

Energy, Environment, and Sustainability

Series Editors: Avinash Kumar Agarwal · Ashok Pandey

Avinash Kumar Agarwal

Jai Gopal Gupta

Nikhil Sharma

Akhilendra Pratap Singh *Editors*

Advanced Engine Diagnostics



 Springer

Energy, Environment, and Sustainability

Series editors

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Jai Gopal Gupta · Nikhil Sharma
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Editors

Advanced Engine Diagnostics

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Preface

Energy demand has been rising remarkably due to increasing population and urbanization. Global economy and society are significantly dependent on the energy availability because it touches every facet of human life and its activities. Transportation and power generation are two major examples. Without the transportation by millions of personalized and mass transport vehicles and availability of 24×7 power, human civilization would not have reached contemporary living standards.

The International Society for Energy, Environment and Sustainability (ISEES) was founded at Indian Institute of Technology Kanpur (IIT Kanpur), India, in January 2014 with the aim of spreading knowledge/awareness and catalyzing research activities in the fields of energy, environment, sustainability, and combustion. The society's goal is to contribute to the development of clean, affordable, and secure energy resources and a sustainable environment for the society and to spread knowledge in the above-mentioned areas and create awareness about the environmental challenges, which the world is facing today. The unique way adopted by the society was to break the conventional silos of specializations (engineering, science, environment, agriculture, biotechnology, materials, fuels, etc.) to tackle the problems related to energy, environment, and sustainability in a holistic manner. This is quite evident by the participation of experts from all fields to resolve these issues. ISEES is involved in various activities such as conducting workshops, seminars, and conferences in the domains of its interest. The society also recognizes the outstanding works done by the young scientists and engineers for their contributions in these fields by conferring them awards under various categories.

The second international conference on “Sustainable Energy and Environmental Challenges” (SEEC-2018) was organized under the auspices of ISEES from December 31, 2017, to January 3, 2018, at J N Tata Auditorium, Indian Institute of Science, Bangalore. This conference provided a platform for discussions between eminent scientists and engineers from various countries including India, USA, South Korea, Norway, Finland, Malaysia, Austria, Saudi Arabia, and Australia. In this conference, eminent speakers from all over the world presented their views

related to different aspects of energy, combustion, emissions, and alternative energy resources for sustainable development and a cleaner environment. The conference presented five high-voltage plenary talks from globally renowned experts on topical themes, namely “Is It Really the End of Combustion Engines and Petroleum?” by Prof. Gautam Kalghatgi, Saudi Aramco; “Energy Sustainability in India: Challenges and Opportunities” by Prof. Baldev Raj, NIAS Bangalore; “Methanol Economy: An Option for Sustainable Energy and Environmental Challenges” by Dr. Vijay Kumar Saraswat, Hon. Member (S&T), NITI Aayog, Government of India; “Supercritical Carbon Dioxide Brayton Cycle for Power Generation” by Prof. Pradip Dutta, IISc Bangalore; and “Role of Nuclear Fusion for Environmental Sustainability of Energy in Future” by Prof. J. S. Rao, Altair Engineering.

The conference included 27 technical sessions on topics related to energy and environmental sustainability including 5 plenary talks, 40 keynote talks, and 18 invited talks from prominent scientists, in addition to 142 contributed talks, and 74 poster presentations by students and researchers. The technical sessions in the conference included Advances in IC Engines: SI Engines, Solar Energy: Storage, Fundamentals of Combustion, Environmental Protection and Sustainability, Environmental Biotechnology, Coal and Biomass Combustion/Gasification, Air Pollution and Control, Biomass to Fuels/Chemicals: Clean Fuels, Advances in IC Engines: CI Engines, Solar Energy: Performance, Biomass to Fuels/Chemicals: Production, Advances in IC Engines: Fuels, Energy Sustainability, Environmental Biotechnology, Atomization and Sprays, Combustion/Gas Turbines/Fluid Flow/Sprays, Biomass to Fuels/Chemicals, Advances in IC Engines: New Concepts, Energy Sustainability, Waste to Wealth, Conventional and Alternate Fuels, Solar Energy, Wastewater Remediation, and Air Pollution. One of the highlights of the conference was the rapid-fire poster sessions in (i) Energy Engineering, (ii) Environment and Sustainability, and (iii) Biotechnology, where more than 75 students participated with great enthusiasm and won many prizes in a fiercely competitive environment. More than 200 participants and speakers attended this four-day conference, which also hosted Dr. Vijay Kumar Saraswat, Hon. Member (S&T), NITI Aayog, Government of India, as the chief guest for the book release ceremony, where 16 ISEES books published by Springer under a special dedicated series “Energy, Environment, and Sustainability” were released. This is the first time that such significant and high-quality outcome has been achieved by any society in India. The conference concluded with a panel discussion on “Challenges, Opportunities & Directions for Future Transportation Systems”, where the panelists were Prof. Gautam Kalghatgi, Saudi Aramco; Dr. Ravi Prashanth, Caterpillar Inc.; Dr. Shankar Venugopal, Mahindra and Mahindra; Dr. Bharat Bhargava, DG, ONGC Energy Center, and Dr. Umamaheshwar, GE Transportation, Bangalore. The panel discussion was moderated by Prof. Ashok Pandey, Chairman, ISEES. This conference laid out the road map for technology development, opportunities, and challenges in energy, environment, and sustainability domains. All these topics are very relevant for the country and the world in the present context. We acknowledge the support received from various funding agencies and organizations for successfully conducting the second ISEES conference SEEC-2018, where these

