Progress in Energy and Combustion Science 68 (2018) 169–196

Contents lists available at ScienceDirect

Progress in Energy and Combustion Science

journal homepage: www.elsevier.com/locate/pecs

Recyclable metal fuels for clean and compact zero-carbon power

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ARTICLE INFO

Article History:
Received 2 March 2018
Accepted 10 May 2018
Available online xxx

Keywords:
Metal fuels
Solar fuels
Electrofuels
Low-carbon economy
Metal-water reactions
Hydrogen production
Metal flames
External-combustion engines

ABSTRACT

Metal fuels, as recyclable carriers of clean energy, are promising alternatives to fossil fuels in a future low-carbon economy. Fossil fuels are a convenient and widely-available source of stored solar energy that have enabled our modern society; however, fossil-fuel production cannot perpetually keep up with increasing energy demand, while carbon dioxide emissions from fossil-fuel combustion cause climate change. Low-carbon energy carriers, with high energy density, are needed to replace the multiple indispensable roles of fossil fuels, including for electrical and thermal power generation, for powering transportation fleets, and for global energy trade. Metals have high energy densities and metals are, therefore, fuels within many batteries, energetic materials, and propellants. Metal fuels can be burned with air or reacted with water to release their chemical energy at a range of power-generation scales. The metal-oxide combustion products are solids that can be captured and then be recycled using zero-carbon electrolysis processes powered by clean energy, enabling metals to be used as recyclable zero-carbon solar fuels or electrofuels. A key technological barrier to the increased use of metal fuels is the current lack of clean and efficient combustor/reactor/engine technologies to convert the chemical energy in metal fuels into motive or electrical power (energy). This paper overviews the concept of low-carbon metal fuels and summarizes the current state of our knowledge regarding the reaction of metal fuels with water, to produce hot hydrogen on demand, and the combustion of metal fuels with air in laminar and turbulent flames. Many important questions regarding metal-fuel combustion processes remain unanswered, as do questions concerning the energy-cycle efficiency and life-cycle environmental impacts and economics of metals as recyclable fuels. Metal fuels can be an important technology option within a future low-carbon society and deserve focused attention to address these open questions.

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https://doi.org/10.1016/j.pecs.2018.05.001

1. Energy and climate problems and solutions

Multiple indicators of quality of life, from reduced childhood malnutrition to increased gender equality [1], correlate directly with how much energy is harnessed by a society per person, as well as how efficient that society is in converting that energy into useful products and services that improve living conditions [1–6]. Energy is needed to produce and transport all raw materials and manufactured goods, to provide all services, and underpins all economic activity and wealth creation [5]. The average citizen of a (energy) rich country takes advantage of around 80 times more energy than is produced by their own metabolisms, a feat enabled by our access to fossil fuels [5].

The global economy is currently driven by the international production, trade, and consumption of fossil fuels because they: are relatively cheap and have been readily available, are energy dense, can be burned in internal-combustion engines at high power densities, and are easily transportable and relatively safe to handle. The impressive energy density of fossil fuels can be appreciated by considering the fact that a teaspoonful of hydrocarbon fuel contains chemical energy, when burned with air, equal to the kinetic energy of a 1000 kg automobile travelling at 100 km/hr [7].

1.1. Climate change and fossil energy resources

Unfortunately, combustion of fossil hydrocarbon fuels produces carbon dioxide emissions that cause climate change [8–10]. Limiting anthropogenic global warming to 2 °C requires limiting consumption of fossil energy sources, which would also limit our future economic growth [8,11], leaving a gap that must be filled through development of renewable energy sources [10].

Meanwhile, we may have already passed the peak in conventional crude oil production, or Peak Oil [4,12,13], and may soon be