Sulfur and ferrite-based thermochemical cycles for water splitting

Martin Roeb

SFERA WinterSchool 2011, Zurich, March 24th 2011

Outline

- Ferrite based thermochemical cycle: HYDROSOL
  - Materials
  - System Model
  - Prototypes and tests
  - Pilot plants
  - Scale-up, economics
- Sulphur based thermochemical cycle: HycycleS
  - Materials
  - Prototypes
  - Modelling
  - Scale-up
- Summary
1. Ferrite based thermochemical cycle

The HYDROSOL CONSORTIA

**HYDROSOL**
- APTL (GR)
- DLR (D)
- Heliotech (DK)
- Johnson Matthey (GB)

**HYDROSOL-2**
- APTL (GR)
- DLR (D)
- STC (DK)
- Johnson Matthey (GB)
- CIEMAT (ES)

**HYDROSOL-3D**
- APTL (GR)
- DLR (D)
- CIEMAT (ES)
- Total (F)
- Hygear (NL)
Thermochemical Cycle using Mixed Iron Oxides: Reaction Scheme

1. Step: Water Splitting
\[ \text{H}_2\text{O} + \text{MO}_{\text{red}} \rightarrow \text{MO}_{\text{ox}} + \text{H}_2 \]

2. Step: Regeneration
\[ \text{MO}_{\text{ox}} \rightarrow \text{MO}_{\text{red}} + \frac{1}{2} \text{O}_2 \]

Net reaction: \[ \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2 \]

Typical redox materials:
- ZnFe$_2$O$_4$
- NiZnFe$_2$O$_4$
- MnFe$_2$O$_4$
- CoFe$_2$O$_4$

The HYDROSOL process concept

1200 °C
800-900 °C
1200 °C
800-900 °C
The HYDROSOL Process

**Basic Features**
- Use of solar radiation absorbing ceramic honeycomb structures
- Synthesis of active water-splitting redox nanomaterials with non-conventional techniques
- Fixing/coating of the redox materials on the channels of the honeycomb

**Advantages**
- No circulation of (hot) solid reactants
- Product separation straightforward
- No movable components at high temperatures

**Objectives of HYDROSOL-2**
- To design and build a solar Hydrogen pilot plant (100 kW<sub>th</sub>) based on thermo-chemical water-splitting, carried out on monolithic ceramic honeycombs coated with active redox materials
- To set the stage for further scale-up of the HYDROSOL technology and its effective coupling with solar thermal concentration systems, in order to exploit and demonstrate all potential advantages
- To develop and identify redox materials most suitable for this cycle
- To develop and verify suitable process strategies, in particular control strategies
- To develop a fully scalable receiver-reactor to carry out the reactions involved
Objective: Integration in a Solar Tower System

“MODULAR” DESIGN

Materials development and characterisation
Consideration of Thermodynamics

Pre-Selection ➔ Phase analysis ➔ Yield ➔ Efficiency

Phase analysis (calculated with FACTsage)

Reduction of CoFe$_2$O$_4$

Graph showing the reduction of CoFe$_2$O$_4$ under varying temperatures and the formation of different phases such as Spinel, CoO Monoxide, FeO Monoxide, and O$_2$.
Yield (calculated)

Simulation of mixed oxides type MFe$_2$O$_4$ (M=Co, Ni, Mn, Mg)

Oxidation  \( \rightarrow T^{\text{reg}} = 1500^\circ\text{C} \)

Ellingham-Diagram: Transition Metals
Ellingham-Diagram: Desired Material

Reaction Schemes employed for Mixed Iron Oxides synthesis

**Solid phase self-propagating high-temperature synthesis (SPSHS)**

$$2k \text{Fe} + (1-k) \text{Fe}_2\text{O}_3 + x \text{MnO} + (1-x) \text{ZnO} + 1.5 \text{zO}_2 \rightarrow (\text{Mn}_x\text{Zn}_{1-x})\text{Fe}_2\text{O}_4$$