books germinated. We would therefore like to acknowledge SERB, Government of India (special thanks to Dr. Rajeev Sharma, Secretary); ONGC Energy Center (special thanks to Dr. Bharat Bhargava), TAFE (special thanks to Sh. Anadrao Patil); Caterpillar (special thanks to Dr. Ravi Prashanth); Progress Rail, TSI, India (special thanks to Dr. Deepak Sharma); Tesscorn, India (special thanks to Sh. Satyanarayana); GAIL, VOLVO; and our publishing partner Springer (special thanks to Swati Meherishi).

The editors would like to express their sincere gratitude to a large number of authors from all over the world for submitting their high-quality work in a timely manner and revising it appropriately at short notice. We would like to express our special thanks to Dr. Atul Dhar and Dr. Pravesh Chandra Shukla, who reviewed various chapters of this monograph and provided their valuable suggestions to improve the manuscripts.

Currently, IC engines are facing many challenges related to fuel supply, energy efficiency, and emissions, which require serious research efforts. This monograph is based on such advanced engine diagnostics such as advanced combustion strategies, combustion simulations, engine fault diagnostics techniques, tribological investigations, emission control systems, and the use of new alternative fuels in IC engines. These topics are the main areas of research in the field of IC engine. Therefore, this monograph is intended for practitioners working in the automotive sector and provides them new directions for future research. We hope that the book would be of great interest to the professionals and postgraduate students involved in fuel, IC engine, engine instrumentation, and environmental research.

Kanpur, India
Ajmer, India
Kanpur, India
Madison, USA

Avinash Kumar Agarwal
Jai Gopal Gupta
Nikhil Sharma
Akhilendra Pratap Singh

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Akhilendra Pratap Singh is a Postdoctoral Fellow at University of Wisconsin-Madison, USA. He received his master's and Ph.D. in mechanical engineering from Indian Institute of Technology Kanpur, India, in 2010 and 2016, respectively. His areas of research include advanced low-temperature combustion; optical diagnostics with special reference to engine endoscopy and PIV; combustion diagnostics; engine emission measurement; particulate characterization and their control; and alternative fuels. He has edited 5 books and authored 17 chapters and 34 research articles in journals and conferences. He is a member of numerous professional societies, including SAE, ASME, and ISEES. He is a member of the editorial board of the *Journal of Energy, Environment and Sustainability*.

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Part I

General

Chapter 1

Introduction to Advanced Engine Diagnostics



**Avinash Kumar Agarwal, Jai Gopal Gupta, Nikhil Sharma
and Akhilendra Pratap Singh**

Abstract In last two decades, advancements in automotive engines and after-treatment technologies have resulted in better engine performance, lower fuel consumption, and lower emissions; however, system complexity and higher number of control parameters have led to optimization issues. Implementation of advanced combustion diagnostic techniques/strategies in internal combustion (IC) engines further reduced the tail-pipe emissions, especially oxides of nitrogen (NO_x) and particulates; however, these combustion strategies have generated a new set of control parameters, which need to be optimized for superior engine performance and emission characteristics. To resolve these complex issues, researchers have combined different techniques such as advanced combustion strategies with after-treatment systems, and experimental research supported by simulations using computational fluid dynamics (CFD) tools. This monograph covers all these topics including advanced fuels and combustion, emission control techniques, after-treatment systems, simulations, and fault diagnostics.

