improve its autoignition characteristics. The liquid fuel supplemented the lean natural gas–air mixture introduced upstream in the intake manifold. Dual-fuel HCCI operation was achieved from idle to 5.5 bar BMEP, which corresponded to about 35% of the peak engine torque. Fuel blending was an effective way to control the heat release rates in HCCI mode, which were considerably higher than SI operation. HCCI operation resulted in up to 15% fuel conversion efficiency benefits compared to SI operation and a simultaneous reduction of NO_x by 95–99%. However, HCCI operation resulted in higher CO and UHC emissions than SI operation at the same conditions.

Papagiannakis et al. performed experimental testing of dual-fuel natural gas–diesel combustion on a single-cylinder DI diesel engine (Papagiannakis and Hountalas 2004). The engine was operated using a premixed natural gas–air mixture and direct injection of a small amount of diesel fuel to control autoignition. Dual-fuel operation resulted in lower heat release rate and pressure rise rate compared to conventional diesel combustion. At low loads, dual-fuel operation showed lower fuel conversion efficiency than diesel, but high load operation was equally efficient. In all cases, dual-fuel operation exhibited low-temperature combustion characteristics, which resulted in lower NO_x formation compared to conventional diesel combustion.

Kong studied natural/DME HCCI combustion using CFD with detailed chemical kinetics and compared the modeling results against experimental data from a single-cylinder Yanmar diesel engine modified for dual-fuel operation (Kong 2007).

Natural gas and DME were premixed upstream in the engine intake manifold, and DME was used as an additive to the fuel–air mixture to promote autoignition. Modeling results showed that HCCI combustion is facilitated by the addition of DME, and by increasing the DME concentration, the low-temperature heat release increases and drives the autoignition of the mixture. The modeling results were used to establish engine operating limits at different concentrations of natural gas and DME in the mixture (Fig. 2.5). As the natural gas concentration increased, the operating range becomes narrower and HCCI combustion becomes unstable.

Nieman et al. performed CFD simulations of a heavy-duty RCCI engine operated with natural gas and diesel (Nieman et al. 2012). Natural gas was used as a replacement for gasoline as the low reactivity fuel, because its higher RON created larger reactivity gradient between the two fuels when mixed in the cylinder. A broad speed and load range were investigated; six operating points from 4 to 23 bar IMEPn and 800 to 1800 rev/min were optimized, which represent typical heavy-duty engine operating conditions. Using a compression ratio of 16:1, it was determined that operation up to 13.5 bar IMEP can be achieved without EGR, while still maintaining high efficiency and low emissions. Natural gas/diesel operation was compared against gasoline/diesel operation at 9 bar IMEPn and was found that in the natural gas/diesel gases 90–95% of UHC emissions were methane. The sensitivity of high load RCCI combustion to injection parameters was examined, and the results showed that precise injection control is necessary.

Fathi et al. performed experimental testing on a single-cylinder CFR engine operated in HCCI mode with n-heptane/natural gas fuel (Fathi et al. 2011) and focused on understanding the effects of EGR on combustion phasing control. The

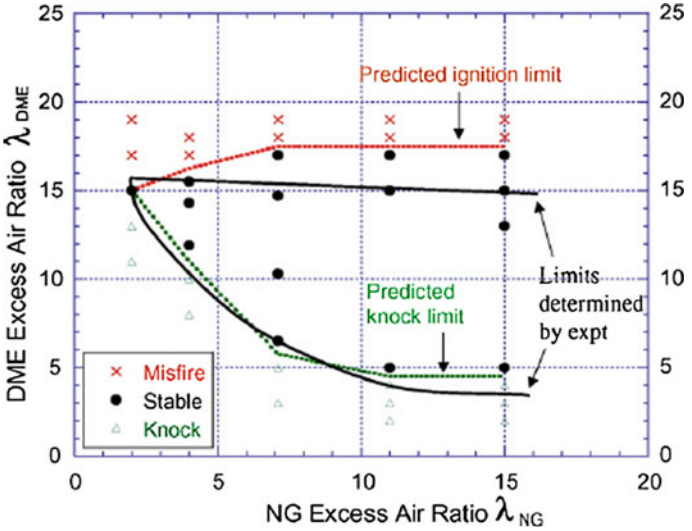


Fig. 2.5 Predicted operating limits for a dual-fuel natural gas–DME HCCI engine at different natural gas and DME concentrations, as presented by Kong (2007)

