Development and Testing of the Zigzag Flow Reactor for Thermochemical Energy Storage

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1. Introduction

As the world gears up for a transition to renewable energy, the need for a multi-level energy storage infrastructure, covering a period of hours to months, is rising [1]. A wide space of available materials gives thermochemical energy storage (TCES) a great promise in meeting, cost-effectively, the medium term energy storage demand (20-200 h.) [2]. In TCES, countercurrent flow of solid and gas in the charging (i.e. thermal reduction) step, as well as significant solid-gas mixing, are essential for maximal utilization of the available reaction potential [3]. Some of the main TCES challenges include low reduction extents and poor particle residence times in moving particle-based thermal reduction reactors [4]. Building on the available knowledge, we report on the designing and testing of the *Zigzag Flow Reactor* (ZFR), a next generation reactor for thermochemical reduction of metal oxide particles.

2. Theoretical, Experiment, and Results

The ZFR, schematically shown in **Figure 1,** allows the metal oxide particles to operate close to thermochemical equilibrium to maximize efficiency [3]. Electrical heaters bring incoming particles to reaction temperature, as they flow along vertically stacked, slightly inclined (~15°), particle-opaque, metal meshes. The meshes are transparent to the inert sweep gas (ISG) flowing from bottom to top (50% open area). This counterflow - crossflow setup significantly enhances the solid-gas mixing, and together with the high τ_R (~30 s with 12 meshes) exhibited by the ZFR, offers a great opportunity for the reaction to operate close to equilibrium. ISG picks up the evolved O_2 maintaining inert conditions in the heated section and exits from the open top. The front and bottom of the ZFR are semipermanently sealed. Particles exit the reactor and rapidly cool below the reoxidation temperature in an externally cooled nitrogen filled particle chute to minimize particle reoxidation. Reduced particles collect in a nitrogen filled particle collection bin to further prevent reoxidation. A sample of reduced particles from the particle collection is reoxidized at 620 °C in air and the resulting weight gain provides information about the particle reduction extent (Δδ). An oxygen sensor analyzes a small sample of the outlet ISG flow (~10-15%) to measure pO_2 near the particle inlet and a load cell monitors the reactor exit mass flow.

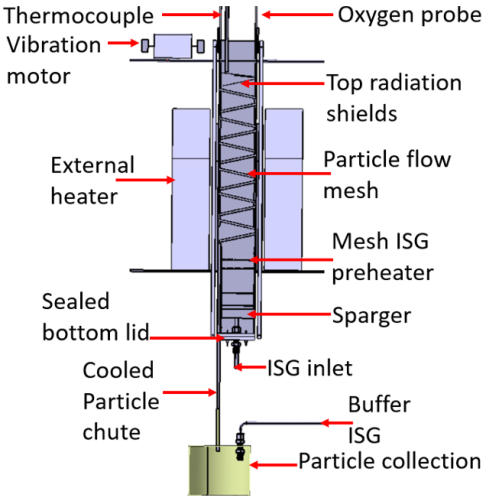

Figure 1. Cutout view of the Zigzag Flow Reactor CAD model.

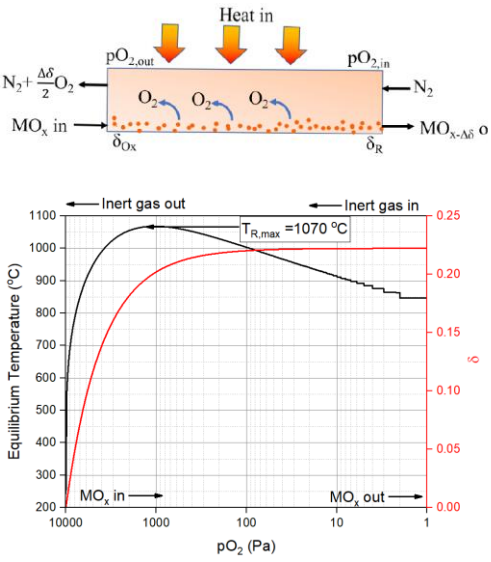

Figure 2. (a) Oxygen mass balance in a countercurrent reactor. (b) $T - p_{O_2} - \delta$ example at equilibrium in a countercurrent flow reactor.

The reaction approaches the ideal reversible path if the reactions occur at a specific reaction coordinate and material dependent temperature where ΔG→0 followed by rapid

removal of evolved oxygen from particle vicinity at each infinitesimal point along the reacting path. With an inert swept reactor with single ISG inlet (**Figure 2a**), $\Delta G = 0$ requires a variable temperature profile as a fuction of the reaction coordinate (**Figure 2b).** A vibration motor enables the particle flow in ZFR and offers some control over the particle residence time (τ_R).

With a maximum thermal reduction temperature of 875 °C, a minimum ISG pO_2 of 17 Pa and an input particle flow of ~0.23 g/s, **Figure 3** shows the pO_2 measured near the particle inlet and the corresponding exit mass flow rate of CAM28 particles against time of operation. **Figure 3** shows that after a small delay after the start of particle flow, the pO_2 starts rising indicating the onset of particle reduction. The pO_2 follows the exit mass flow rate and achieves steady state with the input flow rate (~0.23 g/s) after a small delay (~60 s). Once all the particles are inside the reactor, the outlet particle flow rate drops along with the pO_2 as the reactor empties. The reoxidation of particles from the particle collection indicate a $\Delta\delta = 0.0287$ with 68% reactive particles.This reduction extent is 2.87 times the reduction extent achieved in previous attempts at a maximum temperature of ~850 °C [4]. This improved performance is primarily due to the large τ_R and high solid-gas mixing. Further optimization of temperature gradient, minimization of O_2 ingress and minimizing reoxidation after the particle exit can lead to further increase in $\Delta\delta$.

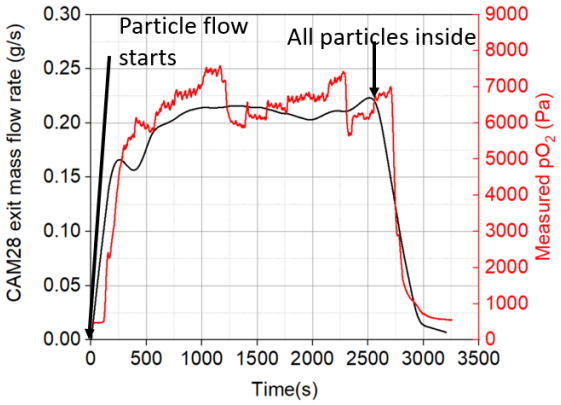

Figure 3. Dependence on reactor exit flow rate and pO_2 near measured the particle inlet on time of operation..

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References

[1] O. Schmidt et al., Joule, **3**(1), pp. 81–100.
[2] S.M. Babiniec et al., Int. J. Energy Res., 40(2), pp. 280–284.
[3] A. de la Calle et al., Int. J. Hydrogen Energy. 47 (2022) 10474–10482.
[4] A.J. Schrader et al., Appl. Therm. Eng., 173(December 2019), p. 115257.