Keywords Advanced combustion techniques · After-treatment systems
Emission control · Simulations · Fault diagnostics

Internal combustion (IC) engines transform the heat produced from combustion of fuel into mechanical work. Compression ignition (CI) and spark ignition

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(SI) engines have been widely adopted as power plants for passenger and commercial automotive applications, electricity generation, and other industrial applications. Excessive use of petroleum origin fuels has led to sustainability issues and harmful pollutant emissions. Both these issues are quite serious for mineral diesel-fuelled CI engines, which are preferred over gasoline-fuelled SI engines due to their higher power density and greater thermal efficiency. CI engines emit relatively higher oxides of nitrogen (NO_x) and particulates compared to SI engine. NO_x and particulates emitted by CI engines are harmful for both human health and the environment. To resolve the emission issues, there are two approaches, namely (i) pollutant formation reduction using advanced combustion techniques and (ii) pollutant reduction using after-treatment systems. This monograph covers some of these topics, which are divided into four sections: (i) general, (ii) advanced fuels and combustion techniques, (iii) emission control techniques and after-treatment systems, and (iv) simulation and fault diagnostics. This chapter is part of the first section, and it introduces the monograph.

The second section of this monograph covers application of alternative fuels and advanced combustion techniques for achieving higher efficiency and lower emissions. In this section, a novel combustion strategy, namely reactivity-controlled compression ignition (RCCI), is included. RCCI combustion is a dual-fuel technique in which low-reactivity fuels such as gasoline, alcohols are introduced upstream of the intake valve, to ensure a high level of fuel-air homogeneity in the combustion chamber, and high-reactivity fuels such as mineral diesel, biodiesel are injected directly in the combustion chamber to initiate the combustion (Kokjohn and Reitz 2013). RCCI combustion offers more complete combustion based on reactivity of both fuels; therefore, it offers a superior control over the combustion. RCCI combustion can reduce harmful emissions of NO_x and particulates simultaneously. Utilization of alcohols in RCCI combustion is another interesting feature, which can potentially reduce the excessive consumption of mineral diesel. In this section, first chapter describes the detailed mechanism of RCCI combustion and its characteristics while using different alcohols as low-reactivity fuel. Another chapter in this section describes the potential of low temperature combustion (LTC) techniques, namely homogeneous charge compression ignition (HCCI), partially premixed charge compression ignition (PCCI), and RCCI combustion. This chapter shows that HCCI and PCCI combustion techniques are capable of reducing particulate and NO_x emissions from diesel-fuelled engines (Agarwal et al. 2013; Jain et al. 2017). Detailed description about the soot formation process and factors affecting soot formation are few other important topics covered in this chapter. For utilization of alternative fuels, a dual-fuel diesel engine fuelled with hydrogen and producer gas is included in this section. This chapter discusses the performance and emission characteristics of dual-fuel engine operated up to full engine load. Results showed that use of hydrogen and producer gas improves the engine efficiency.

Third section of the monograph covers the application of advanced engine technologies and after-treatment systems for pollutant emission reduction from diesel engines. This section starts with the conventional techniques for diesel

engines to reduce harmful emissions. A review on effectiveness of common rail direct injection (CRDI) system is presented in the first chapter of this section. This chapter shows that CRDI systems can reduce particulate emissions; however due to the introduction of stricter emission norms (as Euro VI), only CRDI systems are not able to comply with such stringent emission norms. Therefore, it becomes necessary to use after-treatment systems along with these advanced engine techniques. Therefore, different after-treatment systems such as diesel particulate filter (DPF), selective catalytic reduction (SCR), lean NO_x trap (LNT) are discussed in the next chapter. This chapter shows that these systems can reduce NO_x and particulate emissions; however, these systems use precious and expensive rare earth metals, which increase the cost of the vehicle significantly. Therefore, the use of low-cost non-noble metal-based catalysts has been discussed in the next chapter. These non-noble metals can reduce the particulate emissions by increasing the soot oxidation. A chapter about the use of ceria-based mixed oxide nanoparticles for emission control from diesel engines has also been included in this section. This chapter describes different aspects of this technique such as properties of ceria-based nanoparticles, its preparation, and characterization using different techniques such as scanning electron microscopy (SEM), dynamic light scattering.