fuel blend was premixed and introduced at the engine intake manifold. Experimental data showed that EGR reduced the bulk cylinder temperature as well as the pressure rise rate and peak pressure during combustion. EGR also delayed autoignition and increased the burn duration due to its effect on the physical and chemical properties of the mixture (Fig. 2.6). However, in the cases where EGR resulted in considerably delayed combustion phasing, the thermal efficiency was reduced. Although EGR reduced the peak cylinder temperatures and thus reduced NO_x formation, it had an adverse effect on CO and UHC emissions.

Doosje et al. also performed experimental testing of RCCI combustion in a six-cylinder, 8.0 L, heavy-duty engine, using natural gas as the low reactivity fuel and cooled EGR (Doosje et al. 2014). The engine was used to explore the operating limits of RCCI combustion. Experimental results showed that RCCI operation could be achieved between 1200 and 1800 rev/min, 2 and 9 bar BMEP, with engine-out NO_x and soot emissions that satisfied the Euro VI emissions regulations. UHC emissions were high, but the high exhaust gas temperature was suitable for using an oxidation catalytic converter. The effect of diesel injection timing on the

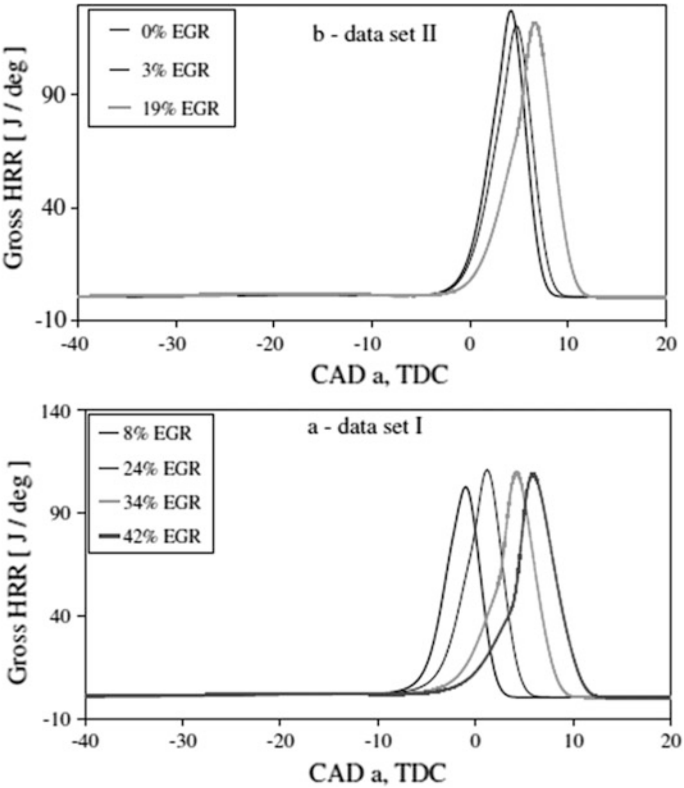


Fig. 2.6 Effect of EGR on the heat release rate of n-heptane/natural gas HCCI combustion, as presented by Fathi et al. (2011)

heat release was investigated, and experimental results showed that when the start of injection (SOI) was advanced beyond 34 CAD before TDC, further advancement resulted in delayed heat release rate, an indication of operation in the RCCI regime. For all operating points considered, the engine thermal efficiency in RCCI mode was comparable to or better than conventional diesel combustion. Total UHC was high, but 80–85% of them comprised of methane. For the operating conditions examined, any methane number (MN) variation in the 70–100 range had negligible effects on RCCI combustion.

