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Review

Recent progress in the use of hydrogen as a fuel for internal combustion engines

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ABSTRACT

Hydrogen-fueled internal combustion engines (H_2ICEs) have been the topic of research for many decades, and contemporary reviews have surveyed the relevant literature. Because of a number of relatively large R&D projects that have been ongoing recently, much progress has been made that is worth reporting. Specifically, this paper reviews the advancements made in plotting the possibilities offered by direct injection of hydrogen, in-cylinder heat transfer, modeling and combustion strategies (on an engine as well as vehicle level). These efforts have resulted in impressive efficiency numbers, both at peak and part load operation, while keeping emissions far below regulatory limits and reaching satisfactory specific power outputs. New demonstration vehicles have been put on the road showing the relatively low barriers (on a vehicle level) to introduce hydrogen engined transportation and these are briefly described. The paper discusses the merits of H_2ICEs but also what makes them potentially unfit as a realistic alternative. Finally, the paper concludes with the main areas of research that require further efforts.

1. Introduction

1.1. *Why?*

It is clear that the transportation sector is in need of other energy carriers and/or prime movers. Currently it is almost exclusively dependent on fossil fuels, leading to major contributions to anthropogenic emissions of carbon dioxide and pollutants. This in itself is enough of a reason to search for alternatives, but in addition fossil fuels' usage is still increasing, while reserves are finite, so prices continue to rise and many countries are looking for ways to secure their energy supply. This has led to investments in renewable energy and non-conventional fuels, and policies aiming at increasing energy efficiency. Hydrogen, as a means to chemically store energy, has been advanced as an interesting energy storage or carrier. Given the wide variety of ways to produce hydrogen, and the possibility of producing energy from hydrogen with no or ultra-low emissions, hydrogen has the potential to be used for buffering renewable energy. One way is to produce hydrogen when renewable energy production exceeds energy demand, and convert it back to (electrical) energy when demand outweighs production (energy storage). Another way is to top off excessive renewable energy through

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producing hydrogen, and use it as a fuel for powering transportation (energy carrier).

With hydrogen possibly available as a fuel, there are two main options for using it to power vehicles. Arguably to most investigated one is the fuel cell powered vehicle (FCV). Fuel cells using hydrogen are attractive for their potential efficiency, particularly at part load (important for passenger cars), their emissions (only water vapor), quiet running and modularity. On the other hand, they are currently compromised due to cost and durability concerns. The second option is to use hydrogen in an internal combustion engine.

Using the ubiquitous internal combustion engine (ICE) to produce motive power from hydrogen is attractive for a number of reasons, with perhaps the most obvious one being the possibility of relying on a mature industry and a vast production infrastructure. A second advantage lies in the fuel flexibility of ICEs. An ICE can be run on different fuels, provided the engine control unit is suitably adapted and material compatibility with the different fuels is ensured. This makes H_2ICEs prime candidates for introducing hydrogen as a transportation fuel: clearly, fueling stations cannot be extended with a hydrogen pump overnight, so in the event hydrogen is deployed on a large scale, vehicles with “flex-fuel” capability offer the user much more comfort during the transition period (being able to switch to e.g. gasoline when no hydrogen pump is around). This feature, that could aid in the development of a hydrogen infrastructure, was the main reason for the H_2ICE being the subject of a Department of Energy funded program (see below).

Other attractive features of the H_2ICE are the lower requirements for hydrogen purity compared to fuel cells, leading to cheaper fuel; the potential for ultra-low emissions (quantified in this paper); and the increased peak and part load efficiency compared to most commonly fueled ICEs (also described more fully in the following). Finally, the fact that it does not rely on rare materials [1] could broaden its potential application beyond that of a “bridging the gap” technology. Both FCVs and BEVs (battery-electric vehicles) rely on materials of which the supply, in the large quantities as required for making an impact on the transportation fleet, could potentially limit or prevent the widespread adoption of these alternatives. For fuel cells the bottleneck is the availability of platinum. This material is also the reason for the high cost of current fuel cells, with prices potentially increasing even further once demand increases. For BEVs, making rare earth elements available in large quantities is a challenge. Contrary to what their name suggests, these elements are not that rare, but ramping up their production has been reported to potentially be too slow [2].

To summarize, H_2ICEs are attractive for:

- reducing local pollution,
- reducing global emissions of carbon dioxide,
- increased efficiency compared to current, fossil-fueled ICEs;

These being shared advantages with the fuel cell; and additionally as they:

- can be made fuel-flexible,
- do not rely on rare materials, i.e. can be made in large quantities and affordably,
- are tolerant for fuel impurities, enabling them to use hydrogen from most sources, without the need for expensive purification,
- can be introduced relatively easily, with the possibility of retrofitting engines [3–7].

1.2. Why not?

Although many papers on H_2ICEs limit the introduction to why H_2ICEs are attractive, it is important to be realistic and also pay attention to potential show-stoppers. The most important question is probably whether hydrogen can be justified as an energy carrier. Next to the attractive features listed above, it cannot be forgotten that there are enormous hurdles to overcome. Much of them are down to the low density of hydrogen, rendering distribution and storage difficult, costly and inefficient [8]. When hydrogen would be produced from fossil sources, as is the case for the majority of the hydrogen produced today, the losses in producing, distributing and storing hydrogen (“well-to-tank”) have been reported to potentially be offset due to the higher efficiency (“tank-to-wheel”) when used in fuel cells, resulting in an overall decrease in CO_2 emissions. According to Shelef and Kukkonen, this is not the case for H_2ICEs [9]. However, given this statement was based on (efficiency) numbers available two decades ago, this will be revisited later in this paper.

In any case, it can be safely stated that the eventual use of hydrogen relies on the abundant availability of renewable energy. Even if this would be the case, the difficulty in storing hydrogen currently means that on-board storage is limited and expensive. It is hard to see hydrogen vehicles competing with conventional vehicles in terms of price, although one could argue that there are a lot of hidden, societal costs of present-day vehicles [10].

Coming to H_2ICEs, it is currently not yet possible to combine high efficiency, low emissions, adequate specific power output and durability all in one concept. As will be touched upon later, there are a number of mixture formation concepts for hydrogen, with the port fuel injection (PFI) and direct injection (DI) spark-ignited ones being the most investigated. In the case of PFI, part load efficiency can be quite high, with ultra-low emissions, but low power output. DI engines have been demonstrated to offer very high efficiencies, with controllable emissions, but rely on DI injectors that still have to prove their durability. Moreover, full freedom in optimizing injection strategies asks for high injection pressures. This effectively limits on-board hydrogen storage options: either liquid hydrogen is stored in cryogenic tanks, and injection pressures are generated on-board [11], or compressed hydrogen is stored but then the full tank capacity cannot be utilized (unless there would be a “limp home” mode once tank pressures have dropped below the highest injection pressures). Compressing gaseous hydrogen on-board would negate the efficiency benefits of DI.

This explains the viewpoint of a number of authors that the best way of using hydrogen is to chemically convert it to a fuel that is liquid at atmospheric conditions, making it much easier to handle. The extra processing step upstream, with associated losses, can be compensated by the lower losses of