Last section of the monograph is based on the simulations and fault diagnostics. In this section, different simulation techniques have been discussed, which directly or indirectly affect the IC engines. This section starts with a chapter based on model-based fault detection system, which becomes essential for modern engines equipped with sophisticated digital control systems and complex electronic hardware such as input–output sensors, actuators, and processing units. This chapter describes different techniques and fault diagnostic methodologies, which can be used to diagnose any number of signal faults. Next chapter is based on the carbon emission reduction using carbon capture and storage (CCS) technologies. Chemical looping combustion (CLC) is a promising oxy-fuel carbon capture technology consisting of two interconnected fluidized beds with a metal oxide as a bed material/oxygen carrier. The particles, which circulate between both reactors, firstly absorb oxygen in the air reactor (AR) and secondly provide the oxygen for the combustion in the fuel reactor (FR). This chapter shows that superior results from this technique can be achieved by scale-up investigations and sensitivity analysis. Last chapter of this monograph is based on the tribological studies of an IC engine. Reliable and safe operation of an engine requires effective lubrication of moving parts to allow them to slide smoothly over each other. This chapter describes the optimal conditions for the oil film formation in all friction-coupled interfaces such as a piston cylinder, piston rings' cylinder, main bearings. Proper lubrication in an engine directly affects the life of different moving components by reducing wear. It also affects the engine efficiency and fuel consumption because frictional losses affect the power supplied to the engine shaft. Therefore, it is very relevant topic of research for advanced IC engine.

This monograph presents different technologies, which can be used for increasing thermal efficiency and lowering the emissions. Specific topics covered in this monograph include:

- Introduction to Advanced Engine Diagnostics
- Reactivity-Controlled Compression Ignition Combustion Using Alcohols
- Effect of Hydrogen and Producer Gas Addition on the Performance and Emissions on a Dual-Fuel Diesel Engine
- Characteristics of Particulate Emitted by IC Engines Using Advanced Combustion Strategies
- Non-Noble Metal-Based Catalysts for the Application of Soot Oxidation
- Ceria-Based Mixed Oxide Nanoparticles for Diesel Engine Emission Control
- On-Board Post-Combustion Emission Control Strategies for Diesel Engine in India to meet Bharat Stage VI Norms
- Modelling and Experimental Studies of NO_x and Soot Emissions in Common Rail Direct Injection Diesel Engines
- Model-Based Fault Detection on Modern Automotive Engines
- Study of Instability Nature of Circular Liquid Jet at Critical Chamber Conditions
- Transient Reacting Flow Simulations of Chemical Looping Combustion Reactors
- Tribological Studies of an Internal Combustion Engine.

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Part II
Advanced Fuels and Combustion
Techniques

Chapter 2

Reactivity-Controlled Compression Ignition Combustion Using Alcohols



Akhilendra Pratap Singh, Nikhil Sharma, Dev Prakash Satsangi,
Vikram Kumar and Avinash Kumar Agarwal

Abstract Rapidly increasing fossil fuel consumption along with increasing fuel cost and serious concerns about carbon dioxide (CO₂) emission reduction from the transportation sector motivated the automotive researchers to explore new internal combustion (IC) engine technologies, which can deliver higher engine efficiency with a lower impact on the environment and human health. These issues can be resolved by using advanced combustion strategies, which are also capable of utilizing alternative fuels. In last few years, reactivity-controlled compression ignition (RCCI) combustion has attracted significant attention due to its capability of ultra-low oxides of nitrogen (NO_x) and particulate emissions without any soot-NO_x trade-off and superior engine efficiency compared to compression ignition (CI) and spark ignition (SI) combustion. RCCI combustion is a combination of dual-fuel and partially premixed combustion (PPC) techniques, in which a low-reactivity fuel such as gasoline, compressed natural gas (CNG), alcohols are injected into the intake port and a high-reactivity fuel such as mineral diesel, biodiesel is directly injected into the combustion chamber. Blending of these two fuels in the combustion chamber controls the heat release rate (HRR) and combustion phasing. Premixed ratio and spatial stratification between these two fuels control the combustion phasing and combustion duration. RCCI combustion and emission characteristics are also dependent on fuel injection strategies such as fuel injection pressure (FIP), number of injections, start of injection (SOI) timings, exhaust gas recirculation (EGR) rate, and intake charge temperature. This chapter reviews all these factors and presents important features of RCCI combustion for application in future automotive engines. A separate section for use of alcohols in RCCI

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combustion is also included in this chapter, which shows various pathways for alternative fuel utilization in this advanced combustion technique. Roadmap for future research directions for RCCI combustion is also discussed in this chapter.

