

Dense energy carrier assessment of four combustible metal powders

Luc Dirven^a, Niels G. Deen^a, Michael Golombok^{a,b,*}

^a Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

^b Shell Global Solutions International B.V., Grasweg 31, 1031 HW Amsterdam, The Netherlands

ARTICLE INFO

Keywords:

Energy carrier
Metal powder
Cycle efficiency
Dry route

ABSTRACT

Metal powders show great potential as dense energy carriers. This conceptual cycle for application presents a number of challenges which we address in this paper. In this study we narrowed down on four readily available promising candidates: aluminium, silicon, iron and zinc. Based on static power generation we estimated amounts required, transportation, cycle efficiency and physical explosion hazards. The scale required for transportation is much larger than in the current metal powder industry. The shipping requirements are comparable to coal. The handling hazards are only serious for aluminium. Iron and silicon emerge as the materials of choice.

Introduction

Current energy scenarios envision a society less dependent on fossil fuels and making much more use of renewable energy. This requires that we address the intermittency of renewable sources as well as the geographical mismatch between supply and demand of renewable power. An example is high-intensity solar power. In densely populated areas such as China, India and Europe the solar irradiation is substantially less than in areas such as Australia and Africa. To transport the energy to areas where it is needed, a commodity to store and globally trade energy is required: a dense energy carrier (DEC).

A DEC has two essential properties: a high energy density, and it is convenient to transport. For sustainability, the storage cycle should be regenerative, and no greenhouse gases should be emitted. Examples of energy carriers include:

- Batteries: a regenerative energy carrier, but with a limited lifetime. Batteries have a low energy density which make them prohibitive to use for large-scale storage and global transportation of energy.
- Hydrogen: an energy carrier which can be generated from water electrolysis. The current cycle efficiency is relatively low. Additionally hydrogen has to be compressed and cooled in storage which requires energy.

A recent proposal by Bergthorson [1] considers metal powder as a dense energy carrier (DEC). In a metal DEC cycle, energy is stored in such a metal powder. The complete cycle is shown in Fig. 1. At the power generation plant, metal powder is burned to generate heat which is converted to electricity. The combustion of the metal generates

metal-oxide powder that is captured and transported to the regeneration plant. At the regeneration plant, the metal-oxide powder is reduced by using renewable energy. In this process, energy is stored in the metal powder, and the powder can be transported to the power generation plant where it is burned in the next cycle to produce electricity. The metal powder cycle also can be defined as an energy storage medium i.e. it captures energy that can be produced for later use. However the high density of the storage and its relative ease in transportability – as we shall see below – raise it to the status of candidate dense energy carrier.

The economics of this process rely on the mismatch between the locations of for example high intensity solar irradiation for regeneration, and world areas with high population density and industrial growth. An initial investment is required for the metal which becomes “fixed capital” – and for the purposes of this study is assumed not to deplete. The amount of powder in storage then depends on variables, such as the power supply of the regeneration plant (assumed to be “for free”), the electricity demand at the consumer side, the load size of the transportation vessel and the lead time of transportation. We assume transport between lands not too far apart. For example if we consider power demand, this peaks in winter in the Netherlands whereas solar PV power peaks in Morocco in the summer. The economic incentive is the levelling of the intermittent supply and demand of power by storage in metal powder.

One of the challenges identified in enabling the metal DEC cycle is thus transport and handling of the powders. These processes are potentially hazardous, and the scales that would be involved are significantly greater than currently applicable in the metal powder industry. The aim of this study is to address these concerns. Section

* Corresponding author at: Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands.

E-mail address: michael.golombok@shell.com (M. Golombok).

Nomenclature		ld	load
<i>Symbols</i>		HFO	heavy fuel oil
E	energy content	h	hot
ΔH	enthalpy difference of a process	M	metal
K_{st}	deflagration index	MO	metal-oxide
m	mass	od	heat transfer
P	power	pg	power generation
p	pressure	rg	regeneration
T	temperature	r	reduction
t	time	tr	transportation
t_l	lead time	tot	total
P	power	<i>abbreviations</i>	
V	volume	BOE	barrel of oil equivalent
<i>greek</i>		CLC	chemical looping combustion
H	efficiency	DEC	dense energy carrier
<i>sub/superscripts</i>		FC	fuel consumption
c	cold	HC	hydrocarbon
com	combustion	HV	higher heating value
		MEP	maximum explosion pressure
		MRP	maximum rate of pressure rise

“Background” briefly reviews the background to metal powder combustion. Section “Materials” considers material constraints. Section “Application analysis” reviews the three main issues: after a demonstration example in large scale power generation with the implications, we estimate the cycle efficiency and evaluate the main hazard which is explosion.