**Liquid phase self-propagating high-temperature synthesis (LPSHS/GC)**

$$2\text{Fe(NO}_3\text{)}_3 + x \text{Mn(NO}_3\text{)}_2 + (1-x) \text{Zn(NO}_3\text{)}_2 + 3 \text{C}_6\text{O}_7\text{H}_8 + 8 \text{NH}_3 + 9.5 \text{O}_2 \rightarrow (\text{Mn}_x\text{Zn}_{1-x})\text{Fe}_2\text{O}_4 + 18 \text{CO}_2 + 8 \text{N}_2 + 24\text{H}_2\text{O}$$

**Aerosol spray pyrolysis synthesis (ASP)**

$$2\text{Fe(NO}_3\text{)}_3 + x \text{Mn(NO}_3\text{)}_2 + (1-x) \text{Zn(NO}_3\text{)}_2 + (3 \text{C}_6\text{O}_7\text{H}_8 + 8 \text{NH}_3) + 9.5 \text{O}_2 \rightarrow (\text{Mn}_x\text{Zn}_{1-x})\text{Fe}_2\text{O}_4 + 18 \text{CO}_2 + 8 \text{N}_2 + 24\text{H}_2\text{O}$$

**Solid state synthesis (SSS)**

$$\text{Fe}_2\text{O}_3 + x \text{MnCO}_3 (\text{Mn}_3\text{O}_4) (\text{NiO}) + (1-x) \text{ZnO} \rightarrow (\text{Mn}_x (\text{Ni})_x \text{Zn}_{1-x})\text{Fe}_2\text{O}_4 + x \text{CO}_2$$
**Materials characterization: specific surface area**

- **SSS**
  - 1-2 m²/g
- **SPSHS/GC**
  - 20-40 m²/g
- **LPSHS/GC**
  - 4-5 m²/g
- **ASP**
  - 80-120 m²/g

**Phase and color evolution during calcination in air**

\[ \text{Mn}_{0.5}\text{Zn}_{0.5}\text{FeO} \]

<table>
<thead>
<tr>
<th>Phase and Color Evolution during Calcination in Air</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fe₂O₄</strong> as-synth.</td>
</tr>
<tr>
<td><img src="image1.png" alt="Image" /></td>
</tr>
</tbody>
</table>

---

**Deutsches Zentrum für Luft- und Raumfahrt e.V.**
in der Helmholtz-Gemeinschaft
Tests with coated monoliths: Testing of Mn-Fe-O mixed oxide with respect to cyclic H$_2$ production (800 °C)

Continuous Hydrogen production
small monolith SiSiC coated with YSZ/ Mn-2Fe-O (SHS)

Hydrogen yield (experiment)

Stoichiometry:
Zn-Fe oxide material

**ASP-synthesized materials exhibit the highest H$_2$ yield**, followed by the SHS- and GC-produced ones.

For a given synthesis route, there is no significant variation of the amount of H$_2$ produced, within 700-900°C.
Kinetics of water splitting

Experimental Set-Up

Water Splitting

- **O₂**
- **H₂**
- **N₂**
- **H₂O**(g)
- **H₂O**(fl)
- **H₂O+**N₂
- **H₂+N₂
- **N₂**
- **Electric furnace**
- **Ceramic tube**
- **Peristaltic pump**
- **Mass flow controller**
- **Mass spectrometer**
- **Collecting vessel**
- **Thermocouple**
- **Water cooler**
- **Feed unit**
- **Mass flow controller**
- **Water source**
Experimental Set-Up

H₂ production curve

Water vapour input

<table>
<thead>
<tr>
<th>% O₂</th>
<th>% H₂</th>
<th>% CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

Time of day

peak H₂ production
Reaction Model

**Shrinking Core Model**

Shrinking Core Model derives different approaches for

\[ X_{\text{solid}} : \text{conversion of solid phase} \]

\[ X_{\text{solid}} = f(t) \]

<table>
<thead>
<tr>
<th>Film diffusion</th>
<th>Internal diffusion</th>
<th>Chemical reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ t = k_1 \cdot X_{\text{solid}} ]</td>
<td>[ t = k_2 \cdot \left( 1 - 3 (1 - X_{\text{solid}})^{2/3} + 2 (1 - X_{\text{solid}}) \right) ]</td>
<td>[ t = k_3 \left( 1 - (1 - X_{\text{solid}})^{1/3} \right) ]</td>
</tr>
</tbody>
</table>

