Chapter 1
Introduction to Advanced Combustion Technologies: The Role of Natural Gas in Future Transportation and Power Generation Systems

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Abstract Among the many alternatives to gasoline and diesel, natural gas is considered a viable fuel for future transportation and power generation applications. The present chapter provides an introductory overview of the role of natural gas in future transportation and power generation systems. Current and projected trends (up to 2040) for global energy consumption and the associated contribution of natural gas in various sectors (industrial, transportation, residential, etc.) are discussed. The advantages and challenges of natural gas as a combustion fuel, natural gas fuel storage and transportation challenges (as compressed natural gas and liquefied natural gas), and natural gas utilization in internal combustion (IC) engines are reviewed. Advanced natural gas low-temperature combustion (LTC) strategies for IC engines, natural gas combustion in spark ignition (SI) engines with a specific focus on direct injection of natural gas, natural gas utilization in marine SI and compression ignition (CI) engines, natural gas utilization in light-duty, heavy-duty, industrial, and marine engines, emissions control technologies for natural gas-fueled engines, and a review of natural gas-powered residential scale micro-combined heating and power (CHP) systems are the major topics explored in the book. The organizational rationale of the book is discussed, and brief summaries of various chapters in the book are provided.

Keywords Natural gas · Low-temperature combustion · Advanced combustion Dual fuel · Spark ignition

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1.1 Introduction

With increasing global population and economic development, energy consumption is expected to increase significantly, while the energy resource portfolio is expected to become increasingly diverse. According to the 2018 International Energy Outlook (IEO 2018) provided by the US Energy Information Administration (EIA 2018), the world energy consumption is projected to increase from about 575 quadrillion British Thermal Units (BTUs) in 2015 to 739 quadrillion BTU by 2040. Of this, natural gas accounts for a significant fraction as an energy source. For example, while natural gas accounted for about 125 quadrillion BTU ($\sim$22% of total) of the energy consumption in 2015, it is projected to increase to 182 quadrillion BTU (nearly 25% of total) of the energy consumption in 2040, likely accounting for the largest increase in global primary energy consumption by source. Global natural gas consumption statistics in 2015 (IEA 2017) indicated that nearly 38% of the total was utilized in the industrial sector, 30% in the residential sector, while the remainder was used in transportation (7%), commercial and public service (13%), and non-energy sector, agriculture, fishing, etc. (12%). One of the challenges of using natural gas, especially in transportation applications, is onboard natural gas storage. Two options for natural gas storage are in compressed natural gas (CNG) form (typically at 3600 psig or 250 bar) or in liquefied natural gas (LNG) form at −260 °F (or −160 °C) (US DOE 2018). Although cryogenic natural gas storage as LNG is technically more complicated and economically more demanding, it is clearly advantageous in terms of substantially lower storage space and weight requirements and significantly longer durations between fuel refueling compared to CNG (because of higher fuel energy density for a given storage volume when stored in liquefied form). With the increasing market penetration of LNG transported via ships to different parts of the world, it is natural to consider LNG (and CNG) as a primary fuel in marine applications.

Natural gas has several inherent advantages that augur well for its being adapted for transportation and power generation applications. For example, natural gas typically exhibits high resistance to autoignition (high octane number, allowing the use of higher compression ratios), lower carbon-to-hydrogen ratio (leading to lower post-combustion CO_2 emissions), suitability for lean combustion (leading to higher fuel conversion efficiencies), and a well-established infrastructure for production and distribution in many parts of the world.

Considering the general energy trends discussed above and some of the advantages of natural gas compared to other fuels, it is clear that natural gas is (and will continue to be) a significant energy resource in a variety of sectors, including transportation, industrial power generation, and residential applications (e.g., home heating). For transportation and industrial power generation applications, combustion of natural gas in internal combustion (IC) engines will remain an important energy conversion strategy for the foreseeable future. This book focuses on advanced natural gas combustion and emissions control technologies, including both transportation applications (including light-duty, heavy-duty, and marine) and stationary power generation for residential applications.

