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Fuel reforming in internal combustion engines

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ABSTRACT

This article offers a comprehensive overview of research on fuel reforming in internal combustion engines (ICE). It includes a historical perspective of research in this field, a discussion on the considerations to be made prior to choosing a primary fuel for reforming purposes, and the main processes in fuel reforming. Steam reforming offers a moderate degree of thermochemical recuperation and is applicable to methanol and ethanol feeding. Reforming with air reduces the degree of recuperation, but opens up the use of heavier fuels such as gasoline and diesel fuel. Dry reforming (with CO_2) offers the best recuperation but is prone to fast coking. The choice of catalyst and the expected side reactions for each fuel are also discussed. While there is extensive literature on steam reforming catalysts and kinetics at atmospheric pressure, studies at higher pressures and/or on decomposition reactions are very few. The thermodynamics of fuel reforming in ICE and simulation approaches are also discussed. The paper also reports on engineering aspects of fuel reformer design and provides an overview of engines with thermo-chemical recuperation (TCR), fuel supply, and load control strategies in ICE with TCR. In-cylinder fuel reforming as well as application of fuel reforming for performance improvement of emission aftertreatment systems are subsequently discussed. This overview reveals ongoing diverse research activities in the field of onboard fuel reforming. However, several problems, including reformate burning velocity at typical for ICE conditions, in-cylinder behavior of directly injected reformates and particle formation still need to be addressed. A discussion on some of these unresolved issues is attempted herein.

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1. Introduction

1.1. Required improvement of energy efficiency and emission mitigation

Transportation is responsible for the majority of global fuel consumption. According to the data from the International Energy Agency (IEA) [1], about 26% of all energy-related CO_2 emissions in 2007 were caused by transportation. This value is likely to increase in future unless special measures are adopted. Following the recommendation of the United Nations Intergovernmental Panel on Climate Change (IPCC), by 2050, the annual global greenhouse gas (GHG) emissions must be reduced by 50 - 85% of the emission levels recorded in 2000. This will result in limiting the long-term global heating to 2.0 - 2.4 deg. C [2]. However, more recent studies have indicated that climate change is occurring faster than previously expected and that even a 50% reduction in global GHG emissions by 2050 may not be enough [3].

In 2006, road transportation was responsible for about three-quarters of the global energy consumption in the transportation segment [4]. In Europe this number is even higher and reached 82.5% in 2009 [5]. Nowadays, road transportation is almost entirely dependent ($\sim$ 95%) on crude oil [6]. Therefore, to meet GHG emission targets and decrease oil dependency, the overall energy consumption of road vehicles must be significantly reduced. The major challenge in reaching this goal is to reduce vehicle carbon emissions without disrupting transportation patterns and population mobility.

According to the World Business Council for Sustainable Development (WBSCD), the vehicle GHG intensity is determined from the following factors [7]:

1) The amount of energy required by an average vehicle to perform a given amount of transport activity in each transportation mode. This factor depends on the energy consumption of the vehicle.
2) The carbon content of the used fuel together with its production and distribution methods.
3) The total volume of transportation activity, which is dependent on the number of operating vehicles and their usage patterns. This is a function of consumer demand.
4) The modal composition of transportation activity, which is dependent on consumer choice, mode pricing, and fiscal measures that influence mode selection.

The first two modes have the biggest impact on vehicle GHG intensity. According to the IEA, 80% of the necessary reduction in GHG emissions can be achieved by improving vehicle energy efficiency and fuel decarbonization. This provides a strong incentive for research and development of new technologies based on alternative energy sources and energy carriers [8].

1.2. Thermochemical recuperation as a method of simultaneous waste heat recovery and hydrogen production

Intensive research aimed at the development of internal combustion engine (ICE)-based propulsion systems with 60% brake thermal efficiency and ultra-low pollutant emissions is ongoing [9–12]. There is wide consensus that waste heat recovery (WHR) is necessary in achieving this ambitious goal [12,13]. Various known WHR methods, including turbocharging [14], turbo-compounding [15], thermo-electrics [16], the Rankine cycle [17], in-cylinder WHR [18], and cabin heating and cooling [19] are being developed at different rates of intensity. The most mature and widely applied WHR method is turbocharging [8]. Waste heat can also be used to sustain endothermic reactions of fuel reforming, a method often referred to as thermochemical recuperation (TCR) [20]. TCR presents two major advantages over turbocharging: firstly, the amount of utilized energy is not limited by isentropic expansion and secondly, the gaseous reforming product mixture (reformate) usually comprises a high hydrogen content to afford increased flame velocity, wider flammability limits, and reduced combustion irreversibility [21]. Hence, TCR improves the ICE efficiency because of the increased heating value of the fuel as a result of WHR as well as lean burning options, approaching the efficiency of an ideal Otto cycle and providing the possibility of applying higher compression ratios.

Notably, fuel reforming through TCR allows convenient vehicle fueling with a liquid fuel, while the engine is fed by a gaseous H_2-rich reformate produced onboard. Thus, the major issues related to H_2 use as an alternative fuel, such as fueling infrastructure and H_2 storage onboard a vehicle, are eliminated. The challenge of onboard H_2-storage is directly related to the physical properties of hydrogen: a very low volumetric energy content (10.3 MJ/m^3 at 1 bar or $\sim$ 3000 MJ/m^3 at 350 bar compared to 33,750 MJ/m^3 for gasoline) and extremely low boiling point (20 K). Fig. 1 compares various hydrogen storage technologies with reference to conventional and some alternative liquid fuels. None of the H_2 storage methods reach the volumetric energy densities of gasoline and other liquid fuels to provide a vehicle driving range comparable to that afforded by conventional and liquid alternative fuels.

Wide flammability limits and very low ignition energy of H_2 present storage safety concerns at limited ventilation conditions because of the danger of explosive mixture formation that may cause severe damage. However, this is partially compensated for by a very high mass diffusivity of H_2 (0.78 $m \cdot 10^{-4}/s$), which is an order of magnitude higher than that of gasoline (0.07 $m \cdot 10^{-4}/s$). Storage of syngas (mainly hydrogen and carbon monoxide) has also proven to be problematic for the same reasons. The hazards of pure H_2 and syngas storage and transport hamper the commercialization and market penetration of hydrogen- and syngas-fed engines. Taking this into account, the production of H_2 or H_2-rich gaseous fuel by onboard reforming of a liquid primary fuel with coincident WHR through TCR is attracting much attention. To date, works in this area have been reported by Dai et al. [22], He et al. [23], Ji et al. [24], Liao & Horng [25], Li et al. [26], Sall et al. [27], Tartakovsky et al. [28], Nguyen &Verhelst [29], among other.

Nowadays, TCR has been commercialized and is successfully used in various stationary applications, including gas turbines in power plants for distributed power generation [30–33] and furnaces [34]. Fuel reforming is being broadly studied as an onboard hydrogen production method for fuel cells. A comprehensive review of fuel reformers for fuel cells was performed by Pettersson & Westerholm [35]. Additionally, recent progress in this field was surveyed and analyzed in detail in review articles by Alves et al. [36], Xu et al. [37], Iulianelli et al. [38], Gur [39] and Timurkutluk et al. [40]. Proton-exchange membrane (PEM) fuel cells require pure hydrogen for their efficient operation as even small traces of CO result in degradation of