Power generation game changers: Metal fuels to propel our future

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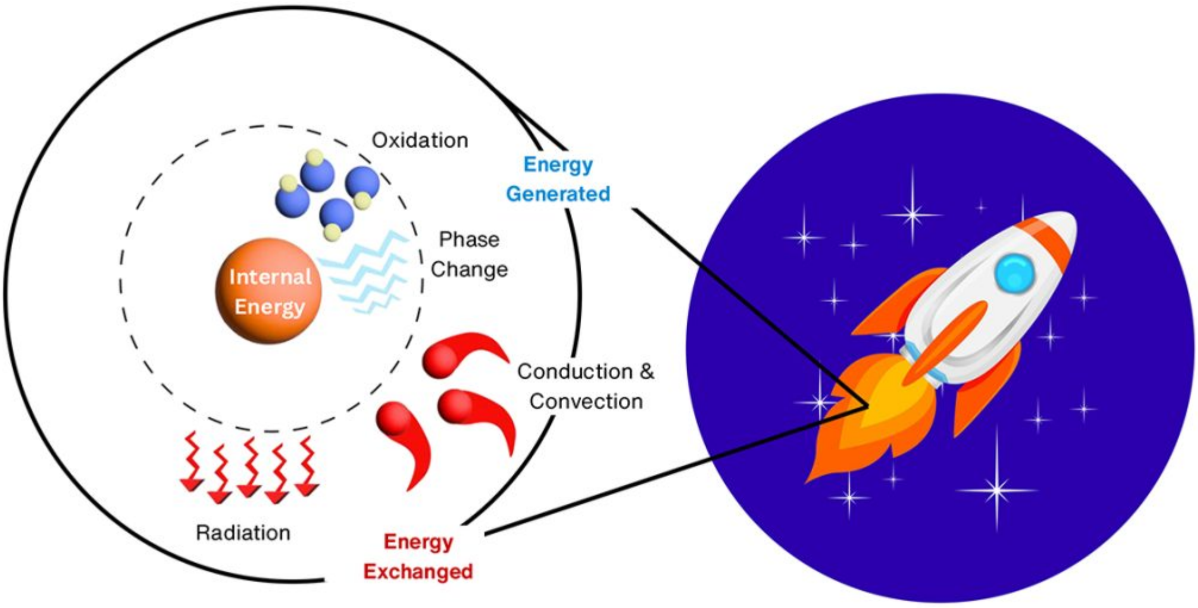

Figure 5. Energy exchange processes will be engineered to impact power generation for the future.

Dr Michelle Pantoya of Texas Tech University examines the advantages of metal fuels compared to traditional hydrocarbons, emphasizing their potential importance in future energy generation

Hydrocarbon combustion may be the workhorse of our economy, but metal fuels are steeling the limelight for their high energy density and potential to transform power generation capabilities. A brief history of fuels provides the context inspiring today's advancements. Key challenges limiting the rate of energy release can be overcome with a newfound perspective on interface properties and interface reactions. Since power is rate-limited energy, increasing the rate of energy generation by the highest energy-dense materials on Earth will naturally create unprecedented power, propelling us into the future of space exploration and hypersonics.

The outlook on metal combustion: What was, what is, and what will be

2.1 What was: a gift from our ancient oceans

Hydrocarbons have satisfied our energy needs for years. They ushered us through the industrial revolution to transform regional economies into global ones by connecting people across land and sea. Combustion scientists have studied hydrocarbons to optimize their energy-generating efficiency and nearly eliminate pollution. In fact, as new students enter combustion science, classic textbooks are anchored in hydrocarbons, with very few pivots toward other fuels. But we need more power, and we are approaching solutions.

2.2 What is: the silent giants

High-energy, fuels lie within our grasp but go largely unnoticed by most sectors of society. Metals like aluminum (Al), magnesium (Mg), and boron (B) appear as humble little powders, but they can pack a powerful punch. Explosives, such as TNT, hold about as much energy as fats (e.g., butter, oils). So, how is it possible that TNT can provide enormous power?