1.2 Organization of the Book

The book is organized as follows. Chapter 2 provides a discussion of advanced natural gas low-temperature combustion (LTC) strategies for IC engines. Chapters 3 through 6 deal with the fundamentals and applications of natural gas combustion in spark ignition (SI) engines with a specific focus on direct injection of natural gas. Natural gas utilization in marine SI and compression ignition (CI) engines is discussed in Chap. 7. Chapters 8 through 12 deal with natural gas utilization in light-duty, heavy-duty, industrial, and marine engines. Chapter 13 discusses emissions control technologies for natural gas-fueled engines, while Chap. 14 presents a review of natural gas-powered residential-scale micro combined heating and power (CHP) systems. Both experimental and computational analyses of natural gas combustion, performance, and emissions are covered.

Natural gas combustion in IC engines can occur over a wide range of operating conditions. Depending on the type of engine, the combustion strategy utilized, and the application, natural gas combustion can occur at different compression ratios (higher for CI compared to SI), overall fuel–air equivalence ratios (lower for CI), injection strategies (port injection vs. direct injection), in-cylinder fuel stratification (homogeneous vs. heterogeneous), and in-cylinder conditions of temperature and pressure. Various natural gas combustion strategies have been investigated over the past several decades. These include lean-burn natural gas combustion using a variety of ignition systems (e.g., spark ignition, laser ignition, turbulent jet ignition with pre-chambers), conventional diesel-ignited natural gas dual-fuel combustion, homogeneous charge compression ignition (HCCI) combustion of natural gas, dual-fuel LTC of premixed natural gas with diesel pilot or diesel micro-pilot ignition, high-pressure direct injection (HPDI) of natural gas and diesel leading to stratified diesel-ignited natural gas dual-fuel combustion, and reactivity controlled compression ignition (RCCI) combustion. Naturally, the chapters in this book present an eclectic mix of different current approaches as well as promising natural gas combustion and emissions control technologies for the future.

For example, Chap. 2 reviews advanced natural gas LTC concepts such as HCCI and RCCI and discusses their potential benefits (e.g., low emissions of oxides of nitrogen (NO_x), particulate matter (PM), and CO_2) and important challenges (e.g., unburned hydrocarbons (UHC), knock).

Partially stratified combustion of natural gas in SI engines is dealt with in Chap. 3. A combined experimental and computational fluid dynamics (CFD) approach is adopted to analyze natural gas PSC in both a constant volume combustion chamber (CVCC) and a single-cylinder research engine (SCRE). A large eddy simulation (LES), coupled with a partially stirred reactor model for considering the non-resolved turbulence-chemistry interaction, is first validated with Schlieren images obtained in the CVCC and subsequently used for extensive numerical analysis of PSC in the SCRE. With detailed CFD simulations and partial fuel stratification, ultra-lean SI combustion of natural gas is demonstrated with improved engine performance on the SCRE.

Natural gas DI technology is explored numerically in Chap. 4 as a means to improve volumetric and brake thermal efficiencies in natural gas-fueled SI engines. Volumetric efficiency and engine brake power are improved in natural gas DISI by obviating intake air displacement and throttling losses due to manifold induction or port fuel injection (PFI) of natural gas. Modeling strategies for natural gas DI are reviewed, followed by detailed studies of the gas injection process through poppet-type outwardly opening injectors. Specifically, the effect of gas injection on the in-cylinder flow field (e.g., the occurrence of compression shocks, expansion fans, jet collapse) and fuel–air mixing is studied using high-fidelity LES and unsteady Reynolds-averaged Navier–Stokes (URANS) CFD models.

The prospects and challenges of natural gas DI combustion in SI engines in comparison with natural gas PFI are presented in Chap. 5. After a discussion of DI nozzle geometry, the performance of natural gas DI injectors is investigated using Schlieren and planar laser-induced fluorescence (PLIF) imaging. The effect of start of injection (SOI) of natural gas, brake mean effective pressure (BMEP), and equivalence ratio on natural gas DI operation are studied on an SCRE.

Chapter 6 examines the effects of EGR on the performance of SI engines fueled by natural gas and natural gas–hydrogen blends (with 40% v/v of hydrogen). Based on experimental results obtained from a naturally aspirated light-duty SI engine and a turbocharged heavy-duty SI engine, the authors show that EGR can be utilized to yield high specific power and improved fuel conversion efficiency with lower thermal stress. It is shown that hydrogen-enriched natural gas can counteract the reduction of combustion rates with EGR (especially at high EGR levels) and also mitigate the adverse impact of EGR on UHC emissions.