Analysis of Water Splitting Step

Conversion vs. Time

Fit function: 
\[ t = k_1 \cdot X_{\text{solid}} + k_2 \cdot \left[1 - 3(1 - X_{\text{solid}})^{2/3} + 2(1 - X_{\text{solid}})^{1/3}\right] + k_3 \left[1 - (1 - X_{\text{solid}})^{1/3}\right] \]

Diagram showing conversion over time for different temperatures:
- T = 800 °C
- T = 900 °C
- T = 1000 °C
- T = 1100 °C
- T = 1190 °C

Results from Shrinking Core Model Curve Fit

<table>
<thead>
<tr>
<th>(T_{\text{Splitting}})</th>
<th>(k_1)</th>
<th>(k_2)</th>
<th>(k_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0</td>
<td>6312974</td>
<td>0</td>
</tr>
<tr>
<td>900</td>
<td>0</td>
<td>800484</td>
<td>0</td>
</tr>
<tr>
<td>990</td>
<td>0</td>
<td>210547</td>
<td>0</td>
</tr>
<tr>
<td>1100</td>
<td>0</td>
<td>33721</td>
<td>0</td>
</tr>
<tr>
<td>1190</td>
<td>1308</td>
<td>7037</td>
<td>0</td>
</tr>
</tbody>
</table>

- Reaction is mainly limited by internal diffusion
- Possible film diffusion limitation at about 1200 °C
Milestones of Materials Development

Water-splitting on redox coated honeycombs

Redox material coated SiSiC honeycombs

SEM analysis for the investigation of the quality of coating and the effect of solar water splitting

50-cycles of solar water-splitting

Field evaluation of coated monoliths

Key milestone

Reactor concept and reactor design
Reactor for continuous hydrogen production

- Reactor with two modules
- 10 kW two-chamber system
- Two different alternating processes:
  - Production: 800°C, water steam, nitrogen, exothermic
  - Regeneration: 1200°C, nitrogen, endothermic
- Transient steps like
  - Switching between half cycle
  - Start-up / Shutdown
- Closed system: quartz window
- Four-way-valve

HYDROSOL:
Continuously operating reactor during exposure to sunlight
Hydrosol technology scale-up

- **2004:**
  - First solar thermochemical H₂ production

- **2005:**
  - Continuous STC H₂ production

- **2008:**
  - Pilot reactor (100 kW)

PSA solar tower

DLR solar furnace

Pilot plant installation and testing
Scale-up: 100kW-pilot-plant

Process strategy for thermal cycling

Focus 1 (east): Groups 1, 2, 3, 4
Focus 2 (west): Groups 5, 6, 7, 8
Switch-over groups (east and west): 0, 9, 10, 11
Reserve group (east and west): R

Distance from tower

Focal length

- 162 m
- 136 m
- 119 m
- 97 m
- 67 m
Experiments – Solar Flux

Flux Measurement at test operation

\[ \text{Flux}_{\text{Max}}^{\text{both Modules}} = 115 \text{ kW/m}^2 \]

Experiments: Thermal cycling

[Graph showing temperature changes over time]
Parametric study – mass flow

![Graph showing mass flow](image)

Parametric study – heliostats

![Graph showing heliostats](image)
First Hydrogen Production

![Graph showing hydrogen production](image)

**Hydrogen production in experimental series in July 2009**

![Graph showing time and concentration](image)
Hydrogen production on June 18th 2010

Hydrogen production on June 17th 2010
Hydrogen production on June 21\textsuperscript{st}/22\textsuperscript{nd} 2010

![Graph showing hydrogen production on June 21\textsuperscript{st} and 22\textsuperscript{nd} 2010.]