The TNT molecule holds fuel (carbon and hydrogen) and oxidizer (oxygen and nitrogen) together through molecular bonds. In contrast, a metal fuel particle is discretely separated from an oxidizer (i.e., oxygen in air, or a solid oxidizer like ammonium perchlorate), so mass and energy transport is required before ignition can occur. Transport is inherently slower (milliseconds) than bond breaking (microseconds). Thus, explosives are the kings of power generation.

Metal fuels are unique because they are naturally pyrophoric (unlike coal). Nature protects us from their fiery core by passivating the particle surface with a nascent oxide shell. So, unlike coal, metal fuels have a core-shell architecture, which is an added complexity.

Moreover, since the core-shell structure generally corresponds to a mismatch in material properties associated with a metal core and ceramic shell, the architecture could not be more paradoxical. Typically, metals melt hundreds (even thousands) of degrees less than ceramics. Metals are typically soft and malleable, while ceramics are strong, hard, and brittle. Knowledge of material properties is important, and not just for the individual metals and ceramics, but also for properties unique to their inter-facial junction.

Because mass and energy transport are required for ignition, reactions are called ‘diffusion controlled’. Diffusion describes the molecular movement of mass and energy and reminds us that the distance between fuel and oxidizer is one way to control the rate of energy release. This is the key reason why the advent of nanotechnology infused such excitement in the metal combustion community. When the first metal nanoparticle powders were produced circa 2000, there was a rush to discover the golden nugget of power generation. On the nanoscale, diffusion distances are at least three orders of magnitude reduced from their microscale counterparts, increasing the potential for energy release rate (i.e., power) by at least three orders of magnitude, and inspiring researchers to find power surpassing TNT.

The problem was that reducing particle size also increased metal oxide concentration. The passivation shell thickness does not change with particle size, but for nanoparticles, up to 30% of the powder could consist of passivation material. Since metal oxides are ceramics and heat sinks, they can retard energy propagation. A bigger problem was that the reduced diffusion distance markedly increased ignition sensitivity. (1) High ignition sensitivity is not a benefit when handling powder fuels because unintentional ignition events can be dangerous. On the flip side, for nanoparticles, processes that occur at the metal-ceramic or ceramic-surroundings interfaces were amplified and, in some cases, were observed for the first time. (2) Here lay the golden nugget, although it went largely masked by the more obvious pitfalls of ceramic dead weight and heightened ignition sensitivity. All tallied, even though nanoparticles were generally a bust, we learned a lot from studying nanoparticles that has influenced the new wave of research focusing on the interface of microscale metal particles.

2.3 What will be: the future is bright

The Holy Grail for finding tremendous power from high-energy metal fuels will be a partnership between scientists and engineers with expertise in material physics, interfacial chemistry, and combustion. The unique core-shell architecture of metal fuels presents challenges but also offers opportunities previously cloaked by our inability to recognize processes occurring at the surface and unmasked by the advent of nanotechnology.

From my time studying metal combustion, I can identify two physical phenomena that need attention to transform power generation (3). Understanding these processes will be a game-changer for the future of power generation.

1. Internal boiling on the condensed oxide-metal interface could explain several experimental puzzles related to metal particle combustion. The capabilities to unravel the mysteries of interface physics are available in the technologies of today.
2. Condensed-luminescent energy loss during nano-oxide formation. While chemical energy stored in metal particles is high, energy associated with phase change can be equivalent, if not higher. Condensation energy is mainly channeled as radiant transfer, inevitably lost to the surroundings. Technologies addressing the physics of condensation and radiant emission are emerging today and poised for their application in solid fuel combustion.

In summary, the puzzle pieces of the past come together to produce a picture of the next chapter of human life. The vision for metal fuels goes beyond capitalizing on their energy; it is exploiting them to transform power generation. The potential for power from metal fuels will propel humanity beyond our Universe and into new realms of life and posterity. It’s an exciting time to study metal fuel combustion!

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References

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