Chapter 6
Simultaneous Reduction of NO\textsubscript{x} and Smoke Emissions in Dual Fuel and HCCI Engines Operated on Biogas

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ABSTRACT
Biogas has emerged as a promising alternative to fossil fuels in internal combustion engines in recent times. It could be used as the primary fuel in Compression Ignition (CI) engines in combination with a small quantity of a high cetane fuel in two modes – dual fuel or Homogeneous Charge Compression Ignition (HCCI). This chapter compares the performance, combustion, and emission parameters of a CI engine operated with biogas in dual fuel and HCCI modes vis-à-vis conventional diesel operation. The effects of biogas composition (quantified in terms of the methane content), location of secondary fuel injection and engine load are investigated. It is observed that the use of biogas has the potential to reduce both NO\textsubscript{x} and smoke emissions simultaneously, with HCCI mode offering ultra-low emissions. Operating the engine in dual fuel mode can provide high thermal efficiency and significant diesel substitution.

INTRODUCTION
Major fuel resources like such as coal, fossil fuels, nuclear fuel and natural gas are not renewable. Their fast decline, consequent price rise, environmental concerns, increased worldwide energy demand and emission norms have motivated the search for renewable, alternative energy sources such as solar, biofuels

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and wind. Furthermore, petroleum reserves are mainly located in certain geographical regions. Countries in other areas face a serious problem in procuring fuel supplies to meet the ever-increasing energy demand. The combustion of fossil fuels also leads to pollution, acid rain, carbon dioxide build-up etc., thereby placing people and the environment at risk. Diesel fuelled Compression Ignition (Cl) engines generate substantial amounts of NOx and smoke emissions. Among alternative fuels, biofuels such as vegetable oils, bio-alcohols, biogas, and bio-diesels have earned significant attention because of their renewability and intrinsic ability to reduce net carbon dioxide (CO2) emissions. Using biogas addresses three major challenges – harnessing methane, a powerful greenhouse gas that emanates from the decomposition of biomass, efficient disposal of biological waste and tapping a renewable power source. Biogas provides a number of benefits over other biomass-derived fuels (Tippayawong & Thanompongchart, 2010). Biogas burns quicker than solid fuels such as coal, is more eco-friendly and does not leave residues behind. Biogas is formed from biomass, which in turn is derived from vegetation, which absorb CO2 during their lifetime. Thus biogas can be regarded as a CO2-neutral fuel despite CO2 emissions during combustion (Demirbas, 2004). Compared to other biofuels such as bio-diesels and bio-alcohols, biogas production also needs less handling effort and cost (Demirbas, Balat, & Balat, 2011).

Biogas has great potential for developing economies with rural background. India, for instance, had a cattle headcount of approximately 30 crores in 1996, about one-fifth of the global total. The annual production of dung in 1996 amounted to 980 million tons, capable of generating nearly 63.8 trillion liters of biogas, which could provide 1.3 trillion MJ of electricity (Vijay, 2007). In 2012, the cattle population increased to 512 million (Dept.of Animal Husbandry Dairying & Fisheries, 2012), showing a corresponding increase in biogas energy potential to 2.2 trillion MJ. Because of the variation in the composition of biomass, some characteristics of biogas samples, e.g. fractions of constituent elements and ignition temperature, differ from sample to sample (Demirbas, 2004).

The present work is an attempt to identify the most effective modes of operating a CI engine with biogas as the primary fuel. The impact of methane fraction of biogas and location of secondary fuel injection on engine performance, combustion and emissions are explored for the full load spectrum.

**BIOGAS PRODUCTION**

Different waste-to-energy (WTE) techniques have been explored to convert biological waste, such as industrial and municipal solid waste (MSW), into biogas (Demirbas et al., 2011; Gunaseelan, 1997). These techniques can be divided into four broad groups: a) hydrogenation, b) pyrolysis, c) gasification, and d) bio-conversion. A digester is one of the most common means of generating biogas, where biomass is subjected to anaerobic digestion. Anaerobic digestion is a three-stage method of bioconversion involving hydrolysis, acid formation and methane generation. The biogas thus produced is mainly a combination of CH4, CO2 and H2S (Khoiyangbam, Gupta, & Kumar, 2011). Some important properties of biogas are presented in Table 1. The cost of methane generation by anaerobic digestion is similar to those of other sources of biomass energy such as synthesis gases and ethanol (Chynoweth, Owens, & Legrand, 2000). There are different types of anaerobic digesters available, e.g. floating drum and fixed dome designs (Khoiyangbam et al., 2011).

Biogas typically has 25 - 40% carbon dioxide by volume (Khoiyangbam et al., 2011). It can react with water to form corrosive carbonic acid, which can potentially damage pipelines and machinery. As carbon dioxide is non-combustible, it lowers the calorific value and energy density of the fuel. Compared