Modelling of reactor and process
Model of Solar Furnace Reactor

Monolith

Absorber model

Overall Model of Solar Furnace Reactor

Model includes:

- Irradiation and conduction among the individual absorber elements
- Intrusion of solar irradiation into the absorber channels
- Solar power input: gaussian distribution
- Irradiation losses through the reactor front window
- Thermal losses through the housing
Hydrogen Production

H₂ and O₂ production

Peak hydrogen production decreases

Ferrite Composition

Oxygen uptake capacity of ferrite

Low temperatures at the absorber rear side → poor regeneration
Scale-up

Flow sheet of HYDROSOL process
Economics

<table>
<thead>
<tr>
<th></th>
<th>Hydrosol 1 MW</th>
<th>Hydrosol 50 MW</th>
<th>Hybrid-Sulphur Cycle</th>
<th>Water Electrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total investment</td>
<td>1.46</td>
<td>1.07</td>
<td>2.03</td>
<td>0.18 €/kgH₂</td>
</tr>
<tr>
<td>Operational costs</td>
<td>13.02</td>
<td>5.73</td>
<td>2.64</td>
<td>6.32 €/kgH₂/year</td>
</tr>
<tr>
<td>By-product credits</td>
<td>23,277</td>
<td>3,484,955</td>
<td>3,140,705</td>
<td>2,069,475 €/a</td>
</tr>
<tr>
<td>Hydrogen production costs</td>
<td>15.38</td>
<td>6.75</td>
<td>5.35</td>
<td>5.80 €/kgH₂</td>
</tr>
</tbody>
</table>

Hydrosol 3D

- The principal objective of HYDROSOL-3D is the in-detail preparation of a plant for solar thermo-chemical hydrogen production from water via the HYDROSOL technology, in a 1 MW scale on a solar tower.
- HYDROSOL-3D focuses on the next step towards commercialization and involves all activities necessary to prepare the erection of a HYDROSOL-technology-based 1 MW solar demonstration plant.
- In this respect HYDROSOL-3D is concerned with the complete pre-design and design of the whole plant including the solar hydrogen reactor and all necessary upstream and downstream units needed to feed in the reactants and separate the products and the calculation of the necessary plant erection and hydrogen supply costs.
Process variation: synfuels

CO$_2$ reduction using metal oxides

2-step synthesis of CO using multi-valent metal oxides

1. Step: Reduction

$$\text{MO}^{\text{oxidiert}} \leftrightarrow \text{MO}^{\text{reduziert}} + \frac{1}{2} \text{O}_2$$

2. Step: Oxidation oder CO$_2$ splitting

$$\text{MO}^{\text{reduziert}} + \text{CO}_2 \leftrightarrow \text{MO}^{\text{oxidiert}} + \text{CO}$$
2. Sulphur Based Thermochemical Cycles

Examples of Sulphur based thermochemical cycles
Project Overview: HycycleS

Main topics:
- Suitability of construction and catalyst materials for $\text{H}_2\text{SO}_4$ decomposition section
- Material and design of $\text{H}_2\text{SO}_4$ decomposer (as heat exchanger)
- Material and design of $\text{H}_2\text{SO}_4$ decomposer (as solar receiver-reactor)
- Materials and design of $\text{SO}_2/\text{O}_2$ separator (membranes for enhancing the performance of $\text{SO}_3$ decomposition)

HycycleS - Materials and components for Hydrogen production by sulphur based thermochemical cycles

EU FP7 - ENERGY

Duration: January 2008 – March 2011

Solar reactor development, testing and simulation
Objective

- Development of a solar receiver-reactor (multi-chamber concept)
- Evaporation and decomposition of sulphuric acid
- Volumetric receiver-reactor concept
- Testing in DLR solar furnace
- Variation of operating conditions and configuration
- Analysis of different catalyst systems

H$_2$SO$_4$ decomposition in 2 steps

1. Evaporation of liquid sulphuric acid (400°C)
   
   \[
   H_2SO_4(\text{aq}) \rightarrow H_2SO_4(\text{g}) + H_2O(\text{g})
   \]
   
   \[
   H_2SO_4 \rightleftharpoons SO_3 + H_2O
   \]

2. Decomposition (reduction) of sulphur trioxide (850°C)
   
   \[
   SO_3 + H_2O \rightleftharpoons SO_2 + \frac{1}{2}O_2 + H_2O
   \]

Absorbers:

- SiSiC foam
- SiSiC honeycomb
Procedure of technology development

1. Preliminary design of a multi-chamber concept
2. Numerical analysis: FEM, Dymola, CT and continuum model
3. Finalization of the design
4. Construction and assembling of the reactor
5. Initial operation followed by first testing series
6. Optimisation of the set-up followed by second testing series
7. Further optimisation and testing (if necessary)

