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Metal fuels for zero-carbon heat and power — Progress and outstanding fundamental and applied challenges

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Abstract

The current roadblock to the clean-energy transition is the lack of viable, cost effective, energy dense, and safe solutions for the storage and off-grid transport of renewable energy. Batteries have too low of an energy density due to the fact that they carry all of their reactants on board. In order to maximize energy-storage density, by mass or volume, fuels that react with oxygen in the air are required. While hydrogen has long been considered the optimal zero-carbon fuel, safety concerns and difficulties in its storage and transport, due to its flammability and low energy density, motivate a search for other options.

Metal powders have long been used as fuels in rocket propellants for their high energy density, but have only recently been considered as alternative fuels. Metals can be recycled from their oxides (ores) using clean energy without carbon dioxide or other greenhouse-gas emissions, storing the renewable electricity as chemical energy. The resulting metal fuels, in powder form, can be burned in air to produce heat, which can be converted into electrical or motive power using heat engines. Alternatively, metal fuels can be reacted with water to produce hot hydrogen on demand for engines or fuel cells. In both the direct-combustion and the metal-water approaches, the products are solid metal oxides that can be captured for recycling, making the use of metal fuels sustainable for the long term. The abundance of these metal resources, and their widespread use today, suggests that metal fuels can be the lowest cost option for the conversion of renewable energy into commodities for global energy trade. Metal fuels can replace diesel fuel in remote power generation, residential, commercial and industrial heating, and for heavy duty transportation, including trucks, locomotives, ships, and even spacecraft.

This talk will overview the concept of metal fuels and the novel metal-fuel technologies developed by the Alternative Fuels Laboratory at McGill. Our team has demonstrated efficient reaction of coarse metals, including aluminum, with supercritical water to generate hydrogen on demand. Our team has also stabilized the first turbulent flame of pure iron-powder fuels and demonstrated that the iron-oxide combustion products can be captured in cyclones for recycling at high efficiency. These lab-scale demonstrations have proven the technology for scale up, demonstration and deployment as zero-carbon energy solutions.

Metal-fuel technology development must be supported by fundamental understanding of the combustion physics and chemistry of metal fuels. Metal combustion is unique compared to traditional hydrocarbon fuels due to the high melting and boiling temperatures of the metal fuels and the metal-oxide products, which, along with the fact that most metal vapours react with oxygen with negligible activation energies, prevents premixing of fuel and oxidizer at the molecular scale. The fast reaction rates between metals and oxygen results in most metal combustion processes being limited by the diffusion rates of oxygen to, and heat from, microflames that surround the metal particles after their ignition. The fast reaction rates and the point-like nature of the solid fuel particles in suspension leads to a novel regime of flame propagation termed the *discrete regime*, where the flame speed becomes independent of the reaction rate and, instead, becomes sensitive to the random distribution of particles in space. Our team is leading an international microgravity research effort to study the physics of flames in the discrete regime. There is evidence that the discrete regime is applicable to the conditions in practical metal-fuel combustors, motivating experimental and theoretical efforts to unravel the physics of this new type of flame.

Clean-energy technologies based on metal fuels can serve the most intransigent emissions sectors and enable a transition to a low-carbon economy. Metal-fuel combustion science lags far behind that for traditional hydrocarbon fuels and there are many unanswered fundamental research questions, and unsolved technical challenges, that present opportunities for our community.

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