Zoldak et al. performed a computational study on RCCI combustion using natural gas as the low reactivity fuel on a 15.0 L heavy-duty diesel engine (Zoldak et al. 2014). The trade-offs between fuel consumption, pressure rise rate, peak cylinder pressure, and emissions formation were examined, and the results showed that RCCI combustion had the potential for 17.5% NO_x reduction, 78% soot reduction, and 24% decrease in fuel consumption compared to conventional diesel combustion at the rated power condition using the same air–fuel ratio and EGR level. Modeling results showed that the amount of diesel fuel injected directly into the cylinder dictated the mixture reactivity and thus the combustion phasing and pressure rise rate. The maximum pressure rise rate and peak pressure increased compared to conventional diesel combustion, but both were within acceptable limits for engine durability. The large reduction in soot formation in RCCI mode resulted from the lower level of mixture stratification compared to conventional diesel, as well as from having natural gas as the low reactivity fuel.

Similar studies were performed by Dahodwala et al., who focused on analyzing experimental RCCI combustion data on a heavy-duty diesel engine operated at 6 bar BMEP and different speeds (Dahodwala et al. 2014, 2015). The study evaluated the impact of various control variables, such as natural gas substitution rate, EGR rate, and injection strategy on achieving RCCI combustion, and thereby establishing a framework for identifying the in-cylinder mixture properties required for RCCI. Experimental data were also collected at 14 bar BMEP in order to investigate high load RCCI operation as well. A CFD model with detailed chemistry was also used to support the analysis of experimental data. Increasing the natural gas substitution resulted in delayed combustion phasing and lower burn rate, and also increased CO and UHC emissions. Combustion phasing and burn duration could also be controlled through the EGR rate, although increasing EGR resulted in lower combustion efficiency. Increasing the amount of diesel fuel injected in the cylinder led to more mixture stratification and advanced combustion phasing. The injection strategy dictates the combustion mode of the engine, and the timing of injection changes with engine speed. For conventional diesel combustion, NO_x emissions were higher at lower engine speeds. However, for RCCI combustion NO_x emissions were higher at higher engine speeds. Reduced engine speed in RCCI mode also reduced CO and UHC emissions.

Kakaee et al. used CFD modeling to study the effects of natural gas composition and engine speed on combustion and emission characteristics of natural gas/diesel RCCI combustion (Kakaee et al. 2015). RCCI combustion was found to be sensitive to fuel composition and engine speed. Specifically, the Wobbe number

(WN) of the fuel affected the ignition timing and burn rates. Higher WN resulted in higher peak cylinder pressure and temperature, higher NO_x emissions, but lower CO and UHC emissions. Gas with lower WN exhibited lower heat release rate, which resulted in lower combustion efficiency at high engine speeds. Overall, gas with higher WN was found to be beneficial for efficiency and emissions at high engine speed operation. The same group studied the effects of piston bowl geometry on combustion and emissions of natural gas/diesel RCCI engine using CFD modeling (Kakaee et al. 2016). Three different piston bowl geometries were studied: a conventional reentrant bowl for diesel operation, a bathtub-shaped, and a cylindrical bowl (Fig. 2.7). Modeling results showed that the piston bowl geometry did not affect RCCI combustion at low engine speeds, but had an increasing effect as engine speed increased. By increasing the bowl depth, cylinder pressure and temperature increased, which in turn increased NO_x emissions. CO and UHC emissions were minimized at bowl depth of 1 mm. Also, by increasing the piston chamfer size, the cylinder pressure and temperature increased, which again increased NO_x but also increased the gross indicated efficiency. Using a chamfered ring-land can reduce UHC emissions particularly at chamfer sizes greater than 3 mm.