Keywords Reactivity-controlled compression ignition (RCCI) • Fuel reactivity
Fuel injection strategy • Alcohols

2.1 Introduction

Demand of fuel-efficient engines is an active research area worldwide due to current issues related to rapidly depleting petroleum reserves, rising environmental concerns and the adverse effect of pollutants on human health. From the beginning of internal combustion (IC) engines, mineral diesel-fueled compression ignition (CI) engines are preferred over the spark ignition (SI) engines due to their higher thermal efficiency and superior fuel economy. High compression ratios as well as less throttling losses are the main factors leading to their higher efficiency. These engines are used in various applications such as power generation, agriculture, and transport sector. However, these engines are associated with higher emissions of oxides of nitrogen (NO_x) and particulates, which limit their application in mega-cities. These toxic emissions have an adverse effect on human health as well as on the environment. To resolve these issues, exhaust gas after-treatment systems such as diesel particulate filters (DPF), lean NO_x trap (LNT), and selective catalytic reduction (SCR) have been installed in modern diesel engines, with a view to reduce toxic emissions. These after-treatment systems have successfully reduced the tailpipe emissions; however, higher cost of these systems and issues related to their durability limit their application in vehicles (Dec 2009).

In recent years, various advanced combustion strategies have been developed, which reduce the formation of pollutants in the combustion chamber. These strategies include partially premixed charge compression ignition (PCCI), homogeneous charge compression ignition (HCCI), and reactivity-controlled compression ignition (RCCI). Figure 2.1 shows the basic features of advanced combustion strategies and their evolution over time. These techniques were developed for simultaneous reduction of particulates and NO_x emissions, while keeping thermal efficiency of the engine equivalent to conventional CI engines. In HCCI technique, premixing of fuel and air occurs outside the cylinder before the charge induction into the engine cylinder. Thereafter, this combustible charge is ignited by compression, similar to CI engines. However, in PCCI combustion, a fraction of fuel is injected during the early compression stroke, which mixes with air and forms partially premixed charge before the start of ignition. This premixed charge helps in the combustion of fuel injected during the main injection. It has been reported that PCCI and HCCI methods help reduce particulate and NO_x emissions; however, they increase carbon monoxide (CO) and unburnt hydrocarbon (UHC) emissions (Agarwal et al. 2013; Saravanan et al. 2015). Lack of an adequate combustion

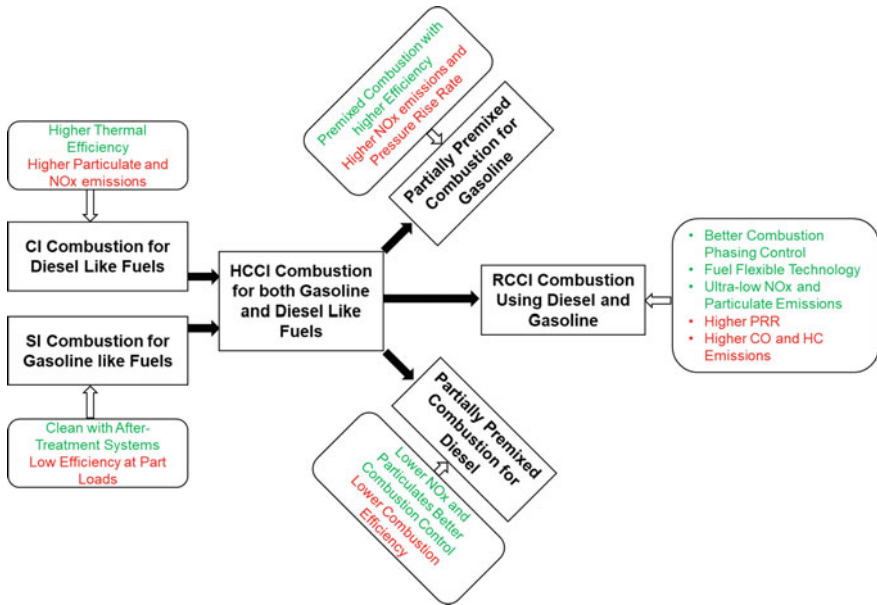


Fig. 2.1 Different combustion strategies

phasing control and heat release rate (HRR) are few other challenges faced by these combustion techniques, which limit their application at higher engine loads. Due to these issues, several other combustion techniques have been developed, in which RCCI combustion is the most important one.