Background

The idea of using solid powdered fuels has existed for over a century – the nearest analogues are of course coal fired power stations. Rudolf Diesel experimented with coal dust in a diesel engine [2]. He already faced the inherent issues of solid fuels: his engine plugged up by dust build-up and the internal components suffered from severe erosion. Nonetheless, almost a century later, the vice chairman of General Motors still claimed [3] that commercial coal-powered vehicles would be “products of the next century”.

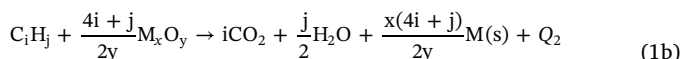
Although an internal combustion engine fuelled by powder was never realised, powders are used for a variety of other applications. For example, metal powders are applied in nanofluids, gelled propellants, solid propellants, solid fuels and thermites [4]. The potential of metal powder as an energy carrier has recently gained more interest [5,6]. There have been two main routes identified: Metal powder combustion (“dry route”) which produces metal oxides [7] and the “wet route”

reaction with water which yields hydrogen [8]. For the latter process aluminium and magnesium are the best performers although the rate is limited by the formation of protective (effectively “anodized”) oxide layers [9,10]. A major factor is the way the metal needs to be prepared for the process to enable reasonable reaction rates [11]. This corresponds to an increase in the energy cost of the regenerative step of the cycle (see below). In this study we are only concerned with the dry route as we seek a replacement combustion reaction in for example coal fired power stations, rather than assuming a whole new infrastructure that would be associated with hydrogen replacing natural gas. A large part of our study does concern the reduction aspects and so is relevant to the wet as well as the dry cycle on which we now concentrate.

The combustion of metal is similar to the metal-air reaction in chemical looping combustion (CLC). CLC can be used in carbon capture and storage (CCS) systems [12]. The purpose of CLC is to obtain a pure stream of CO₂ from the combustion of (hydro)carbons. A typical CLC system is based on two reaction mechanisms. The first reaction involves the oxidation of a metal (M) with air, shown in Eq. (1a). This reaction results in a gas stream of pure nitrogen and solid metal-oxide particles.



where Q_1 is the exothermicity of the direct metal oxidation. The second reaction (in chemical looping combustion) involves the oxidation of a (hydro)carbon with the metal-oxide particles



In this second reaction, the metal-oxide particles are reduced, and the fuel is oxidized. Of course if one balances the first and second reactions for one mole of hydrocarbon then the sum of the energies corresponds to the heating value (HV) of the hydrocarbon. In general $Q_1 \gg HV$ so the combustion of metals is certainly interesting from an energetic point of view [10]. The two reactions for chemical looping combustion take place in separate reactors and nitrogen and CO₂ are obtained separately. CLC shows similarities with the metal DEC cycle, but there are also some fundamental differences. Firstly, the main goal of CLC and the metal DEC cycle differs. In CLC, the main goal is to obtain a separate CO₂ stream for CCS. The main goal of the metal DEC cycle is to transport and store energy. Secondly, in CLC the oxidation

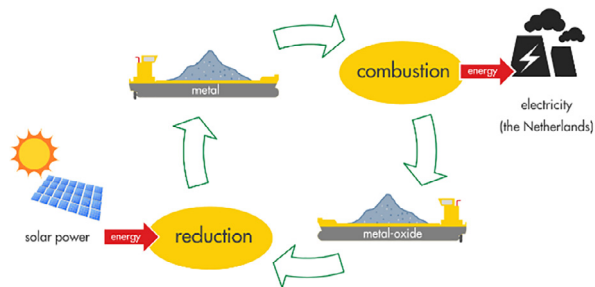


Fig. 1. The outline of the regenerative process of energy storage in metal powder. Renewables power reduction of metal oxides which are then shipped to power stations.

Download English Version:

<https://daneshyari.com/en/article/10147945>

Download Persian Version:

<https://daneshyari.com/article/10147945>

[Daneshyari.com](https://daneshyari.com)