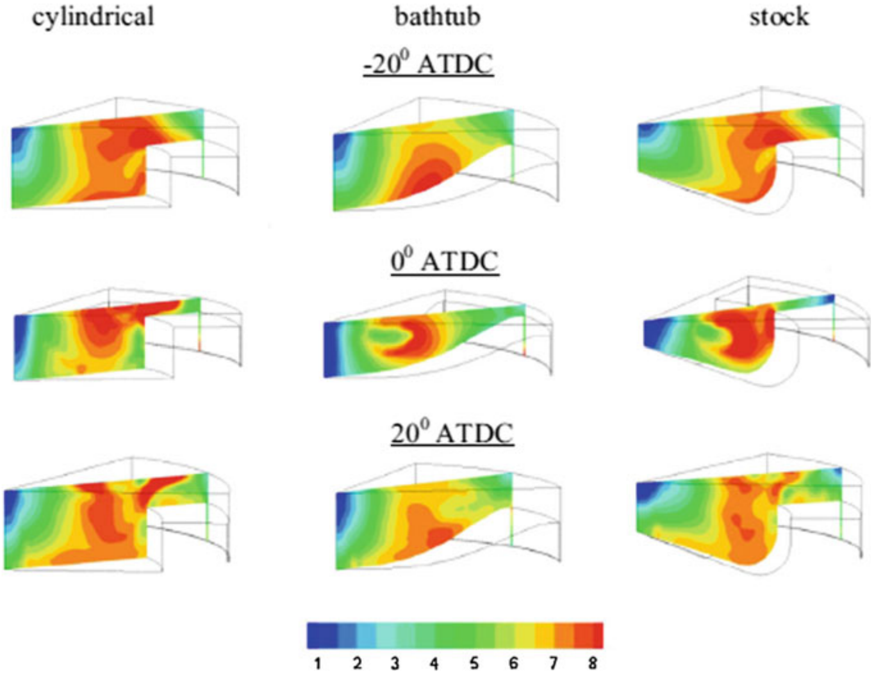


Fig. 2.7 Simulated cylinder velocity (m/s) cutplanes at −20° ATDC, TDC, and 20° ATDC, for three different piston bowl profiles for natural gas/diesel RCCI combustion, as presented by Kakaee et al. (2016)

Jia et al. performed experimental testing of natural gas/diesel RCCI combustion on a single-cylinder AVL 501 heavy-duty diesel engine and focused on analyzing the effects of diesel injection timing and duration on combustion at 1200 rev/min and 9 bar BMEP (Jia and Denbratt 2015). Experiments were conducted at two compression ratio levels, 14:1 and 17:1. It was found that reducing the compression ratio to 14:1 had favorable effects on combustion phasing control and NO_x emissions, but increased UHC emissions. The lower compression ratio resulted in longer ignition delay times, longer combustion duration, and also lower heat release rate. Delaying the injection of diesel fuel made the fuel–air mixture more stratified, which reduced the ignition delay and increased the burn rate. Overall, it was shown that RCCI combustion with low NO_x and almost zero soot emissions can be achieved, albeit with high UHC emissions which can be treated in the emissions control system.

Paykani et al. performed a similar study on investigating injection strategies for natural gas/diesel RCCI combustion, using CFD modeling (Paykani et al. 2015). Direct-injected diesel was split into two injections, and it was shown that the timing of each injection as well as the fuel fraction split has significant effects on RCCI combustion. Delaying the second injection was found to increase mixture stratification, local fuel reactivity, and burned gas temperatures, which advanced combustion phasing and increased NO and soot emissions as well as the ringing intensity. Similar effects were seen by increasing the amount of diesel fuel injected in the second injection. The injection timing and duration also played a role when engine speed was increased, because the available time for fuel–air mixing was reduced. Therefore, as engine speed increased, the peak pressure and temperature decreased, which resulted in later combustion phasing and increased CO and UHC emissions. The simulated mid-load case had over 50% gross indicated efficiency, with low NO_x and soot without using EGR. Combustion phasing could be accurately controlled through the ratio of the natural gas and diesel, as well as through the ratio of diesel fuel split between the two direct injections. Additionally, it was found that the large difference in reactivity between natural gas and diesel helped the engine to achieve low pressure rise rate.

