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Sustainable power generation with large gas engines

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Large gas engines will play a significant role in distributed power generation for the energy supply of the future. The lower amount of carbon in natural gas in comparison with other fossil fuels can be used to bridge the gap between a carbon-based and a carbon-free energy supply. The main objective of this paper is to provide an overview of the technological challenges the next generation of gas engines will face. Improvements in robustness and dynamic behavior will allow gas engines to meet the high transient requirements for the future power supply. The great fluctuations in gas quality anticipated with grid gas and liquefied natural gas impose high demands on both the transient behavior and the knock resistance of the engine. Technologies that enhance fuel flexibility by enabling sustainable power and heat generation using hydrogen-rich syngas from biomass and the efficient use of waste gases will be key. The most important technological components that maximize power output and efficiency as well as transient operation at very low emission levels are discussed. An advanced development methodology is applied in order to deal with the requirements presented by the technological challenges. The main future goals of gas engine development will be described by use of examples to illustrate the application of the methodology.

In summary, the research and technological developments presented in this paper will support the transition from conventional to carbon-free fuel for reliable and sustainable power generation that meets future requirements for large gas engines.

1. Introduction

In the power generation systems of the future, the fraction of renewable energy sources such as solar power and wind power will increase. The dependence of these power sources on the weather as well as the decentralization of the energy market are increasing demand for fast-reacting and well-controlled sources of electrical energy to compensate for peak loads or drops in power generation. In this scenario, the difference between production and consumption of electrical energy will continue to increase. In general, low-carbon energy production strategies have to be pursued. One example of such a strategy can be found in a recent study [1] comparing the perspectives for low-carbon energy production in two EU countries in the next few decades. Different strategies, i.e. renewable energy sources (wind, hydro, solar, bioenergy), carbon capture and sequestration strategies, are assessed and recommendations based on the regional boundary conditions are made with consideration of the cost of electricity.

Internal combustion engines will play a significant role in decentralized power generation for the energy supply of the future because they are able to quickly react to fluctuations in demand for power and incorporate a compensation measure to stabilize the electric grid. From an environmental point of view, gas engines are a key factor in power generation due to their comparatively low environmental impact, which is further enhanced by the great progress in terms of efficiency and power output that has been achieved in recent years.

A number of studies show that the global share of natural gas for power generation will continue to develop, cf. [2], which analyzes the challenges emerging from the fuels of the future for internal combustion engines and assesses feasible fuel options. A prognosis made by the International Energy Agency (IEA) about the development of global power generation as divided into shares of the individual energy carriers (World Energy Outlook 2012) [2] shows that the share of natural gas in power generation will increase significantly in the next 20 years. This trend is mainly driven by the large amount of natural gas reserves in conventional and unconventional deposits (e.g., shale gas, tight gas and coal bed methane). The discussion about a strategy to phase out nuclear energy in various countries (e.g., Germany and Japan) as well as the

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trend towards lower natural gas prices are also encouraging the use of gas. Moreover, natural gas helps to bridge the gap between carbon-based and carbon-free energy sources.

Various applications for gas engines currently exist. One of the most important gas engine applications is the combined heat and power plant, where combustion engines produce electricity and heat. Many power generation applications of gas engines are in use that are independent of the grid, in particular generator sets and mechanical drive applications for pumps and compressors (e.g., petrochemistry, oil and gas production, wastewater treatment). In addition, special gases such as landfill gas, waste gases from industry, and flare gas are more frequently exploited as sources of fuel for gas engines. Recent studies [3,4] evaluate how these special gases can be applied in internal combustion engines.

2. Sustainability

Although gaseous fuels for power generation are already widely available today, numerous signs indicate that attitudes towards their use continue to change around the world. Sustainable power generation from renewable sources instead of classic fossil fuels or nuclear fission is a global goal. The EU Climate & Energy Framework 2030 has set three targets: that greenhouse gas emissions fall to levels at least 40% lower than the 1990 levels, that the share of renewable energy increases to 27% and that energy efficiency increases by at least 27%. To reach these targets, the power sector in particular will need to reduce greenhouse gas (GHG) emissions drastically [5]. To be sustainable, it is imperative that electrical power is generated from a combustion process that is either CO_2 neutral or produces as little CO_2 as possible. In addition, overall pollutant emissions should be as low as possible. In the area of power and heat generation from combustion engines, one promising path towards achieving sustainability is to make the transition from carbon-based to carbon-free energy sources.