Chapter 7 forms a sort of natural transition between natural gas-fueled SI and CI engines. It presents an operational, environmental, and economic assessment of natural gas-fueled, two-stroke, and four-stroke dual-fuel CI engines and four-stroke SI engines used in marine applications. Fuel conversion efficiency, power density, ignition stability, knocking tendency, and exhaust emissions are considered for both SI and dual-fuel CI engines, and the inherent trade-offs in adapting natural gas as a primary fuel for marine applications are discussed.

Advanced combustion and ignition technologies for natural gas-fueled CI and SI engines are dealt with in Chap. 8. Natural gas-fueled HCCI, RCCI, and dual-fuel LTC strategies are reviewed, and the PREmixed Mixture Ignition in the End gas Region (PREMIER) combustion concept is presented in significant detail. With control of pilot fuel injection quantity and pressure, pilot fuel injection timing, gaseous fuel equivalence ratio, and exhaust gas recirculation (EGR) levels, it is shown that a reasonable compromise can be achieved between fuel conversion efficiency and exhaust emissions using the PREMIER concept. In addition, advanced ignition systems such as laser ignition and plasma-assisted ignition of lean natural gas–air mixtures at relatively high compression ratios are also reviewed.

In Chap. 9, a parametric analysis is performed for diesel–natural gas RCCI in a light-duty CI engine. Specifically, the impact of natural gas substitution, EGR, compression ratio on RCCI performance and emissions is presented. The authors show that, by optimizing the combustion chamber and the aforementioned dual-fuel engine operating parameters, it is possible to reduce engine-out exhaust emissions (UHC emissions, in particular) while simultaneously improving fuel conversion efficiency.

Design and calibration strategies for improving diesel–methane dual-fuel HCCI engines are described in Chap. 10. Results from a full factorial design-of-experiments study of the effects of compression ratio, intake pressure, diesel pilot injection timing and injection pressure, and methane substitution on combustion evolution, engine performance, and pollutant emissions are presented. The results show that dual-fuel HCCI combustion can be achieved both with early and late SOIs when combined with high intake pressures to yield very low NO_x emissions and maximum pressure rise rates with very little penalty on fuel conversion efficiency, HC, and carbon monoxide (CO) emissions.

Chapter 11 presents results from a combined experimental and computational investigation of diesel–natural gas dual-fuel combustion in a light-duty industrial engine. The authors leverage calibrated CFD and 1D models of dual-fuel combustion and experiments at different engine loads and speeds to optimize dual-fuel operation (without EGR) and demonstrate virtual elimination of soot, significant NO_x and CO_2 reduction, and improvements in brake fuel conversion efficiency. The authors report higher engine-out UHC and CO emissions, which may be eliminated with an effective exhaust oxidation catalyst.

One of the challenges in conventional diesel–natural gas dual-fuel combustion and dual-fuel LTC is unstable engine operation, especially at low loads. Cyclic combustion variations, which lead to engine instabilities and high UHC and CO emissions in dual-fuel LTC, are discussed in Chap. 12. Inconsistent fuel–air mixing from one engine cycle to another, leading to cyclic inconsistencies in ignition and combustion phasing as well as combustion duration, may be an important cause of cyclic combustion variations in dual-fuel LTC. Therefore, strategies to mitigate cyclic combustion variations may include ensuring appropriate local stratification of diesel-to-methane fractions such that the combustion process is just sufficiently premixed to achieve low NO_x and soot emissions without compromising engine stability.

A review of the performance, combustion-generated emissions, and emissions control strategies, and exhaust aftertreatment technologies used for natural gas-fueled CI and SI engines is provided in Chap. 13. In particular, lean-burn vs. stoichiometric operation, the impact of EGR with hydrogen enrichment, the importance of spark timing, performance enhancement with hydrogen addition, and aftertreatment systems (e.g., performance of three-way catalytic converters) for natural gas SI engines are discussed. Similarly, for CI engines operating on dual-fuel combustion, the benefits of EGR, pilot fuel quantity and type, and pilot injection timing on mitigating exhaust emissions are also reviewed.

Finally, Chap. 14 presents a detailed review of the state of the art in residential-scale, natural gas-powered CHP systems utilizing IC engines, Stirling engines, Brayton cycle engines, and micro-Rankine cycle engines as prime movers. The authors conclude that natural gas-fueled reciprocating IC engines provide the best benefits vis-à-vis fuel conversion efficiency and load-following, but they also face technical hurdles in terms of heat transfer, incomplete combustion, and pumping and friction losses, which become more pronounced for small-scale engines.

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