Ansari et al. used experimental testing of a 1.9 L diesel engine and CFD modeling to map the efficiency and emissions of light-duty natural gas/diesel RCCI combustion (Ansari et al. 2016). The engine was operated at speeds of 1300–2500 rev/min and loads of 1–7 bar BMEP. Operation was limited to 10 bar/deg of maximum pressure rise rate and 6% Coefficient of Variation (COV) of IMEP. The engine operating envelope was explored by varying the natural gas/diesel blend ratio, the diesel injection fuel split and timing, and the EGR amount. More than 80% of the required fuel energy input in RCCI mode was provided from natural gas. Experimental results showed that the pressure rise rate is very sensitive to the pilot injection timing and the fuel split ratio between the two direct injections. At low loads, RCCI combustion provided brake thermal efficiency equivalent to or lower than diesel; however, as speed and load increased, the efficiency increased as well. The maximum recorded brake efficiency for RCCI combustion was 39% at 2500 rev/min and 6 bar BMEP, compared to 34% for conventional diesel combustion. Up to 92% reduction in NO_x was achieved through precise control of the injection parameters. The majority of the RCCI operating points had exhaust gas temperature below 450 °C, which is a typical light-off temperature for methane oxidation catalysts. Therefore, the low exhaust gas temperature and the high CO and UHC emissions present a major challenge for the commercial adoption of natural gas/diesel RCCI engines.

Hockett et al. focused on developing a reduced chemical kinetics mechanism for performing detailed chemistry calculations of natural gas/diesel dual-fuel engines (Hockett et al. 2016). In this mechanism, natural gas is modeled as a mixture of methane, ethane, and propane, while diesel is modeled as n-heptane. The mechanism consists of 141 species and 709 reactions and has been validated against experimental premixed laminar flame speed measurements of $CH_4/O_2/He$ mixtures, ignition delay and lift-off length from a diesel spray experiment in a constant volume chamber, and also against dual-fuel engine experiments using CFD simulations. The results showed that this mechanism accurately reproduces the chemical kinetic behavior of larger detailed mechanisms and captures the laminar flame speeds at high pressure, the ignition delay and lift-off length of the diesel experiment, and the heat release rate in the engine experiments. Also, this reduced mechanism is able to accurately model varying natural gas reactivity without relying on rate constant tuning.

Poorghasemi et al. performed CFD simulations with detailed chemical kinetics to study the effect of diesel injection strategies on natural gas/diesel RCCI combustion in a light-duty engine (Poorghasemi et al. 2017). The parameters that were varied in the simulations included the premixed ratio of natural gas, the diesel fuel fraction split between the first and second injection, the timing of the two injections, the injection pressure, and the spray included angle. The modeling results showed that by increasing the premixed ratio of natural gas, the mixture reactivity is reduced, resulting in increased ignition delay and lower heat release rates. The diesel injection strategy has significant effects on RCCI combustion because it controls the local reactivity of the mixture. As the direct injections are moved toward TDC, the local reactivity of the mixture increases the temperature during combustion by raising the local equivalence ratio. Increasing the amount of diesel fuel injected in the first pulse resulted in higher heat release rates and cylinder pressure. However, more diesel fuel is accumulated in the crevice volume and on the cylinder wall, which increased CO and UHC emissions. By increasing the spray angle, more fuel was burned in the centerline of the spray and the squish region of the combustion chamber. However, by decreasing the spray angle, more fuel was burned in the cylinder bulk. The latter results in higher CO and UHC emissions generated near the cylinder walls, as well as higher NO_x formation due to locally richer zones that result in higher burned gas temperature.

Rahnama et al. used CFD modeling to investigate natural gas/diesel RCCI combustion in a heavy-duty engine and focused on investigating the effects of using hydrogen, reformer gas, and nitrogen on combustion (Rahnama et al. 2017). The lower reactivity of natural gas compared to gasoline resulted in compromised engine performance at low loads, but the addition of hydrogen or syngas (reformer gas) as additives can improve the combustion process at low loads (Fig. 2.8). They can increase the combustion and thermal efficiencies and significantly reduce the UHC and CO formation. However, high values of hydrogen and syngas were found to increase cylinder temperature and thus NO_x emissions.

The modeling results showed that adding hydrogen or syngas to RCCI combustion increases the combustion efficiency and is more favorable than increasing the fuel fraction of the direct-injected diesel, because the latter increases soot formation. The ignition delay and start of combustion were not significantly affected by the addition of hydrogen or syngas, and it can be well controlled by the diesel fuel fraction and the intake temperature. Medium load operation was not greatly benefited by the additive gases, despite the fact that thermal efficiency was increased, and UHC and CO emissions were reduced compared to the baseline RCCI engine.