Design of multi-chamber solar reactor

- Foam
- Honeycomb
- Solar radiation (focus 1)
- Solar radiation (focus 2)
- Front view of evaporator and decomposer
- Rear view
- $\text{SO}_3 + \text{H}_2\text{O}$
- $\text{H}_2\text{SO}_4$
- $\text{SO}_2 + \text{O}_2 + \text{H}_2\text{O}$
HycycleS solar reactor

H$_2$SO$_4$ $\Rightarrow$ SO$_3$ + H$_2$O

400°C

Catalyst materials
- Coated on SiSiC honeycomb

SO$_3$ $\Rightarrow$ SO$_2$ + $\frac{1}{2}$ O$_2$

Construction materials
- Solar absorbers
  - SiSiC foam
  - SiSiC honeycomb
- Piping
  - High-alloyed steel

Assembling of the solar reactor
Solar furnace of DLR in Cologne

- 159 concentrator mirrors
- 57 m² heliostat

22 kW max. power

Power regulation of the two chambers

Segment shutter with 14 lamellae on each side
Receiver-Reactor during operation

Testing and qualification of the receiver-reactor

Temperature of the evaporator

Performance of the SO₃ decomposer
Conversion of SO$_3$: experiment and equilibrium

$$U_{SO_3} = \frac{\dot{V}_{SO_3:\text{aus}}}{\dot{V}_{SO_3:\text{ein}}}$$

![Graph showing SO$_3$ conversion efficiency vs. temperature](image)

Reactor efficiencies

**Evaporator**

**Decomposer**

![Graph showing evaporator and decomposer efficiencies](image)
Reactor efficiencies

Total reactor

Energy Losses

<table>
<thead>
<tr>
<th>Loss</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>9%</td>
</tr>
<tr>
<td>Loss housing</td>
<td>12%</td>
</tr>
<tr>
<td>Loss decomposer window</td>
<td>31%</td>
</tr>
<tr>
<td>Net power evaporator</td>
<td>17%</td>
</tr>
<tr>
<td>Net power decomposer</td>
<td>8%</td>
</tr>
<tr>
<td>Sensible heat</td>
<td>16%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{S,-evap}$</td>
<td>870 W</td>
</tr>
<tr>
<td>$P_{S,decomp}$</td>
<td>1141 W</td>
</tr>
<tr>
<td>Catalyst</td>
<td>Fe$_2$O$_3$</td>
</tr>
<tr>
<td>$V_{H_2SO_4}$</td>
<td>6 ml/min</td>
</tr>
<tr>
<td>$T_{H2,mean}$</td>
<td>852 °C</td>
</tr>
<tr>
<td>Conversion</td>
<td>82 %</td>
</tr>
<tr>
<td>$\eta_{net,decomp}$</td>
<td>39 %</td>
</tr>
<tr>
<td>$\eta_{net,evap}$</td>
<td>15 %</td>
</tr>
</tbody>
</table>
System Model of the Decomposer

Discretisation of the Absorber

- 7 Ring elements x 10 Slices
- 70 elements
- 20 cells per element for chemical reaction modelling
Simulation of the SO₃ Decomposer

Heat balance of solid volume elements
\[ 0 = m \cdot c_p \cdot \frac{dT}{dt} + \dot{Q}_{\text{cond,a}, \text{radial}} + \dot{Q}_{\text{cond,b}, \text{radial}} + \dot{Q}_{\text{cond,c}, \text{axial}} + \dot{Q}_{\text{conv}, \text{axial}} + \dot{Q}_{\text{rad,a}, \text{radial}} + \dot{Q}_{\text{rad,b}, \text{radial}} + \dot{Q}_{\text{rad,c}, \text{radial}} + \dot{Q}_{\text{rad,d}, \text{axial}} - \dot{Q}_{\text{conv}} \]

Heat balance of gas volume elements
\[ 0 = \dot{m}_{\text{in}} \cdot h_{\text{in}} - \dot{m}_{\text{out}} \cdot h_{\text{out}} - \dot{Q}_{\text{reaction}} + \dot{Q}_{\text{conv}} \]