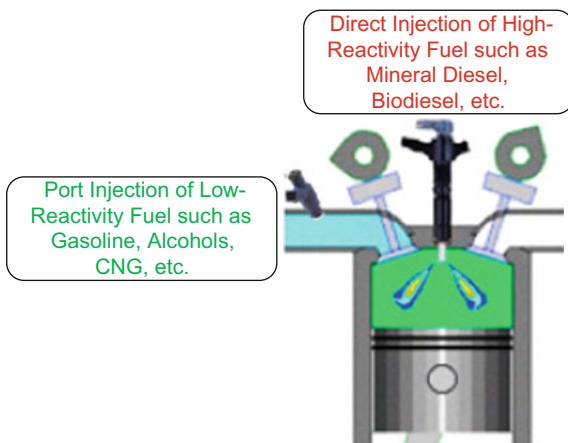
2.2 Reactivity-Controlled Compression Ignition (RCCI)

RCCI combustion technique was first demonstrated at Engine Research Center of University of Wisconsin–Madison. RCCI combustion is a dual-fuel technique, in which two fuels of different reactivity are used. The concept of dual-fuel in diesel engines has been used since 1955, which allows the in-cylinder blending of two different fuels (Karim 1980). In RCCI combustion technique, a low-reactivity fuel such as gasoline/alcohols/compressed natural gas (CNG) is used to create a homogeneous fuel–air mixture either using port fuel injection (PFI) or by using early direct injection. A high-reactivity fuel such as mineral diesel/biodiesel is injected in the compression stroke, early enough to mix below particulate and NO_x formation equivalence ratios, similar to PPC. Combustion starts in high-reactivity regions and then proceeds to low-reactivity regions. The combustion duration is controlled by the spatial stratification of fuel reactivities, which decreases with increasing mixing duration. RCCI combustion gives excellent results in terms of

performance and emissions over the entire operating range of the engine. The dual-fuel strategy allows easy control of combustion phasing, which is controlled by the local concentration of high-reactivity fuel and start of injection (SOI) timing of high-reactivity fuel. Since the combustion duration is controlled by the reactivity gradient, it can be effectively used to reduce pressure rise rates (PRRs) and combustion noise. For higher thermal efficiency and lower NO_x and particulate emissions, RCCI combustion also uses multiple injection strategy in one cycle, along with EGR. These parameters affect the fuel–air chemical kinetics (in-cylinder reactivity), which can be used to optimize the combustion phasing and combustion duration (Reitz and Duraisamy 2015). Due to these advantages, RCCI engine has attracted global attention and motivating researchers to further develop RCCI combustion concept for commercial applications.

In a slightly different way, RCCI combustion can be defined as combustion achieved by charge stratification in the combustion chamber using two fuels (with low and high cetane numbers). Low cetane number fuel with lower reactivity is injected in the port, which is premixed with air outside the combustion chamber, and thereafter, it enters the combustion chamber. At the end of the compression stroke, high cetane number fuel with higher reactivity is directly injected into the combustion chamber, which is already filled with lower reactivity fuel–air mixture (Fig. 2.2). The direct injection of fuel creates layers of fuels; hence for more layer generation, multiple injections strategy is highly desirable. During multiple injections, the first injection of diesel targets the squish region, whereas the relatively late injected diesel acts as an ignition source (Eichmeier et al. 2014). In RCCI combustion, ratio of both fuels quantities is very important because this is critical for combustion control. This leads to superior combustion control in case of RCCI combustion compared to HCCI or PCCI combustion (Reitz and Duraisamy 2015). This results in lower NO_x and particulate emissions, reduced heat transfer loss, and increased fuel efficiency, thus eliminating the need for exhaust gas after-treatment systems.