Gharehghani et al. performed an experimental study of RCCI combustion with natural gas and biodiesel derived from waste fish oil, using a single-cylinder Ricardo E6 diesel engine (Gharehghani et al. 2015). The properties of the biodiesel used in their study are shown in Table 2.1, along with diesel and natural gas.

The waste fish oil biodiesel has higher cetane number and oxygen content than conventional diesel, which resulted in higher heat release rates and more stable combustion in natural gas/biodiesel RCCI operation. Figure 2.9 shows the heat release rates for conventional diesel and RCCI combustion modes using diesel, biodiesel, and natural gas. The higher heat release rate in natural gas/biodiesel RCCI combustion led to 1.6% higher gross thermal efficiency than the natural gas/

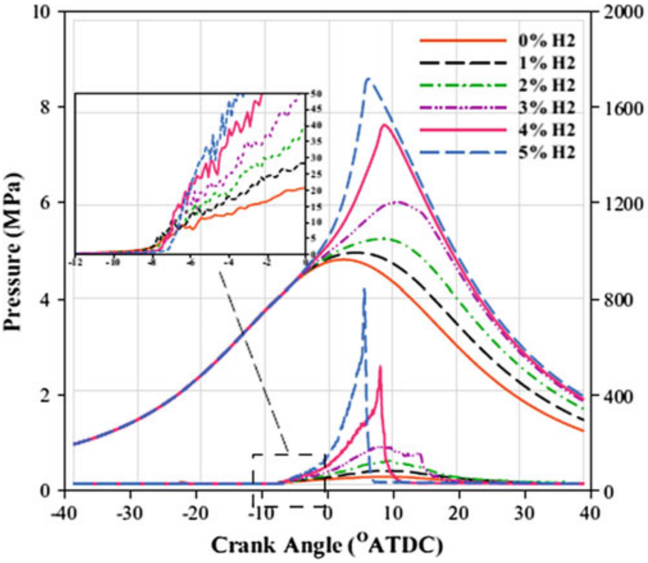


Fig. 2.8 Impact of hydrogen addition on the heat release rate and cylinder pressure of a heavy-duty natural gas/diesel RCCI engine, as presented by Rahnama et al. (2017)

Table 2.1 Properties of waste fish oil biodiesel, diesel, and natural gas used for RCCI engine experiments, as presented by Gharehghani et al. (2015)

Parameter	Biodiesel	Diesel	NG
Content of C (%)	82.06	84.2	–
Content of H (%)	8.64	15.7	–
Content of O (%)	9.3	<0.1	–
Flash point (PM, °C)	164–173	74–76	–
Density (15 °C, kg/m^3)	870–880	830	–
Kinematic viscosity (40 °C, mm^2/s)	4.142	3.4	–
Cetane index	51.5	50	–
Low heating values (MJ/kg)	41	43.15	45
Methane (Mole. %)	–	–	90.30
Ethane (Mole. %)	–	–	4.28
Propane (Mole. %)	–	–	0.63
Butane (Mole. %)	–	–	0.08
Nitrogen (Mole. %)	–	–	3.6

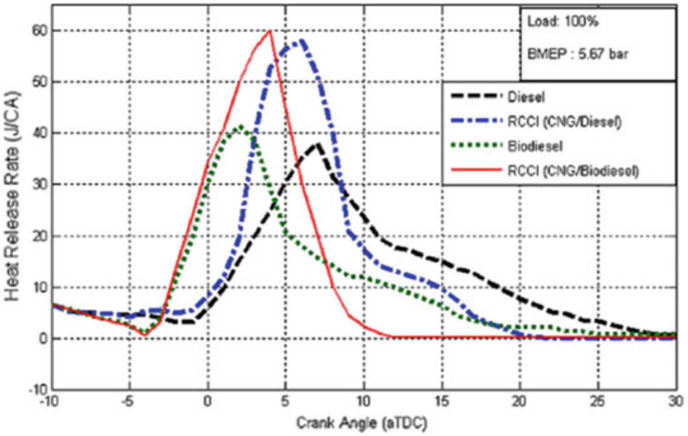


Fig. 2.9 Heat release rate for conventional diesel and RCCI combustion modes in a single-cylinder engine, using diesel, biodiesel, and natural gas, as presented by Gharehghani et al. (2015)

diesel RCCI, as well as higher combustion efficiency and marginally lower heat transfer losses.