Kinetic model of SO₃ reduction
\[ v_{[1]} = k \cdot \left( X_{\text{SO}_2 \text{out}[i-1]} \cdot c_{\text{gas}} \right)^{\alpha_{\text{SO}_2}} \]
\[ -k_{\text{back}} \cdot \left( X_{\text{SO}_2 \text{out}[i-1]} \cdot c_{\text{gas}} \right)^{\alpha_{\text{SO}_2}} \cdot \left( X_{\text{O}_2 \text{out}[i-1]} \cdot c_{\text{gas}} \right)^{\alpha_{\text{O}_2}} \]

Modelling of Radiation

Heat losses: Thermal radiation
\[ \dot{Q}_{\text{TR}} = \dot{Q}_{\text{TR}, \text{conv}} + \dot{Q}_{\text{TR}, \text{window}} + \dot{Q}_{\text{TR}, \text{ambience}} \]

Thermal radiation through quartz window
\[ \dot{Q}_{\text{TR}, \text{ambient}} = a_{\lambda} \cdot k_{\text{glass}} \cdot \phi_{12} \cdot e_{\text{Absorber}} \cdot e_{\text{ambient}} \cdot C_s \cdot A_{\text{Absorber}} \cdot (T_{\text{Absorber}}^4 - T_{\text{ambient}}^4) \]
Validation: conversion and reactor efficiency

\[ \eta_{\text{reactor}} = \frac{\dot{Q}_{\text{net, reactor}}}{P_{\text{solar}}} = \frac{\dot{Q}_{\text{H}_2\text{SO}_{4} - \text{dissociation}} + \dot{Q}_{\text{SO}_2 - \text{decomposition}} + \dot{Q}_{\text{sensible heat}}}{P_{\text{solar}}} \]

Efficiency of the SO₃-decomposition

\( T_{\text{inlet}} = 450 \, ^\circ \text{C}, \, w = 96 \%, \, l_{\text{Absorber}} = 0.15 \, \text{m} \)

Efficiency in %

Solar Flux Density in kW/m²

Two different fixed minimum conversions
Case studies: Gradient of Solar Flux

Case 1: The prototype test reactor as used in the solar furnace (Gaussian flux profile)
Case 2: Like case 1 but with an ideal homogeneous distribution of the solar flux density.
Case 3: Adiabatic absorber element of a large receiver-reactor on a solar tower.

Higher Conversion in a Large Scale Receiver-Reactor
Case Studies: Efficiency

Model of the evaporator (ETH)
Foam characterization by CT and digitalisation

SiSiC sample (uncoated, 20ppi → \( d_{\text{nom}} = 1.27 \text{mm} \)):

- Photo
- MicronCT
- 3D rendered

Characterisation of the foam

- Geometrical Characterisation
- Radiative Characterisation
- Convective Characterisation
- Heat Transfer Characterisation
- Mass Transfer Characterisation
Development of a continuum model

- Continuum model based on
  - Energy conservation, solid and fluid
  - Mass- & Species conservation, fluid
  - Momentum conservation, fluid

- will be able to predict: optimum and maximal mass flow of acid

- Variations in:
  - position of acid inlet
  - porosity and nominal diameter of foam
  - solar input
  - ...

- lead to a deeper understanding of the process and its optimization for maximum solar-to-chemical energy conversion efficiency

Validation of model using experimental data from solar furnace campaigns
Temperature maps and flow regimes of the foam vaporiser

Influence of process parameters on reactor’s energetic and chemical efficiency and mean outlet temperature
Scale-up

Implementation in to a Solar Tower
Summary

- Volumetric Receiver-Reactors well suited for thermochemical hydrogen production
- Observed yield close to therodynamic limits
- Efficiency of the reactor can still be drastically improved (Slow kinetics, high re-radiation losses)
- Materials: Optimum solutions by far not yet reached for redox materials, catalysts, construction materials
- A bunch of capable reactor and process models developed and now available for a broad variety of purposes and applications
- The more one gets into the details of process design, the higher are the production cost

Acknowledgements

The authors acknowledge the co-funding of the European Commission for the projects HYTHEC, HycycleS, HYDROSOL, HYDROSOL-2 and HYDROSOL-3D.

Many thanks for your attention!