Fig. 2.2 RCCI combustion strategy for different test fuels



Reitz (2010) presented a comparison of energy budgets for different combustion techniques achieved in a single-cylinder oil test engine at 9 bar indicated mean effective pressure (IMEP) (Fig. 2.3). This figure clearly indicates that RCCI combustion is capable of generating significantly higher gross IMEP (~59%) compared to other advanced combustion techniques. The RCCI combustion process converts 59% of the recovered heat loss to work, while the high exhaust gas recirculation (EGR) diesel engine converted only 44% of the recovered heat loss to work. In RCCI combustion, improved combustion control is the main reason for more efficient work extraction, by achieving shorter combustion duration. Relatively lower heat transfer loss (HT MEP) makes this combustion technique more attractive compared to conventional diesel combustion (CDC). Table 2.1 shows the comparison of different advanced combustion techniques and conventional combustion strategies.

Li et al. (2014) introduced two parameters, namely global reactivity and reactivity stratification, which affect the RCCI combustion control. Global reactivity depends on quantity of fuel directly injected in the combustion chamber, and reactivity stratification is related to fuel spray penetration and the entrainment of direct-injected higher reactivity fuel with the mixture of lower reactivity fuel and air. The direction of flame propagation depends on the engine type and fuel injection parameters such as SOI timing, injector spray angle. For an effective RCCI combustion and load limit extension, the optimization of fuel properties plays an important role. Fuel property optimization increases the reactivity gradient between directly injected higher reactivity fuel and premixed lower reactivity fuel (Wang et al. 2018). Therefore, researchers explored different fuel pairs (low/high-reactivity) for RCCI combustion, in which gasoline/diesel, CNG/diesel, methanol/diesel, *n*-butanol/diesel, gasoline/biodiesel, methanol/biodiesel, etc., are most used fuel pairs (Dahodwala et al. 2014; Doosje et al. 2014; Dempsey et al. 2013; Zhang et al. 2013; Wang et al. 2015). In these studies, a common fact has been reported that

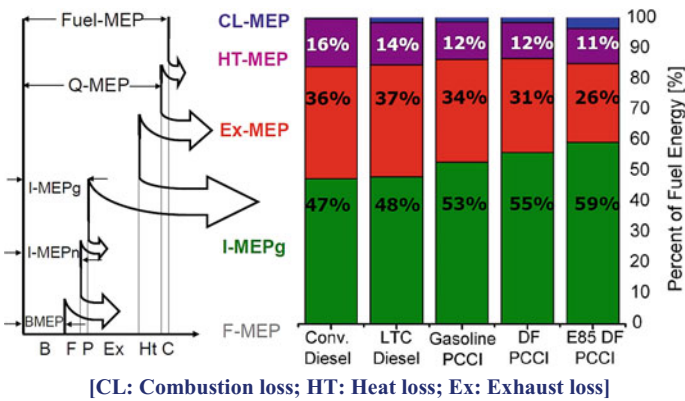


Fig. 2.3 Caterpillar single-cylinder test engine energy budgets (9 bar IMEP). Adapted from Staples et al. (2009), Hardy and Reitz (2006), Hanson et al. (2009, 2010), Reitz (2010)

Table 2.1 Comparison of SI, CI, HCCI, PCCI, and RCCI combustion strategies (Paykani et al. 2016)

	SI	CI	HCCI	PCCI	RCCI
Ignition type	Spark ignited	Compression ignited	Compression ignited	Compression ignited	Compression ignited
Fuel type	High octane	High cetane	Blend of every liquid or gaseous fuel	Blend of every liquid or gaseous fuel	PFI of high octane and DI of high cetane fuel
Power output control	Air-flow control	Fuel-flow control	Fuel-flow control	Fuel-flow control	Fuel reactivity stratification
Fuel-air mixture condition	Near stoichiometric air-fuel ratio	Lean air-fuel ratio	Lean air-fuel ratio or charge dilution	Lean air-fuel ratio or high charge dilution	Air-fuel ratio stratification, typically without charge dilution
Combustion control mechanism	Flame propagation speed	Time for fuel vaporization and mixing	Chemical kinetics	Chemical kinetics and injection timing	Chemical kinetics and fuel reactivity
Particulate and NO _x emissions	Cleaner with three-way catalyst	Higher particulate and NO _x (without after-treatment)	Lower NO _x and particulates	Lower NO _x and particulates	Ultra-low NO _x and particulates
Other emission characteristics	Higher CO ₂	Lower CO ₂	Higher HC and CO and lower CO ₂	Higher HC and CO and lower CO ₂	Very high HC and CO (without after-treatment) and lower CO ₂