2.1. Transition to carbon-free fuels

At the start of the industrial revolution, "solid" sources of energy such as coal were most commonly used to power industry. Mainly driven by the demands of mobility, the advantages of liquid fuels became obvious and their advantages were soon exploited for power generation as well. At present, natural gas offers further advantages; not only are carbon dioxide emissions lower than with liquid fuels but they also have the potential to produce even fewer pollutant emissions [2].

Complete combustion of hydrocarbons always produces carbon dioxide and water. As oxidation of hydrogen yields water and oxidation of carbon yields carbon dioxide, the hydrogen-to-carbon ratio of the fuel determines the fraction of carbon dioxide in the exhaust gas. As can be seen in Fig. 1, the hydrogen-to-carbon atomic ratio of coal is approximately 0:1 while this ratio for gasoline or diesel is roughly 2:1. The hydrogen-to-carbon ratio of natural gas, whose main component is methane (CH_4), is about 4:1. Hence, the combustion of natural gas produces less CO_2 per unit of energy than either coal or gasoline [2].

The transition from solid coal to liquid hydrocarbons and from natural gas to pure hydrogen as a carbon-free fuel can therefore be regarded as a decarbonization pathway [2] and must be pursued further. In this context, due to its CO_2 neutral character, synthetic methane can also be regarded as carbon-free in consideration of the production and consumption cycle. However, the production of hydrogen may still require consumption of fossil fuel sources such as oil and gas when current technologies are applied. Therefore, it is imperative to produce hydrogen using renewable energy sources such as wind power or solar power.

2.2. Power generation with large gas engines

A key target in developing large gas engines for power generation is to obtain the highest possible efficiency. Recent studies [6,7] describe the measures undertaken to attain a remarkable increase in the efficiency of high performance gas engines for distributed power generation. In addition to the increase in efficiency and power of gas engines acquired in recent years, the smaller carbon fraction of natural gas in comparison with other fossil fuels is another factor that enables gas engines to be applied to bridge the gap between carbon-based and carbon-free energy sources. Gaseous fuels for engine combustion can be divided into fossil gases, biologically produced gases and technically produced gases. The gases are classified according to their origin, which influences their compositions and combustion properties.

In this context, three main paths to achieving sustainability emerge. All three paths have a different impact on engine combustion, present different challenges to the engine and therefore require different engine technologies. Fig. 2 provides an overview of these paths and their impact on engine operation.

Three main paths with several variations can be distinguished:

1. The "classic" path still uses fossil fuel sources but seeks to optimize the use of these fuels. Fuels with a high hydrogen to carbon ratio such as natural gas are a good choice since their CO_2 emissions are lower than those of liquid fuels. Furthermore, measures must be taken that increase the efficiency of the engine as well as reduce pollutant emissions of all kinds. The main challenge of this path is to continue to develop combustion systems that achieve the highest possible efficiencies with the lowest possible emissions.
2. A second path is to use fuels that would otherwise not be exploited, e.g., waste gases from industrial processes. One good example is blast furnace gas (BFG), which is created during the steel production process. Flare gas that leaks from petroleum refineries, natural gas processing plants and oil or gas production sites is another type of waste gas. Instead of it being burned off in gas flares, its energy content can be used for power generation and to operate the plant itself. Since flare gas widely varies in its composition depending on where and how it is produced and how much is produced, optimal design of gas engines is critical.
3. The third and most sustainable path is to use renewable fuels. For example, hydrogen can be produced using renewable sources such as wind power or solar power. This hydrogen can be exploited directly or converted into synthetic methane using carbon dioxide from industrial processes by applying the methanation process. This synthetic methane can then be used instead of natural gas. Biomass can be converted into biogas by gasification processes as well as anaerobic digestion. Thus, the composition of biogas greatly varies depending on its source. All these renewable gases can either be added to the gas grid or directly fed to the engine. Gaseous fuels from renewable sources present different challenges for the engine depending on how they are produced and used.

3. Challenges

Along the road to sustainable power generation, technological challenges have to be overcome and the requirements for the engine have to be met by research and application of highly sophisticated engine technologies. Improvements in robustness and dynamic behavior will allow gas engines to compete with diesel engines in applications with high transient requirements caused by fluctuations in the electric grid. The great fluctuations in gas quality anticipated with grid gas impose high demands on both