Based on experimental results, the waste fish oil biodiesel was found to be a good alternative to diesel, with great potential for CO reduction in RCCI mode, especially at medium and high loads. RCCI combustion using premixed natural gas with either diesel or biodiesel was found to have significantly lower NO_x formation than conventional diesel combustion.

Bekdemir et al. performed multi-zone modeling of natural gas/diesel RCCI combustion and focused on deriving real-time, map-based models that can be used for RCCI control system development (Bekdemir et al. 2015). The multi-zone model was used to extract trends of control-relevant quantities, such as CA10, CA50, peak cylinder pressure, peak pressure rise rate, and NO_x emissions, as functions of the start of injection, fuel blend ratio, and engine speed. Overall, the model was able to capture the right trends as functions of the control variables, which can be used for future control system development. However, the model showed sensitivity to the initial temperature of the mixture, which can be addressed by investigating cylinder-to-cylinder and cycle-to-cycle variations.

Advanced and dual-fuel combustion concepts using natural gas have shown great potential for efficiency gains and emissions reduction, but are also susceptible to abnormal combustion phenomena such as knock and Low-Speed Pre-Ignition (LSPI). LSPI has typically been associated with downsized, boosted SI engines, but Zaccardi et al. discussed the occurrence of LSPI in diesel–methane CI engines (Zaccardi and Serrano 2014). The LSPI occurrence in dual-fuel engines has been linked to the diesel pilot start of injection, which can vary and thus affect the temperature of exhaust gases and in-cylinder trapped burned gases. However, the causes of LSPI in CI engines can be multiple and complex to identify. The combustion process of CI dual-fuel engines is radically different than SI engines in terms of mixture preparation and ignition, thus the mechanisms causing LSPI in SI engines (overheated spark plugs, liquid fuel films, and fuel-oil interactions) may not necessarily apply to CI engines. The sources of LSPI in CI diesel–methane engines have been mainly associated with local spontaneous gas phase autoignition, originating from hot residual gases and temperature heterogeneity in the combustion chamber (Zaccardi and Serrano 2014).

Kirsten et al. presented a study on advanced knock detection in diesel/natural gas engines and introduced a novel methodology using the in-cylinder pressure and the knock sensor data (Kirsten et al. 2016). Their methodology accounted for variation in multiple parameters such as diesel rail pressure, start of injection, amount of fuel injected, equivalence ratio, intake air temperature, methane number, compression ratio, and load. Based on these parameters, they developed an algorithm that can distinguish between individual knocking and normal cycles, while considering the premixed and diffusion phases of CI combustion.

2.2 Summary and Future Outlook

The experimental and modeling studies discussed in this chapter have shown that natural gas can be used as a fuel for low-temperature combustion engine concepts such as HCCI and RCCI. Specifically, the lower reactivity of natural gas compared to gasoline makes it suitable for dual-fuel advanced combustion concepts, in which the natural gas is paired with a high reactivity fuel such as diesel or biodiesel. In these applications, natural gas can be used to create a background fuel–air mixture for lean, low-temperature combustion with high thermal efficiency and low soot, NO_x, UHC, and CO formation. These characteristics can enable advanced natural gas and dual-fuel engines to provide solutions for future transportation and power generation systems. The low reactivity of natural gas makes the implementation of single-fuel HCCI engines challenging; however, dual-fuel diesel/natural gas engines are already used in stationary power generation and locomotive applications and have strong potential to be used in heavy-duty on-highway and off-highway applications.

The main challenge of advanced natural gas combustion is associated with unburned fuel (or natural gas slip), which is manifested as methane emissions in the exhaust and needs to be treated in low-temperature aftertreatment systems. Another challenge is the identification and prevention of abnormal combustion phenomena such as knock and LSPI, which are different in nature than those observed in SI engines. Despite these challenges, advanced natural gas engines have strong potential for use in transportation and power generation in the future. Making advanced natural gas engines widely commercially available will result in direct reduction of CO_2 emissions, as well as reduced dependence on liquid petroleum fuels.

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